CARBON SEQUESTRATION AND NITROGEN ADDITION IN SELECTED SOILS OF MOROGORO, MBEYA AND RUVUMA UNDER MAIZE-SOYBEAN INTERCROPPING AND ROTATIONS

SAID HAMADI

THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

2022

EXTENDED ABSTRACT

Soil organic carbon (SOC) is an essential soil property which has implications on soil fertility and crop productivity. Increase in SOC, among other processes is mediated through carbon sequestration by plant photosynthesis which upon decomposition of plant remains, and addition of root exudates. Different soil management practices are crucial for effective carbon sequestration which may add SOC depending on type of crop management practice and time. Agricultural soils may add from 0.4 up to 0.8 Pg C year^{-1} through different crop management strategies/options. However, it may require constant proper management for a long time. Increase in soil organic matter (SOM) can be achieved through addition and/ retaining of crop residue coupled with inclusion of leguminous crops in different cropping systems and management which, in turn, increase SOC and soil nitrogen (N). Residue retention can add up to 57 ± 14 g C m^{-2} yr^{-1} and, mulching can sequester in agricultural soils up to 16 Mg ha^{-1} C yr^{-1}, while addition of 18 - 29 Tg of N in soil can be achieved from different legumes. Despite those management strategies, declining SOC levels have frequently been observed in soils of tropical regions due to excessive C loss attributed to the high temperatures in these regions.

Most African countries are challenged by the need for multiple use of crop residues; and, lack of studies and information that has been generated on proper cropping system/s which will be able to change soils to become potential C sinks. Maintaining SOC to threshold levels on a specific site is crucial for proper soil management and sustainable crop intensification. This information is limited and requires time to generate. Therefore, this research was aimed at investigating different cropping systems of maize and soybean which have influence on the SOC, soil N, and grain and biomass yields in selected soils of Morogoro, Ruvuma and Mbeya regions.

The specific objectives of this study were to (1) undertake pedological characterization of the soils of the study areas, (2) determine the effects of maize-soybean intercropping and/or rotation on gains in soil nitrogen, soil organic carbon and crop yields (3) determine the effects of maize-soybean intercropping and/or rotation on water extractable organic carbon and water stable aggregates (4) determine effect of inorganic N fertilization and biomass addition on maize yield response, gains in soil nitrogen and soil organic carbon (5) were to determine the effect of inorganic N and residue retention on soil organic carbon, nitrogen, water extractable organic carbon and water stable aggregates in a soybean - maize rotation.

To achieve objective 1, two representative pedons namely SUARAT-P1 in Magadu and UYOLE-P1 in Uyole were characterized. A soil sample from each pedon was analysed for physico-chemical properties, described using FAO Guidelines clarifying morphological features, and was classified according to USDA Soil Taxonomy and World Reference Base (WRB) for Soil Resources. The results show that, soils from both sites were very deep with soil texture being Sandy Clay (SC) in topsoil and Clay in subsoil at Magadu and Sandy Loam (SL) in topsoil and Sand Clay Loam (SCL) in subsoil at Uyole. Soil pH ranged from slightly acidic to very strongly acidic in Magadu (pH 6.54 - 4.46) whereas Uyole soils were slightly acidic in top soils to neutral in subsoil horizons (pH 6.35 – 7.32). Soil organic carbon ranged from very low (0.12 %) to low (0.95 %) at Magadu and from medium (1.5 %) to low (1.13 %) at Uyole while nitrogen levels were very low to low at both sites. The Magadu CEC was medium (14.6 Cmol(c) kg^{-1}), whereas Uyole CEC was medium (21 Cmol(c) kg^{-1}) to high (34 Cmol(c) kg^{-1}) ; topsoil BS at Magadu was high (> 50%) in top soil and low (< 50%) in the subsoil while at Uyole had high BS throughout the profile depth. The soil at Magadu and Uyole, were classified, according to USDA Soil Taxonomy as *Typic Kandiustults* and *Andic Dystrudepts*, respectively.

For objective two to be achieved, a field experiment was laid out in a Randomized Complete Block Design (RCBD) involving different cropping systems (treatments) which included: Absolute control, maize monocropping, maize-soybean rotation, maize-soybean intercropping, sole soybean and sole maize under 80 kg N ha^{-1}. Crop yields (grain and crop residue biomass), N, and SOC were determined for each cropping system to assess the performance. The results (Chapter 3) showed that, there were no significant ($p < 0.05$) differences between cropping systems on the SOC sequestration and N addition for three seasons in Magadu, and two seasons in Suluti and Uyole sites. The SOC sequestration among cropping systems at Magadu site was numerically ($p < 0.05$) greater in the continuous sole maize plot amended with inorganic N fertilizer (80 kg N ha^{-1}). Meanwhile the trend of soil N in Magadu appeared to maintain almost the same soil N levels as numerical ($p > 0.05$) increase at Suluti and Uyole were observed. Maize grain yield in Magadu did not significantly ($p < 0.05$) differ between cropping systems second year, however, significantly ($p < 0.05$) higher soybean grain yield in the sole soybean were observed than in the intercropped plots. The maize grain yield in the Suluti was significantly ($p < 0.05$) higher in maize (80 kg N ha^{-1}) plots in the first year (1.34 Mg ha^{-1}), and significantly ($p < 0.05$) higher in the intercropping (2.5 Mg ha^{-1}) in second year. In the Uyole site, the intercropped and the inorganic fertilized maize (80 kg N ha^{-1}) plots had highest yields of 1.5 Mg ha^{-1} in the first year, and significantly ($p < 0.05$) higher in the fertilized maize (80 kg N ha^{-1}) plot in the second year (2.54 Mg ha^{-1}) than other cropping system. The above ground biomass in Magadu ranged from 14.05 Mg ha^{-1} in the maize (80 kg N ha^{-1}) and 5.7 Mg ha^{-1} in sole maize and rotation in the first year but decreased in the third year to 2.41 Mg ha^{-1} in the maize (80 kg N ha^{-1}) and 1.04 Mg ha^{-1} 1.29 Mg ha^{-1} in sole maize and rotation, respectively. Maize biomass yield in Uyole site was 11.3 - 12.96 Mg ha^{-1} in the first season, and ranged from 12.33 Mg ha^{-1} in the maize (80 kg N ha^{-1}), 8.82 Mg ha^{-1} in sole maize, and 6.96 Mg ha^{-1} in intercrop. The result point out that SOC, N, and the crop yield were not significantly enhanced in a three and two years under intercropping, rotation or monocropping periods. However, the grain and biomass yields were greatly influenced in the fertilized maize and intercropping. The C and N sequestration under these cropping systems may need more time to achieve potential SOM increment under this management.

Water extractable organic carbon (WEOC) and water stable aggregate (WSA) were correspondingly evaluated in the specific objective three following treatments in objective two. The results showed that, there were no significant ($p < 0.05$) differences in each cropping year on the WEOC as a result of the differences in cropping systems in Magadu, Suluti and Uyole. There were, however, different trends in the cold water extractable organic carbon (CWEOC) in different sites. Generally CWEOC value increased in the last year in Magadu and Suluti except in the intercrops, but some cropping system decreased or increased the CWEOC in Uyole site. Meanwhile, the hot water extractable organic carbon (HWEOC) at Magadu in the range of 41.6 – 100.2 mg kg^{-1} in the first year and increased in the range of 128.7 - 180.2 mg kg^{-1} in third year as a result of interventions. However, there were noticeable numerical decline in HWEOC at Uyole site from 182.4 – 78.3 mg kg^{-1} in the first year to 90.5 – 51.7 mg kg^{-1} in the second year. The ratio of water extractable organic carbon (WEOC) to total organic carbon (TOC) was different between Magadu, Suluti and Uyole sites. The relative percentage of CWEOC/TOC was highest in the fertilized maize (80 kg N ha^{-1}) at 0.90% in the Uyole site and HWEOC/TOC was highest (1.25%) in intercropping in Magadu. There were no significant ($p < 0.05$) differences between different cropping systems on the distribution of individual aggregate sizes of macroaggregates (>2.00 mm), mesoaggregates (2.00 - 0.5 mm) and microaggregates (< 0.25 mm) in each cropping year. The Magadu and Suluti sites exhibited a higher proportion of macroaggregates in the range of 40 – 58 % and 39 – 55

%, respectively, and lower range in Uyole site (9.8 – 23 %) in the last cropping year. Magadu and Uyole exhibited slowly decline in macroaggregates across cropping years, while Suluti site increased macroaggregate proportion in all cropping systems in the last year. Different cropping systems together with residue incorporation improved WEOC and soil aggregates in some soils and, therefore, can be recommended as management strategy for the future.

To achieve objective four, a field experiment involving maize and soybean intercropping system rotated with maize monocropping were evaluated against impact of different rates of inorganic fertilizer N (40 and 80 kg ha^{-1}) coupled by a combination of crop residue of maize and soybean (1 x maize (2 Mg ha^{-1}) + soybean (0.5 Mg ha^{-1}) and 2 x maize (4 Mg ha^{-1}) + soybean (1.0 Mg ha^{-1})) on soil N, SOC and crop yields.

The results (Chapter 5) showed no significant ($p < 0.05$) differences in the soil N and SOC, between treatments in Magadu, Suluti and Uyole. In the first season in Magadu, the soil N ranged from 0.10% to 0.14% while in the second season where maize alone was planted, soil N declined in the range from 0.103% to 0.096 % but soil N regained in the third season from 0.12% - 0.13%. Soil N values insignificantly increased in both Suluti and Uyole sites in the second season in each treatment after amendments. There were no significant ($p < 0.05$) SOC differences between treatments in each season in Magadu Suluti and Uyole. Insignificant SOC values increment was realized in the treatments with double biomass doses in Magadu from 1.07% – 1.16% and 1.06 – 1.20% in the first and third seasons, respectively. The Suluti maize grain yield ranged between 1.35 – 0.6 Mg ha^{-1} in the first season and 1.18 - 0.75 Mg ha^{-1} in the second season while Uyole site had maize grain yield ranged between 1.9 - 1.01 Mg ha^{-1} and 1.79 - 0.97 Mg ha^{-1} in the first and second season, respectively. Magadu experienced a sharp decrease in grain yield in three season regardless of inorganic N and crop residue addition from 1.9 to 0.38 Mg ha^{-1}, 0.78 to 0.41 Mg $ha^{-1}$and 0.4 - 0.13 Mg ha^{-1} in the first, second and third seasons, respectively. However, at higher mineral N and crop residue dose, the yield was enhanced than other treatments across all seasons in all three sites. The results from this study show that crop residues returned under intercropping coupled with inorganic N may stabilize SOC and N with future prospect to add more SOC and N after a prolonged management. Crop yields were improved by addition of residue and 80 kg N ha^{-1} of inorganic N, nonetheless, subsequent increase in yield require improved soil properties under crop residues returned over a prolonged time.

To achieve objective five, a continued maize and soybean crop rotation under different rates of inorganic N and P (120 kg N ha^{-1} and 20 kg P ha^{-1} as recommended fertilizer input, and 60 kg N ha^{-1} and 10 kg P ha^{-1} as half recommended fertilizer input) and crop residue retention, was carried out to evaluate the soil N, SOC trends, aggregate stability, and water extractable organic (WEOC).

The results showed no significant ($p < 0.05$) differences between cropping treatments on SOC, total N, WEOC and aggregates size distribution after five years. It seems that soil N and SOC increased in the second season in Uyole and Suluti. In Uyole, the CWEOC and HWEOC progressively increased over seasons with higher CWEOC and HWEOC values reached in the sole maize (120 kg N ha^{-1} and 20 kg P ha^{-1}) (197.16 mg kg^{-1}) and in the inoculated soybean (295.7 mg kg^{-1}), respectively. At the Suluti site, the CWEOC values were appreciably higher in the third season and progressively decreasing the HWEOC values with time. In Suluti site as well, a sole maize (120 kg N ha^{-1} and 20 kg P ha^{-1}) also registered insignificant higher CWEOC value of 321.3 mg kg^{-1} than all cropping systems.

In both sites, Uyole and Suluti, mesoaggregates (2.00 mm - 0.5 mm) values were higher than macroaggregates (> 2.00 mm) and microaggregates (<0.250 mm). The trend showed that over time, there were decreases in distribution of macroaggregates and increase in microaggregates.

Major conclusions drawn from this study are that the soils of Magadu and Uyole have different morphological and chemical properties. According to USDA Soil Taxonomy, the soil of Magadu (SUA) and Uyole pedon (UYOLE-P1) are classified as *Typic Kandiustults* and *Andic Dystrudepts,* respectively. The soil of Magadu has been rated as low in organic matter, total nitrogen, and available phosphorus. Generally the soil has poor fertility and need soil management to sustain agriculture. The soil of Uyole has medium rated OM and low N, medium P, and very high K, together with medium to high CEC and BS, the soil is likely to offer moderately favorable soil conditions for crop production

The soil organic carbon, soil nitrogen, and the crop yield were not significantly enhanced after three years in Magadu and two years each in Suluti and Uyole.under intercropping, rotation or monocropping, and that significant increment may require long periods of time to accumulate. On other hand, application of inorganic N fertilizer coupled with residue incorporation insignificantly elevated grain and total biomass yield.

In addition, these cropping systems in three and two years did not improve water extractable organic carbon (WEOC) and aggregate stability significantly; yet, continuous maize under residue retention can retain most of larger aggregates than other cropping systems. Crop residue returned under intercropping coupled with inorganic N appears to insignificantly stabilize SOC and N.

Combination of inorganic N fertilizer and different levels of crop residue returned in soils under intercropping have slightly (not significantly) increased SOC in the third season in Magadu site, and increased in soil nitrogen in Uyole and Suluti. This cropping management may add more SOC and N after a prolonged practice. Moreover, use of crop residue (maize and soybean) and 80 kg N ha^{-1} of inorganic N relatively improved maize grain yield.

In the five years of maize and soybean rotation under maize and soybean residue retention and inorganic N amendment, it is inferred that crop management started to slightly increase the values of soil C and N and, thus over long term there are possibilities of increasing these two soil properties. The loss of larger aggregates whose quantity declined each season due to soil disturbance in the soil preparation could have resulted in C loss over time in both sites and reduced effective SOC sequestration.

Based on the conclusions it is recommended that the C sequestration under different cropping systems including intercropping, rotation and monocropping; residue retention and, residue retention coupled with inorganic N fertilizers will require more time to achieve significant increase in SOC, soil N and, WEOC and soil stable aggregates. However, in order to maximize and maintain SOM, it is suggested to shift to conservation or minimum tillage practice to minimize disturbances to soil aggregate for effective C stabilization and sequestration.

DECLARATION

I, **Said Hamadi**, do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my own original work done within the period of registration and that it has neither been submitted nor concurrently being submitted for degree award in any other institution.

____________________________ __________________

Said Hamadi **Date**

(PhD Candidate)

The above declaration is confirmed by;

____________________________ __________________

Dr. Hamisi J. Tindwa **Date**

(Supervisor)

____________________________ __________________

Prof. Ernest Semu **Date**

(Supervisor)

____________________________ __________________

Prof. Balthazar M. Msanya **Date**

(Supervisor)

COPYRIGHT

ACKNOWLEDGEMENTS

I am very thankful to the Sustainable Intensification Innovation Laboratory Project (SIIL) at Sokoine University of Agriculture for sponsoring my studies, and Dr. Hamisi Juma Tindwa, in particular, for coordinating this programme.

I am intensely indebted to my supervisors Dr. Hamisi Juma Tindwa, Professor Ernest Semu, and Professor Balthazar Michael Msanya for your guidance at all times made this work to be done. I am sincerely thankful for your tireless effort, encouragement and great ideas throughout this journey.

Very special thanks to all staff members of the Department of Soil and Geological Sciences, who gave their full support and encouragement during time I attended the programme, my field, laboratory works, and my entire time spent. If not for their help, concern, and their guidance, this work would not have been achieved.

Special thanks to Dr. Nyambilila Abdallah Amuri and Dr. Hamisi J. Tindwa who were the Head of Soil and Geological Sciences Department during the period of my PhD study at the Department. In additional, other Department staff members namely, Professor Jerome Peter Mrema, Professor Method Kilasara, Professor Filbert Balthazar Rwehumbiza, Professor Balthazar Michael Msanya, Professor Johnson Mashambo Semoka, Professor Ernest Semu, Dr. Peter Wilson Mtakwa, Dr. Mawazo J. Shitindi, and Dr Boniface Hussein Massawe.

I am very indebted to all the laboratory technicians specifically, Mr. Louis Lucas Mdoe, Mr. Mohamed Hamisi, Mr. Stevenson Pelegy Noah, Mr. Yeronimus Yohana Ambrose, Mrs. Pascalina M. Mtanke and the retired staff member Mr. Salum Marangi for their tireless support during my laboratory work.

In a special way I would like to thank the Technician In charge Mr. Amour Suleiman Mohamed for his tireless effort during my hardest time in the laboratory work. Not to forget the former Technician Incharge Dr. Consolata Mhaiki who gave me solutions to many laboratory challenges.

My heartfull thanks go to my Postgraduate student in the Department of Soil and Geological Sciences, namely Mr. Mgeta Steven Merumba, Mr. Said Hussein Marzouk and Mr. Moh'd Mmanga Omary, Mr. Raphael Damiano and Miss. Grace Christopher Mpinda for their daily encouragement and support. I further appreciate former Postgraduates students, Dr Asheri Mwamba Kalala, Dr. Said Masoud, Dr. John Tenga, Dr. Thomas Nestory Bwana, Mr. Steven Gerson Saddick, for their support during our stay as postgraduate students.

I would like to express my gratitude to Agricultural Research Institute - Uyole (ARI-Uyole) to provide a field plot in Uyole (Mbeya) and Suluti (Ruvuma) for these trails. I express my special appreciation to Dr. Fredrick Baijukya of IITA, who provided us authorisation to use the N2Africa research plots to assess parameters cover the interests of this research. My special gratitude go to Mrs. Aida Alex Magelanga, the Incharge of the N2Africa research plots, and Miss. Veronica Twisa at ARI-Uyole and Miss Halima Nyanje in ARI-Uyole (Suluti) who provided assistance during my field work in their respective stations.

I sincerely express my appreciation to my employer, The University of Dar-es-salaam for granting me a study leave to pursue this PhD programme.

I am particularly grateful to my Head of Department and all staff of the Department of Molecular Biology and Biotechnology, University of Dar-es-salaam for their moral support.

Last but not least, to my beloved family: my wife, Adilah Alhad Omar, for her support, encouragement and faith she put on me during my study. To my sons; Salim, Salmaan and, Sameer and Saajid who for sometimes missed me during my travels. To my beloved mother, your constant calls and prayers encouraged me. My father, brothers, sisters, uncles and all Mangushi family.

All mentioned, receive my utmost gratitude, and may Almighty Allah (SW) bless you.

DEDICATION

I dedicate this work to my late grandfather and special friends Mr. Said Salim Amur (Mzee Mangush), my late daddy Hamadi Mohamed Suleiman, my mother Laila Said Salim, and my wife, Adilah Alhad Omar. Opportunity never fails those who hold it firm.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS AND SYMBOLS

%	Percent
AAS	Atomic absorption spectrophotometer
ANOVA	Analysis of variance
BD	Bulk density
BS	Base saturation
C:N ratio	Carbon to nitrogen ratio
$Ca(OH)_2$	Calcium hydroxide
$CaCO_3$	Calcium carbonate
CEC	Cation exchange capacity
CIA	Chemical index of alteration
cm	Centimetre
Cmol(+) kg^{-1}	centimole charge per kg
CO_2	Carbon dioxide
CV	Coefficient of variation
CWEOC	Cold eater extractable organic carbon
DOC	Dissolved organic carbon
dS m^{-1}	deciSiemens per metre
DTPA	Diethylyene triamine penta-acetic acid
EC	Electrical conductivity

ED-XRF	Energy dispersive x-ray fluorescence spectrometer
ESP	Exchangeable sodium percentage
et al.	and others
FAO	Food and Agriculture Organization of the Unites Nation
GENSTAT	General Statistics
GMD	Geometric mean diameter
GPS	Global positioning system
GST	Geological Survey of Tanzania
HWEOC	Hot water extractable organic carbon
K_2O	Potassium oxide
KCl	Potassium chloride
M	Mole
m.a.s.l	metres above sea level
Mg ha^{-1}	Megagram per hectare
mg kg^{-1}	milligram per kilogram
Mg m^{-3}	Megagram per cubic metre
$Mg(OH)_2$	Magnesium hydroxide
$MgCO_3$	Magnesium carbonate
mm	millimetre
MPa	Mega Pascals
MWD	Mean weight diameter
NH_4OAc	Ammonium acetate
NPK	Nitrogen, phosphorus and potassium compound fertilizer
^oC	Degree Celsius
OC	Organic Carbon
P_2O_5	Diphosphorus pentaoxide (phosphorus oxide)

Pg	Petagram
pH	Negative logarithm of hydrogen ions concentration
PhD	Doctor of Philosophy
RCBD	Randomized Complete Block Design
SMR	Soil moisture regime
SO_4^{2-}	Sulphate ions
SOC	Soil organic carbon
SOM	Soil organic matter
SON	soil organic nitrogen
STR	Soil temperature regime
SUA	Sokoine University of Agriculture
TEB	Total exchangeable bases
TN	Total nitrogen
USD	United States of America Dollar
USDA	United States Department of Agriculture
UV/VIS	Ultraviolet visible spectrophotometer
WEOC	Water Extractable organic carbon
WRB	World Reference Base
XRF	X-Ray Fluorescence Spectrometry

CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 Background Information

Soil is the largest reservoir of terrestrial carbon (C), having a total of 2,500 Pg of organic and inorganic C combined within a depth of 1 m from the surface, with the live biomass and detritus materials of the biotic part contributing 560 Pg and 60 Pg C, respectively (Lal, 2010). Carbon sequestration refers to the process of transferring atmospheric carbon dioxide (CO_2) into different C pools through the photosynthesis process (to obtain organic carbon), or the transfer of various inorganic C forms to long-term storage C pools (Olson *et al.*, 2014).

Carbon sequestration in soils is an outcome of various factors, which include inherent soil properties, environmental and management factors, and physical and biological state of the soil. A good balance between the photosynthetic C intake and CO_2 produced through soil respiration is important for the addition and conservation of global C stock (Alidoust *et al.,* 2018) and mitigation of greenhouse gas (GHG) production and global warming (IPPC Climate Change, 2013). This enhancement of soil carbon sink from the atmosphere is also associated with an upturn in soil quality (Alidoust *et al.,* 2018), which consequently results in increased levels of growth, yields and quality of crops (Ohshiro *et al.*, 2016).

Soil organic matter (SOM) confers essential physical, chemical and biological properties of soil, with implications on soil fertility (Condron *et al.,* 2010), and is determined by measuring soil organic carbon (SOC) (Condron *et al.,* 2010). Soils with low levels of SOC have low cation exchange capacity (CEC), low water content and nutrient retention capacity and low supply of nutrients to plants (Lal, 2006). On the other hand, higher SOC enhances soil fertility, structure and water holding capacity (Condron *et al.,* 2010); it prevents soil from adverse pH fluctuations and nutrient leaching (Hobbs, 2007). For example, Lal (2013) estimated that food production might increase by 30-50 million Mg yr^{-1} in developing countries by rising root zone SOC to 1 Mg $ha^{-1.}$

It has also been suggested by Qiu *et al*. (2009) that in China, every addition of 1 g C kg^{-1} of soil could increase maize and wheat grain yield by 454 kg ha^{-1}. However, declining SOC has been frequently observed in tropical regions due to an excessive loss of C attributed to higher temperatures favouring fast turnover rates through microbial decomposition activities (Kaur *et al*., 2005). Microbes in soil control nutrient dynamics through decomposition of available organic materials through immobilization, mineralization and nutrient retention in the ecosystem (Bardgett *et al.,* 2002).

Therefore, building up of SOC above some critical/threshold levels is important (Patrick *et al*., 2013) to ensure higher fertility, health and productivity of a soil, and such an improvement of SOC level could be achieved through good soil management and farming practices (Lal, 2004). Among those practices is intercropping/rotation with leguminous crops which is considered as one of the good approaches/practices to improve SOC sequestration (Cong *et al.,* 2015; Gregorich, 2000). Leguminous crops have the advantage in that they improve physical, chemical and biological properties of the soil which by increasing biomass N through N_2 fixation and upon residue decomposition increases amount of organic matter (Egbe, 2005).

Despite its importance, an understanding of SOM levels that can be achieved through different cropping systems which increase crop production is presently lacking in many African countries (Patrick *et al*., 2013; Snapp *et al*., 1998). The challenge at hand is, therefore, to take such steps that will raise the soil carbon levels above a relevant threshold in a particular location.

1.2 Carbon Sequestration in Agricultural Soils

From ancient times, agriculture was one of the major activities that humans are engaged in for food sustenance at family level. As the human population increased, land use in some areas changed from small to larger farms to supply enough food and for commercial agricultural produce. Currently, approximately 35 % of global land is used for agricultural activities (Wang *et al.,* 2010) and, therefore, through agricultural intensification, there is an advantage of changing soils to become potential C sinks under good management systems (Liao *et al.,* 2015). It is estimated that agricultural soils globally may sequester 0.4 to 0.8 Pg C year^{-1} under good management practices which include no-till or conservation tillage, cover cropping, irrigation efficiency, crop rotation, manure application and crop residues retention, among others (Lal, 2004).

Good agricultural management practices account for substantial contribution to the C sequestered in soils in the form of SOM, the latter being an important factor for improved fertility and biological and physico-chemical properties of soil. Improved soil fertility is important for increased vegetation and biomass production. Although some of the plant-C generated from various processes is rapidly respired and lost as CO_2, some C components have mean residency time in soils extending from a few days to many years; and those with longer residency times play a crucial part in SOC stabilization (Blanco-Canqui and Lal, 2004). Apart from soil C sequestration being able to mitigate CO_2 emission to the atmosphere, it contributes to increased food-crop yield and to improve its sustainability through improving soil fertility.

1.3 Relationship between Carbon Sequestration and Soil Organic Matter Reserves

Soil organic matter refers to the organic content of either animal or plant origin after it has undergone full decomposition. The soil organic matter is mostly contributed by plant debris having up to 90% water and small fraction containing many important elements like magnesium (Mg), phosphorus (P), sulphur (S), potassium (K), nitrogen (N), calcium (Ca) and carbon (C) (Bot and Benites, 2005). Although little amounts of important element are released, SOM serves an important function of soil fertility enhancement and hence crop yield increase in addition to maintenance of physical, chemical and biological properties of the soil (Esmaeilzadeh and Ahangar, 2014).

The soil organic carbon (SOC) which is contained in organic molecules is principally found in SOM and serve as short and long term storage of soil C (Dynasrki *et al.,* 2020). The biotic activities of micro and macrofauna are important in ensuring supply of plant nutrients upon decomposition of animal and plant debris. These groups of organisms are primary decomposers which ensure continuity of soil life by releasing locked nutrients from dead organisms, cells or tissues and build up of SOC (Esmaeilzadeh and Ahangar, 2014; Bot and Benites, 2005).

In sub-soils, which generally contain half of a total world C-stock, the SOM is mainly contributed by root associated exudates, plant roots, dissolved organic matter and bioturbation by macroorganisms like earthworms, termites and others (Rumpel and Kögel-Knabner, 2011). For example, dissolved organic matter (DOM) has been estimated to account for about 10 to 200 kg C ha^{-1} yr^{-1} in subsoils (Rumpel and Kögel-Knabner, 2011), while the contribution from root C can be as high as up to 78 g C m^{-2} yr^{-1} (Kleja *et al*., 2008), contributing to higher soil C reserves in soil.

The soil C reserves from SOM can be divided according to their recalcitrance (mean residence time (MRT) in soil) from active, slow and passive pools. The active pool consists of microbial biomass, soluble carbohydrate and exocellular enzymes whose residence times vary between 0.4 -1.4 years (Woomer *et al*., 2005). This pool is very important in soil fertility as nutrients are fast-released from it as compared to the slow and passive pools (Bot and Benites, 2005).

The slow carbon pool, which is mainly comprised of particulate organic matter which is made of silt and clay, is the most important pool for C sequestration as it is estimated to last decades or even centuries in soil (Beedy *et al*., 2010) while the passive pool which comprises mainly humic and fulvic acids materials is characterized by its very slow turnover rates, from 400 - 22,000 years (Woomer *et al*., 2005).

1.4.1 Mechanisms/processes leading to sequestration of carbon in soils

1.4.1.1 Microbial biomass carbon pools

The top soil contains diverse groups of fungi and bacteria of agricultural importance, which enhance soil formation, and release of important nutrients to plants (Ahemad and Kibret, 2014). Soil microbial interaction from these microorganisms triggered by a coordinated gene expression through quorum sensing (Miller and Bassler, 2001). They are responsible for the formation of soil aggregates by means of microbial glue and mucilages

(Sollin *et al*., 2009). The soil aggregates are composed of some particles of underground C and partially decayed plant residues secured from the microbial attack (decomposition and respiration), thus increasing stability of SOC (Six *et al.*, 2006).

Microbial biomass plays a critical role in nutrient recovery and transformation in soils from decomposition of plant, animal and other available detritus materials (Kara and Bolat, 2008). Studies have shown that microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) in soil can be as high as 16.7 and 2.6 Pg of C and N, respectively, within the 0 – 30 cm depth of the soil profile, and 23.2 and 3.7 Pg of C and N, respectively in the 0 –100 cm depth of soil from the surface.

Therefore, soil microorganisms have a direct influence on dynamics of C and N storage of the soils (Hopkins and Gregorich, 2005). Their proliferation may depend on some climatic factors such as temperature rise, humidity and rainfall (Yang *et al.*, 2010), agricultural amendments such as organic matter inputs (Allison and Martiny, 2008). Microbial biomass variations in soil have an effect on soil organic matter turnover and consequently are used for short term assessment of soil quality (Yang *et al.,* 2010).

1.4.1.2 Arbuscular mycorrhizal fungi - plant associations

Plant-mycorrhizal associations accounts for up to 94% of fungi - plant association (Brundrett, 2009), where a plant directs up to 20% of its photosynthate to the mycorrhizal partner in exchange for supply of nutrients like P and N (Treseder and Allen, 2000), and some trace elements such as copper and zinc by the microbial partner (Fellbaum *et al.*, 2012). Estimates show that Arbuscular Mycorrhizal (AM) fungi can contribute about 54 to 900 kg C ha^{-1} (Zhu and Miller, 2003) and globally up to 5 billion tons of carbon per annum (Bago *et al.*, 2000). Furthermore, the fungi produce glycoproteins containing glomalin, which is estimated to have C that may last from 6 to 42 years in soil (Rillig *et al.,* 2001). The soils are gaining C through the discharge of C onto soil matrix from extraradical hyphae of AM fungi after acquiring C from host plants (Leake *et al.,* 2004). The AM also form aggregates and increase soil aggregate stability through enhancement of glomalin - related soil protein produced by fungi (Xiao *et al.,* 2019). Reports show that endomycorrhizal (EM) fungi receive from their macro partners more plant C than AM fungi do (Soudzilovskaia *et al.,* 2015), thereby contributing approximately 1.7 times more C per unit soil N in soil ecosystem than AM fungi (Averill *et al.,* 2014).

1.4.1.3 Plant root networks

Root network systems of plants produce substantial amounts of mixed carbon compounds of water soluble sugars and other complex compounds produced through photosynthesis. More than 200 different compounds are produced, composed of sugars, amino acids, organic acids, sugar alcohols and some mixtures of polypeptides and polysaccharides (Bais *et al.,* 2006; Kumar *et al.,* 2006). The root system helps in the supply of oxygen and the exudates form an important source of energy to soil microorganisms in the adjacent rhizosphere (Xu *et al.,* 2013). Most of the root carbons from exudates are readily available to microorganisms and fauna in the form of labile carbon, and its availability contributes to the increase in microbial C of the soil (Bradford *et al.,* 2008).

Plant photosynthesis generates about 10 - 40 % of C in the soil (Bias *et al.,* 2006). Hutsch *et al.* (2002) showed that most (64 - 86 %) of the exudates are immediately consumed by surrounding organisms. However, Bird and Torn (2006) found that 70.5 % of the C is reserved in soil as a result of fine root C compared to 42.9% of needle leaf C due to different fractions of the C as labile C compounds. Besides, it is reported that the mean residence time of root C is greater as compared to other C inputs such as shoot litter due to the fact that there is an aggregate formation leading to physicochemical protection of its carbon (Crow *et al.,* 2009; Gale and Cambardella, 2000) and hence form an important soil C reservoir.

1.4.1.4 Falling litter from plant - top biomass

Falling litter from plants represent the largest source of SOC and nutrients to soil (Yan *et al.,* 2013). Litterfall consists of a mixture of carbon-rich compounds like lignin and waxes, among others, which are relatively stable to decomposition (Crow *et al.,* 2009). Aliphatic compounds which comprise cutin, waxes and suberin from litterfall stabilize SOM pools as they gather belowground (Lorenz *et al.,* 2007). Addition of litter would result in an increased number of microbes and some other decomposer organisms and, hence, resulting in more biological activities (Yan *et al.,* 2013). Consequently, the addition of SOC is affected by the quality and quantity of litterfall added to the soils (Crow *et al.,* 2009). Therefore, rates of plant litter decomposition will depend on its quality, whereby compounds with nutrient - rich leaves would decomposes rapidly (Dent *et al.,* 2006).

1.5 Land Management Practices Leading to Accumulation of SOC Stocks

1.5.1 Reduction of mechanical tillage and adoption of no-till or minimum till

Carbon and nitrogen losses from soil have been challenging in agriculture due to human influenced activities. The conventional tillage systems bring disturbance in the soil by disrupting stable soil aggregates, enhancing soil aeration and sometimes bringing in new residues (Six *et al.,* 2000). Hence conventional tillage makes temporarily locked C and other nutrients to be available for microbial processes such as respiration, with C losses as CO_2 (Six *et al.,* 2004). No-till system, on the other hand, increases protection of soil aggregates where they form a physical barrier against microbial attack (Six *et al.,* 2002). Soil management via no-till has proved to increase SOC. Potter *et al.* (1997), for example, reported an increase of total SOC in the surface 20 cm for up to 5.6 Mg C ha^{-1} in a continuous wheat no-till treatment. On the other hand, West and Post (2002) suggested that conversion from conventional tillage to no-tillage management could increase soil C up to 57 ± 14 g C m^{-2} yr^{-1} if crop residue is left on the surface.

However, adoption of the no - till technology has posed an environmental challenge due to the fact that no-till agriculture has often times increased the use of herbicides to kill weeds (Mc Robert *et al.,* 2010) without physically disturbing the soil. Other studies have shown further that No-Till and Strip Till is better than the conventional tillage system in sequestering SOC and SON in the top 15 cm of the soil (Al-Kaisi *et al.,* 2005).

1.5.2 Effect of mulching on C sequestration

Mulching has been proven to be effective in controlling soil erosion, to moderate soil temperatures and in reducing soil moisture evaporation from soil surface (Sarkar *et al.,* 2007), to reduce surface runoff, increasing porosity and the infiltration of water (Glab and Kulig, 2008). The applied mulches are the C source for soil microbes and upon decomposition the SOM form centres for soil aggregation, enhancing formation of macroaggregates by extracellular polysaccharides from the mulches (Jastrow, 1996; Six *et al.,* 1999). According to Farooqi *et al.* (2018), mulching can enhance C sequestration in agricultural soils from 8 to16 Mg ha^{-1} yr^{-1}.

The application of different rates of mulch increases water stable aggregates (WSA) and mean weight diameter (MWD) and increase total and labile C and N in the soil (Kahlon *et al.,* 2013; Gu *et al.,* 2016). Saroa and Lal (2003) also found significant increase of WSA in the 0 - 5 cm in 4 years and 5 – 10 cm in 11 years. The same study also found that at higher mulching rates a significant increase in SOC was observed in the 5-10 cm; and increase in SOC in macroaggregate size classes. The mulching rate and time were determining factors for sustainable C sequestration in soils, increasing from 41% to 52% in the 4th and 11th years, respectively.

1.5.3 Effect of crop residues on C sequestration

Plant residues contain some important nutrients previously exploited from soils and, therefore, decomposition of residues is a way of returning nutrients back to the soil. The practice of incorporating residues into the soil increases SOM (SOC) (Lal, 2009), the C that originally came from atmosphere as a result of plant photosynthesis. Follett (2001) reported that residue biomass has the potential to sequester up to 67 metric tons of C per annum.

The quality and amount of residue type are among factors affecting C sequestration in most soils (Campos *et al.,* 2011). The decomposition rate of crop residues, among other factors, is affected by their C:N ratio and their lignin content (Maobe *et al.,* 2011; Baligar and Fageria, 2007); therefore, selection of crop residue types is of prime importance for C and nutrient recovery in soils (Baligar and Fageria, 2007). Residue quality has an influence on the short but not the long term storage of C in soils (Gentile *et al.,* 2011).

Soil types have different capacities in SOC stabilization under the same treatments of residue addition whereby red clay soils have been shown to bear more SOC, up to 20.4 mg C g^{-1} as compared to 4.8 mg C g^{-1} in sandy soils (Chivenge *et al.,* 2007). The crop residue biomass produced, however, poses a serious challenge in Africa as its competing use as animal feed interferes with the intended aim of sequestering C into soil (Bationo *et al.,* 2007).

1.6 The Potential of Leguminous Plants in C Sequestration

Most leguminous plants form symbiotic association with different rhizobia species to generate (fix) nitrogen for their needs through symbiotic Biological Nitrogen Fixation (BNF) (Hungria and Kaschuk, 2014). Leguminous crops have the advantage of improving physical, chemical and biological properties of the soil through N_2 fixation and to increase amount of soil organic matter (SOM) and C sequestration (Vieira *et al*., 2009). Increase in soil OC in legumes is emphasized through enhanced plant biomass by supplying N in the soil and the decomposition of this plant biomass consequently adds SOM and provides soil with greater attributes to sustainability and health (Cadisch *et al.,* 1998; Meena and Lal, 2018).

Estimates from past research show substantial amounts of N fixed by oilseed, pasture and fodder legume to reach 29.5 Tg, 18.5 Tg and up to 25 Tg of N fixed, respectively (Herridge *et al.,* 2008). Peoples *et al.* (2009) suggested that N_2 fixed reaches approximately 30 - 40 kg in every tonne of dry matter residues produced by legumes.

The leguminous plant has the advantage of increasing the numbers of beneficial microorganisms (i.e. fungi, actinomycetes and bacteria) in soils (Meena *et al.,* 2015; Adediran *et al.,* 2001), and addition of significant amount of biomass (Adediran *et al.,* 2001). The quality of SOM added in soil from these leguminous plants depends on type, amount and size of the residues (Tejada *et al.,* 2008).

However, a large amount of C and N sequestered is achieved in forage legumes, and legume green manures and cover crops (Reckling *et al*., 2014) as compared to legume cereals which extract most of soil N into their grain (Jensen *et al.*, 2012). For example, an increase in SOC was observed from vetch at rates ranging from 0.48 – 1.53 Mg C ha^{-1} $year^{-1}$ in no-tillage systems (Boddey *et al.*, 2010; Jensen *et al.*, 2012).

1.7 Effect of Crop Diversification Incorporating Leguminous Plants on Soil C and N

Crop diversification is a cropping technique where different crops are planted in one area or sequentially on same piece of land. Through legume/cereal crop rotation soil fertility was improved and yields were enhanced (Deutsch, 2006). The SOC was shown to increase in legume/cereal crop rotation (Gregorich, 2000), while mitigating other soil physical, chemical and biological conditions (Vieira *et al.*, 2009), hence regeneration of severely degraded soils.

Many studies have shown a significant impact of crop rotation on C sequestration. Reports show, for example, that a seven years old soybean-maize rotation significantly enhanced soil properties with simultaneous organic C and N increases within a depth of 15 cm from the surface (Al-Kaisi *et al.*, 2005; Mandal *et al.*, 2013). In another study, Uzoh *et al.* (2019) showed that the soil had significantly increased total N, available phosphorus (P), exchangeable potassium (K), magnesium (Mg) and effective cation exchange capacity (ECEC) after different legumes and maize rotation in sandy loam soils. On the other hand, it was shown that long-term intercropping enhanced SOM and root litter decomposition rates as compared to monocropping due to the low C:N ratio exhibited by the combined cereal-legume litter (Cong *et al.*, 2015; Cong *et al.*, 2014).

1.8 Soil Aggregate Stability

Soil aggregate are formed as a result of binding together of smaller soil particles, forming different sizes of independent aggregate units. They occur in different sizes known as macro- and micro-aggregates, where macro-aggregates are > 250 μm in size, as a result of combination of some micro-aggregates of < 250 μm and clay particles of < 2 μm (Wagner *et al.,* 2007). This is an important physical structure of the soil which has direct effect on the water infiltration capacity, aeration, root penetration and as an indicator of stability against soil wind, rainfall or runoff erosions (Kavdir *et al.,* 2004). Soil with good aggregate stability provides a physical barrier and enhances protection of SOC, as binding agent, from being available to microbial decomposition and from microbial respiration (Lützow *et al.,* 2010). These macroaggregates are important in C and N sequestration (Dorodnikov *et al*., 2009).

Soil organic matter is an important constituent which binds together different soil minerals to form different soil aggregate sizes (Li *et al.,* 2017). Increase in SOM is directly linked to the increase in aggregate formation and vice versa, which affects C stocks (Li *et al.,* 2017; Elliot 1986; Tisdall and Oades, 1982). Li *et al.* (2017) found that at higher organic C inputs macroaggregation was enhanced, with decreased proportion of microaggregates. Plant litter consist of easily decomposable and resistant plant materials which, upon fragmentation and decomposition, transform into course particulate organic matter > 250 µm (cPOM) and fine particulate organic matter 53 – 250 µm (fPOM). These POM as readily available source of C to microbes interact with soil textural units including silt and clay-size particles to form stable soil aggregates (Li *et al.,* 2017; Benbi *et al.,* 2014). The resulting blends (organomineral complexes) are important in the formation of stable OC and soil aggregates (Jastrow *et al.,* 2007). Other important SOM fractions are mineral- associated organic matter (Mi-OM; < 53 µm) which, within soil aggregates, are physically and chemically stabilized and are inaccessible from microbial attack because of having relatively longer turnover times (Benbi *et al.,* 2014; Marschner *et al.,* 2008).

Factors affecting stability of aggregates include the cementing agents that builds the aggregates; they include clays, oxides of aluminium and iron (sesquioxides), multi-valent cations and their complexes, SOM, and calcium carbonate ($CaCO_3$) (Zhao *et al.,* 2017; Abiven *et al.,* 2008). Clay particles are important aggregating agents as they possess high specific surface area and cation exchange capacity (CEC) (Besalatpour *et al.,* 2013).

Studies showed that classes and quantity of clay are important in aggregate stabilization (Reichert and Norton, 1994). For instance, it has been shown that high-surface-area clays (e.g. bentonites) are associated with higher aggregation stabilities as compared to low-surface-area clays (kaolinite) at the same quantity (Mazurak, 1950), while significant aggregation is observed when SOM is mixed with substantial portions of kaolinite clay minerals as compared to montmorillonitic clay alone (Stevenson, 1994).

Production of biological glue (polysaccharides and mucilage) from soil organisms is another mechanism for aggregate stabilization from physical activities. They hold together aggregates as a function of network of plant roots, fungal hyphae and mycelium (Rillig *et al.*, 2015; DeGryze *et al.,* 2004).

On the other hand, different organic matter (OM) amendments showed different aggregate stabilization extents in different soil types (Sacker *et al.,* 2018). The polyvalent metal-organic matter complexes of SOM fraction start binding the clay particles into clumps of micro-aggregates (Kavdir *et al.,* 2004), thereby making them inaccessible for decomposition, and this is a way of preserving SOC (Blanco-Canqui and Lal, 2004; Six *et al.,* 2002). Furthermore, the size distribution and aggregate stability are significantly influenced by type of land use and the presence of aluminium (Al) and iron (Fe) oxides. The Al and Fe oxides combination form high tensile strength and high stability of the aggregates through organo-mineral complexes (Kavdir *et al.,* 2004; Barral *et al.,* 1998).

For example, Zhao *et al.* (2017) found that mean weight diameter (MWD) and water stable aggregate (WSA) in paddy soils were significantly higher than in forest and upland soils; the cumulative effect of SOC and oxides of Al and Fe were 84.3 % towards stability and size distribution of aggregation.

In addition, several studies have been undertaken in fungal and bacterial communities on their roles in soil aggregation. In assessing the microbial community and abundance in different sizes of aggregates it has been observed that acidobacteria were markedly observed in macro-aggregates while alphaproteobacteria and actinobacteria were more prominent in micro-aggregates (Mummy *et al.,* 2006). Moreover, findings show that occurrence of different bacterial species may also be influenced by quality and quantity of SOC in aggregates (Davinic *et al*., 2012) and the soil's N status (Väisänen *et al.,* 2005).

1.9 Justification

The adoption of crop residue retention in the field is among the farming practices that increase soil organic matter (SOM), including soil C and N. However, this practice is hard to implement adequately by the smallholder African farmers partly due to minimal crop residue incorporation in soils as it is challenged by secondary uses of the residues and poor knowledge of soil management; residues are often removed from field and used for grazing (Murungu, 2012), biofuel production (Batidzirai *et al.,* 2016) or, most often, burnt for field clearance (Turmel *et al.,* 2015). These practices interfere with the intended aim of sequestering C and N into soil (Bationo *et al.,* 2007).

Snapp *et al*. (1998) reported that 7 Mg of low quality crop residues ha^{-1} $year^{-1}$ or 10 Mg of high quality crop residue ha^{-1} $year^{-1}$ are needed to maintain a 1.0 % organic C level in soil. As an alternative, there are suggestions that an effective increase in SOC sequestration and SON addition is achievable through implementing sound cropping systems and/or soil management practices (Majumdar *et al.*, 2007). An intercropping system involving cereals (such as maize) and legumes has become a favourite system to overcome declining productivity of soils (Marandu *et al*., 2013), mainly due to the multifaceted benefits the practice can offer to the system.

There are still questions, however, as to how much carbon and nitrogen can be sequestered in soil as a result of a cereal-legume intercrop or rotation practice and whether this intercrop/rotation can help to maintain soil organic C above some threshold/ critical levels, improve soil N and other soil properties and thus enhance its productivity especially in the tropics. These were investigated in this research.

1.10 Objectives of the Study

1.10.1 Overall objective

The overall objective of this study were to:

Improve soil nitrogen, carbon sequestration, and crop productivity as a result of maize-soybean intercropping and rotation.

1.10.2 Specific objectives

The specific objectives of this study are to:

i. undertake pedological characterization of the soils of the study areas.

ii. determine the effects of maize-soybean intercropping and/or rotation on gains of soil nitrogen, soil organic carbon and crop yields.

iii. determine the effects of maize-soybean intercropping and/or rotation on water extractable organic carbon and water stable aggregates.

iv. determine effect of inorganic N fertilization and biomass addition in response to maize yield, gains of soil nitrogen and soil organic carbon.

v. determine the effect of inorganic N and residue retention on soil organic carbon, nitrogen, water extractable organic carbon and water stable aggregates in a soybean - maize rotation.

1.11 Organization of the Thesis

This thesis is organized into seven chapters.

Chapter 1: This chapter presents the general introduction providing theoretical background information of the study, justification and objectives of the study.

Chapter 2: This chapter covers pedological characterization of two study sites of, Morogoro and Uyole in Mbeya. The chapter covers soil morphology, physical and chemical characteristics and soil classification. A manuscript of this chapter was authored by Said Hamadi Mohamed, Balthazar Michael Msanya, Hamisi Juma Tindwa and Ernest Semu. Pedological Characterization and Classification of Selected Soils of Morogoro and Mbeya Regions of Tanzania has been published in the International Journal of Natural Resource Ecology and Management. Vol. 6, No. 2, 2021, pp. 79-92. doi: 10.11648/j.ijnrem. 20210602.17.

Chapter 3: This chapter covers influence of maize-soybean intercropping and rotation on gains of soil nitrogen, soil organic carbon and crop yields.

Chapter 4: This chapter covers the effect of different maize - soybean cropping system (monocropping, rotation and intercropping) and crop residue retention on water extractable organic carbon and soil aggregate stability.

Chapter 5: This chapter assessed the impact of different rates of inorganic fertilizer N and crop residue of maize and soybean on soil nitrogen, organic carbon, and crop yields under intercropping.

Chapter 6: This chapter covers the influence of soybean rotation system and residue retention on soil C sequestration, soil N, water extractable organic carbon and aggregates size distribution.

Chapter 7: This chapter presents general conclusion and recommendations from the research.

References

Abiven, S., Menasseri, S., Angers, D. A. and Leterme, P. (2008). A model to predict soil aggregate stability dynamics following organic residue incorporation under field conditions. *Soil Science Society of America Journal* 72(1): 119-125.

Adediran, J. A., Akande, M. O., Banjoko, V. A., Oluwatosin, G. A. and Taiwo, L. B. (2001). Influence of legume fallow on soil properties and yield of maize in South Western Nigeria. *Journal of Agriculture in the Tropics and Subtropics* 102(2): 109-117.

Ahemad, M. and Kibret, M. (2014). Mechanisms and applications of plant growth promoting rhizobacteria: current perspective. *Journal of King Saud University-Science* 26(1): 1-20.

Alidoust, E., Afyuni, M., Hajabbasi, M. A. and Mosaddeghi, M. R. (2018). Soil carbon sequestration potential as affected by soil physical and climatic factors under different land uses in a semiarid region. *Catena* 171: 62-71.

Al-Kaisi, M. M. and Yin, X. (2005). Tillage and crop residue effects on soil carbon and carbon dioxide emission in corn–soybean rotations. *Journal of Environmental Quality* 34(2): 437- 445.

Allison, S. D. and Martiny, J. B. H. (2008). Resistance, resilience, and redundancy in microbial communities. *Proceeding of the National Academy of Science of United State of America* 105: 11512–11519.

Averill C., Turner, B. L. and Finzi, A. C. (2014). Mycorrhiza-mediated competition between plants and decomposers drives soil carbon storage. *Nature* 505: 543–545.

Bago, B., Pfeffer, P. E. and Shachar-Hill, Y. (2000). Carbon Metabolism and Transport in Arbuscular Mycorrhizas. *Plant Physiology* 124: 949 – 957.

Bais, H. P., Weir, T. L., Perry, L. G., Gilroy, S. and Vivanco, J. M. (2006). The role of root exudates in rhizosphere interactions with plants and other organisms. *Annual Review of Plant Biology* 57: 233-266.

Baker, J. M., Costner, T. E., Ventura, R. T. and Griffis, T. J. (2007). Tillage and soil carbon sequestration-What do we really know? *Agriculture, Ecosystems and Environment* 118: 1 – 5.

Baligar, V. C. and Fageria, N. K. (2007). Agronomy and physiology of tropical cover crops. *Journal of Plant Nutrition* 30(8): 1287-1339.

Bardgett, R. D., Streeter, T. C., Cole, L. and Hartley, I. R. (2002). Linkages between soil biota, nitrogen availability and plant nitrogen uptake in a mountain ecosystemin the Scottish Highlands. *Applied Soil Ecology* 19: 121 – 134.

Barral, M. T., Arias, M. and Guerif, J. (1998). Effects of iron and organic matter on the porosity and structural stability of soil aggregates. *Soil and Tillage Research* 46(3-4): 261-272.

Bates, S. T., Berg-Lyons, D., Caporaso, J. G., Walters, W. A., Knight, R. and Fierer, N. (2010). Examining the global distribution of dominant archaeal populations in soil. *International Society for Microbial Ecology Journal* 5: 908–917.

Batidzirai, B., Valk, M., Wicke, B., Junginger, M., Daioglou, V., Euler, W. and Faaij, A.P.C. (2016). Current and future technical, economic and environmental feasibility of maize and wheat residues supply for biomass energy application: Illustrated for South Africa. *Biomass and Bioenergy* 92: 106-129.

Beedy, T. L., Snapp, S. S., Akinnifesi, F. K., and Sileshi, G. W. (2010). Impact of Gliricidia sepium intercropping on soil organic matter fractions in a maize-based cropping system. *Agriculture, Ecosystems and Environment* 138(3-4): 139-146.

Benbi, D. K., Boparai, A. K. and Brar, K. (2014). Decomposition of particulate organic matter is more sensitive to temperature than the mineral associated organic matter. *Soil Biology and Biochemistry* 70: 183–192.

Besalatpour, A. A., Ayoubi, S., Hajabbasi, M. A., Mosaddeghi, M. and Schulin, R. (2013). Estimating wet soil aggregate stability from easily available properties in a highly mountainous watershed. *Catena* 111: 72-79.

Bird, J. A. and Torn, M. S. (2006). Fine roots vs. needles: a comparison of 13 C and 15 N dynamics in a ponderosa pine forest soil. *Biogeochemistry* 79(3): 361-382.

Blanco-Canqui, H. and Lal, R. (2004). Mechanisms of carbon sequestration in soil aggregates. *Critical Reviews in Plant Sciences* 23(6): 481-504.

Blanco-Canqui, H. and Lal, R. (2007). Soil structure and organic carbon relationships following 10 years of wheat straw management in no-till. *Soil and Tillage Research* 95(1-2): 240-254.

Boddey, R. M., Jantalia, C. P., Zanatta, J. A., Conceição, P. C., Bayer, C. and Mielniczuk, J. (2010). Carbon accumulation at depth in Ferralsols under zero-till subtropical agriculture in southern Brazil. *Global Change Biology* 16: 784 – 795.

Borneman, J. and Hartin, R. J. (2000). PCR primers that amplify fungal rRNA genes from environmental samples. *Applied and Environmental Microbiology* 66: 456– 436.

Bot, A. and Benites, J. (2005). *The importance of soil organic matter: Key to drought-resistant soil and sustained food production* (No. 80). Food and Agriculture Organization.

Bradford, M. A., Davies, C. A., Frey, S. D., Maddox, T. R., Melillo, J. M., Mohan, J. E., Reynolds, J. F., Treseder, K. K. and Wallenstein, M. D. (2008). Thermal adaptation of soil microbial respiration to elevated temperature. *Ecology Letters* 11(12): 1316-1327.

Brundrett, M. C. (2009). Mycorrhizal associations and other means of nutrition of vascular plants: understanding the global diversity of host plants by resolving conflicting information and developing reliable means of diagnosis. *Plant and Soil* 320: 37–77.

Cadisch, G., Oliveira, O. C. de, Cantarutti, R., Carvalho, E. and Urquiaga, S. (1998). The role of legume quality in soil carbon dynamics in savannah ecosystems. In I. Bergstrom and H. Kirchmann, eds. Carbon and nutrient dynamics in natural and agricultural tropical ecosystems. Wallingford, UK, CAB International.

Campos, B. C., Amado, T. J. C., Bayer, C., Nicoloso, R. S. and Fiorin, J. E. (2011). Carbon stock and its compartments in a subtropical oxisol under long-term tillage and cropping systems. *Revista Brasileira de Ciência do Solo* 35: 805-817.

Chivenge, P. P., Murwira, H. K., Giller, K. E., Mapfumo, P. and Six, J. (2007). Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. *Soil and Tillage Research* 94(2): 328-337.

Coleman, D. C. and Wall, D. H. (2015). Soil fauna: Occurrence, biodiversity, and roles in ecosystem function. *Soil Microbiology, Ecology and Biochemistry* 4: 111-149.

Condron, L., Stark, C., O'Callaghan, M., Clinton, P. and Huang, Z. (2010). The role of microbial communities in the formation and decomposition of soil organic matter. In: *Soil Microbiology and Sustainable Crop Production.* (Edited by Tilston, E. I. and Dixon, G.R.), Springer Science. pp. 81–118.

Crow, S. E., Lajtha, K., Filley, T. R., Swanston, C. W., Bowden, R. D. and Caldwell, B. A. (2009). Sources of plant-derived carbon and stability of organic matter in soil: implications for global change. *Global Change Biology* 15: 2003–2019.

Davinic, M., Fultz, L. M., Acosta-Martinez, V., Calderón, F. J., Cox, S. B., Dowd, S. E., Allen, V. G., Zak, J. C. and Moore-Kucera, J. (2012). Pyrosequencing and mid-infrared spectroscopy reveal distinct aggregate stratification of soil bacterial communities and organic matter composition. *Soil Biology and Biochemistry* 46: 63-72.

DeGryze, S., Six, J., Paustian, K., Morris, S. J., Paul, E. A. and Merckx, R. (2004). Soil organic carbon pool changes following land-use conversions. *Global Change Biology* 10: 120–1132.

Dent, D. H., Bagchi, R., Robinson, D., Majalap-Lee, N. and Burslem, D. F. (2006). Nutrient fluxes via litterfall and leaf litter decomposition vary across a gradient of soil nutrient supply in a lowland tropical rain forest. *Plant and Soil* 288(1): 197-215.

Dorodnikov, M., Blagodatskaya, E., Blagodatsky, S., Marhan, S., Fangmeier, A. and Kuzyakov, Y. (2009). Stimulation of microbial extracellular enzyme activities by elevated CO2 depends on aggregate size. *Global Change Biology* 15: 1603 – 1614.

Egbe, O. M. (2005). Assessment of biological nitrogen fixing potentials of pigeonpea genotypes intercropped with sorghum for soil fertility improvement in Southern Guinea Savanna of Nigeria. *Agro-Science* 6(1): 33 – 45.

Esmaeilzadeh, J. and Ahangar, A. G. (2014). Influence of soil organic matter content on soil physical, chemical and biological properties. *International Journal of Plant, Animal and Environmental Sciences* 4(4): 244-252.

Farooqi, Z. U. R., Sabir, M., Zeeshan, N., Naveed, K. and Hussain, M. M. (2018). Enhancing carbon sequestration using organic amendments and agricultural practices. *Carbon Capture, Utilization and Sequestration* 2018: 17-35.

Fellbauma, C. R., Gachomoa, E. W., Beesetty, Y., Choudharib, S., Strahanc, G. D., Pfefferc, P. E., Kiersd, E. T. and Bückinga, H. (2012). Carbon availability triggers fungal nitrogen uptake and transport in arbuscular mycorrhizal symbiosis. *Proceedings of National Academy of Science* 7(10): 2666–2671.

Follett, R. F. (2001). Soil management concepts and carbon sequestration in cropland soils. *Soil and Tillage Research* 61(1-2): 77-92

Francaviglia, R., Álvaro-Fuentes, J., Di Bene, C., Gai, L., Regina, K. and Turtola, E. (2019). Diversified arable cropping systems and management schemes in selected European regions have positive effects on soil organic carbon content. *Agriculture* 9(12): 245-261.

Gale, W. J., Cambardella, C. A. and Bailey, T. B. (2000). Root-derived carbon and the formation and stabilization of aggregates. *Soil science society of America Journal* 64(1): 201-207.

Gebeyehu, G. and Soromessa, T. (2018). Status of soil organic carbon and nitrogen stocks in Koga Watershed Area, Northwest Ethiopia. *Agriculture and Food Security* 7(1): 1-10.

Gentile, R., Vanlauwe, B., Chivenge, P. and Six, J. (2011). Trade-offs between the short- and long-term effects of residue quality on soil C and N dynamics. *Plant and Soil* 338(1): 159-169.

Giovannetti, M. and Mosse, B. (1980). An evaluation of techniques for measuring vesicular-arbuscular mycorrhizal infection in roots. *New Phytologist* 84: 489 – 500.

Glab, T. and Kulig, B. (2008). Effect of mulch and tillage system on soil porosity under wheat (*Triticum aestivum*). *Soil and Tillage Research* 99: 169 –178.

Gu, C., Liu, Y., Mohamed, I., Zhang, R., Wang, X., Nie, X., Jiang, M., Brooks, M., Chen, F. and Li, Z. (2016). Dynamic changes of soil surface organic carbon under different mulching practices in citrus orchards on sloping land. *PLoS ONE* 11(12): e0168384.

Herridge, D. F., Peoples, M. B. and Boddey, R. M. (2008). Global inputs of biological nitrogen fixation in agricultural systems. *Plant and Soil* 311(1): 1-18.

Hobbs, P. R. (2007). Conservation agriculture, defined as minimal soil disturbance (no-till) and permanent soil cover (mulch) combined with rotations, is a more sustainable cultivation system for the future than those presently practiced. *Journal of Agricultural Science* 145: 127–137.

Hopkins, D. W. and Gregorich, E. G. (2005). Carbon as a substrate for soil organisms. *Biological Diversity and Function in soils*: 57-79.

Hungria, M. and Kaschuk, G. (2014). Regulation of N2 fixation and NO3−/NH4+ assimilation in nodulated and N-fertilized *Phaseolus vulgaris* L. exposed to high temperature stress. *Environmental and Experimental Botany* 98: 32-39.

Hütsch, B. W., Augustin, J., and Merbach, W. (2002). Plant rhizodeposition—an important source for carbon turnover in soils. *Journal of Plant Nutrition and Soil Science* 165(4): 397-407.

IPCC Climate Change, (2013). The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, USA.

IUSS Working Group WRB (2015). *World Reference Base for Soil Resources 2014. International Soil Classification System for Naming Soils and Creating*

Legends for Soil Maps. World Soil Resources Reports No. 106. Food and Agriculture Organization, Rome, Italy. 203pp.

Jastrow, J. D. (1996). Soil aggregate formation and the accrual of particulate and mineral associated organic matter. *Soil Biology and Biochemistry* 28: 656–676.

Jensen, E. S., Peoples, M. B., Boddey, R. M., Gresshoff, P. M., Hauggaard-Nielsen, H., Alves, B. J. and Morrison, M. J. (2012). Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. *Agronomy and Sustainable Development* 32: 329 – 364.

Johnson, M., Zaretskaya, I., Raytselis, Y., Merezhuk, Y., Mc Ginnis, S. and Madden, T. L. (2008). NCBI BLAST: a better web interface. *Nucleic Acids Research* 36: 5 – 9.

Kahlon, M. S., Lal, R. and Ann-Varughese, M. (2013). Twenty two years of tillage and mulching impacts on soil physical characteristics and carbon sequestration in Central Ohio. *Soil and Tillage Research* 126: 151-158.

Kara, Ö., Bolat, İ., Çakıroğlu, K. and Öztürk, M. (2008). Plant canopy effects on litter accumulation and soil microbial biomass in two temperate forests. *Biology and Fertility of Soils* 45(2): 193-198.

Kaur, K., Kapoor, K. K. and Gupta, P. A. (2005). Impact of organic manures with and without fertilizers on soil chemical and biological properties under tropical conditions. *Journal of Plant Nutrition and Soil Science* 168: 117 – 122.

Kavdir, Y., Özcan, H., Ekinci, H., Yüksel, O. and Yiğini, Y. (2004). The influence of clay content, organic carbon and land use types on soil aggregate stability and tensile strength. *Turkish Journal of Agriculture and Forestry* 28(3): 155-162.

Kleja D. B., Svensson, M., Majdi, H., Jansson, P. E., Langvall, O., Bergkvist, B., Johansson, M. B., Weslien, P., Truusb, L., Lindroth, A. and Agren, G. I.

(2008). Pools and fluxes of carbon in three Norway spruce ecosystems along a climatic gradient in Sweden. *Biogeochemistry* 89: 7–25.

Klute, A. (1986). Water retention. In: *Methods of Soil Analysis, Part 1, and Agronomy Monograph No.* 9. (Edited by Klute, A.). America Society of Agronomy and Soil Science Society of America, Madison, Wisconsin. pp. 635 – 662.

Koyama, A., Wallenstein, M. D., Simpson, R. T. and Moore, J. C. (2014). Soil bacterial community composition altered by increased nutrient availability in Arctic tundra soils. *Frontiers in Microbiology* 5(516): 1 – 16.

Kumar, R., Pandey, S. and Pandey, A. (2006). Plant roots and carbon sequestration. *Current Science* 91(7): 885 – 890.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science* 304: 1623 – 1627.

Lal, R. (2006). Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation and Development* 17: 197 – 209.

Lal, R. (2009). Challenges and opportunities in soil organic matter research. *European Journal of Soil Science* 60(2): 158-169.

Lal, R. (2010). Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *Bioscience* 60(9): 708-721.

Lal, R. (2013). Food security in a changing climate. *Ecohydrology and Hydrobiology* 13: 8–21.

Lal, R., Logan, T. J. and Fausey, N. R. (1989). Long-term tillage and wheel traffic effects on a poorly drained mollic ochraqualf in northwest Ohio. 1. Soil physical properties, root distribution and grain yield of corn and soybean. *Soil and Tillage Research* 14(4): 341-358.

Leake, J., Johnson, D., Donnelly, D., Muckle, G., Boddy, L. and Read, D. (2004). Networks of power and influence: the role of mycorrhizal mycelium in controlling plant communities and agroecosystem functioning. *Canadian Journal of Botany* 82: 1016–1045.

Legendre, P. and Anderson, M. J. (1999). Distance-based redundancy analysis: testing multispecies responses in multifactorial ecological experiments. *Ecological Monographs* 69: 1–24.

Reckling, M., Preissel, S., Zander, P., Topp, C. F. E., Watson, C. A., Murphy-Bokern, D. and Stoddard, F. L. (2014). Legume Futures Report 1.6. Effects of legume cropping on farming and food systems Available from [www.legumefutures.de] site visited on 12/07/2017.

Lehmann, A. and Rillig, M. C. (2015). Understanding mechanisms of soil biota involvement in soil aggregation: A way forward with saprobic fungi? *Soil Biology and Biochemistry* 88: 298-302.

Liao, Y., Wu, W. L., Meng, F. Q., Smith, P. and Lal, R. (2015). Increase in soil organic carbon by agricultural intensification in northern China. *Biogeosciences* 12(5): 1403-1413.

Lützow, M. V. and Kögel-Knabner, I. (2010). Response to the Concept paper: “What is recalcitrant soil organic matter?” by Markus Kleber. *Environmental Chemistry* 7(4): 333-335.

Majumder, B., Mandal, B., Bandyopadhyay, P. K. and Chandhury, J. (2007). Soil organic carbon pools and productivity relationship for a 34 year old rice – wheat – jute agroecosystem under different fertilizer treatments. *Plant and Soil* 297: 53–67.

Mandal, N., Dwivedi, B. S., Meena, M. C., Singh, D., Datta, S. P., Tomar, R. K. and Sharma, B. M. (2013). Effect of induced defoliation in pigeonpea, farmyard manure and sulphitation pressmud on soil organic carbon fractions, mineral nitrogen and crop yields in a pigeonpea–wheat cropping system. *Field Crops Research* 154: 178-187.

Maobe, S. N., Akundabweni, L. S. M., Mburu, M. W. K., Ndufa, J. K., Mureithi, J. G., Gachene, C. K. K., Okello, J. J. and Makini, F. W. (2011). Effect of mucuna green manure application rate on decomposition and soil available nitrogen under field conditions: I. During season of incorporation. *World Journal of Agricultural Sciences* 7(4): 430-438.

Marandu, A. E. T., Semu, E., Mrema, J. P. and Nyaki, A. S. (2013). Contribution of legume rotations to the nitrogen requirements of a subsequent maize crop on a rhodicferralsol in Tanga, Tanzania. *Tanzania Journal of Agricultural Science* 12(1): 23-29.

Marschner, B., Brodowski, S., Dreves, A., Gleixner, G., Gude, A., Grootes, P. M., Hamer, U., Heim, A., Jandl, G., Ji, R. and Kaiser, K. (2008). How relevant is recalcitrance for the stabilization of organic matter in soils? *Journal of Plant Nutrition and Soil Science* 171(1): 91-110.

Mazurak, A. P. (1950). Effect of gaseous phase on water-stable synthetic aggregates. *Soil Science* 69(2): 135-148.

Meena, B. P., Kumar, A., Lal, B., Sinha, N. K., Tiwari, P. K., Dotaniya, M. L., Jat, N. K. and Meena, V. D. (2015). Soil microbial, chemical properties and crop productivity as affected by organic manure application in popcorn (Zea mays L. var. everta). *African Journal of Microbiology Research* 9(21): 1402-1408.

Meena, R. S., Das, A., Yadav, G. S. and Lal, R. (Eds.). (2018). *Legumes for Soil Health and Sustainable Management*. Singapore: Springer. 541pp.

Miller, M. B. and Bassler, B. L. (2001). Quorum sensing in bacteria. *Annual Reviews of Microbiology* 55(1): 165-199.

Moberg, J. P. (2001). *Soil and Plant Analysis Manual.* (Revised Edition). The Royal Veterinary and Agricultural University, Chemistry Department, Copenhagen, Denmark. 133pp.

Mobius, J., Lahajnar, N. and Emeis, K. C. (2010). Diagenetic control of nitrogen isotope ratios in Holocene sapropels and recent sediments from the Eastern Mediterranean Sea. *Biogeosciences* 7: 3901–3914.

Mummey, D., Holben, W., Six, J. and Stahl, P. (2006). Spatial stratification of soil bacterial populations in aggregates of diverse soils. *Microbial Ecology* 51(3): 404-411.

Munsell Color Company (2000). *Munsell soil color charts*. (2000 rev. washable edition), New Windsor, N.Y, Gretag Macbeth, Munsell Color, 2000. 10pp.

Murungu, F. S. (2012). Conservation agriculture for smallholder farmers in the Eastern Cape Province of South Africa: recent developments and future prospects. *African Journal of Agricultural Research* 7(38): 5278-5284.

National Soil Service (1990). *Laboratory Procedures for Routine Soil Analysis*. (3rd Edition), Agricultural Research Institute, Mlingano Tanga, Tanzania. 212pp.

Olson, K. R., Al-Kaisi, M., Lal, R. and Lowery, B. (2014). Examining the paired comparison method approach for determining soil organic carbon sequestration rates. *Journal of Soil and Water Conservation* 69(6): 193A-197A.

Ohshiro, M., Hossain, A. M. D., Nakamura, I., Tamaki, M., Bhowmik, P. C. and Nose, A. (2016). Effects of soil types and fertilizers on growth, yield, and quality of edible Amaranthustricolor lines in Okinawa, Japan. *Plant Production Science* 19(1): 61 – 72.

Patrick, M., Tenywa, J. S., Ebanyat, P., Tenywa, M. M., Mubiru, D. N., Basamba, T. A. and Leip, A. (2013). Soil organic carbon thresholds and nitrogen management in tropical agroecosystems: Concepts and Prospects. *Journal of Sustainable Development* 6(12): 31-43.

Peoples, M. B., Unkovich, M. J. and Herridge, D. F. (2009). Measuring symbiotic nitrogen fixation by legumes. *Nitrogen Fixation in Crop Production* 52: 125-170.

Piccolo, A. and Mbagwu, J. S. (1999). Role of hydrophobic components of soil organic matter in soil aggregate stability. *Soil Science Society of America Journal* 63(6): 1801-1810.

Potter, K. N., Jones, O. R., Torbert, H. A. and Unger, P. W. (1997). Crop rotation and tillage effects on organic carbon sequestration in the semiarid southern Great Plains. *Soil Science* 162(2): 140-147.

Punyalue, A., Jamjod, S. and Rerkasem, B. (2018). Intercropping maize with legumes for sustainable highland maize production. *Mountain Research and Development* 38(1): 35-44.

Qiu, J., Wang, L., Li, H., Tang, H., Li, C. and Ranst, E. (2009). Modelling the impacts of soil organic carbon content of croplands on crop yields in China. *Scientific Agriculture Sinica* 42: 154 - 161.

Reichert, J. M. and Norton, L. D. (1994). Aggregate stability and rain-impacted sheet erosion of air-dried and prewetted clayey surface soils under intense rain. *Soil Science* 158(3): 159-169.

Rezig, F. A. M., Elhadi, E. A. and Abdalla, M. R. (2014). Decomposition and nutrient release pattern of wheat (*Triticumaestivum*) residues under different treatments in desert field conditions of Sudan. *International Journal of Recycled Organic Waste Agriculture* 3(69): 1-9.

Rillig, M. C., Wright, S. F., Nichols, K. A., Schmidt, W. F. and Torn, M. S. (2001). Large contribution of arbuscular mycorrhizal fungi to soil carbon pools in tropical forest soils. *Plant and Soil* 233(2): 167-177.

Robbins, S. G. and Voss, R. D. (1991). Phosphorus and potassium stratification in conservation tillage systems. *Journal of Soil and Water Conservation* 46(4): 298-300.

Rumpel, C. and Kögel-Knabner, I. (2011). Deep soil organic matter—a key but poorly understood component of terrestrial C cycle. *Plant and Soil* 338(1-2): 143-158.

Saka, A. R. and Haque, L. (1993). Methods for analysis for selected soil physical properties. Soil Science Fact Sheet No. 2. Department of Agriculture Research, Chitedze Agricultural Research Station, Lilongwe, Malawi. 74pp.

Saleem, R., Ahmed, Z. I., Ashraf, M., Arif, M., Malik, M. A., Munir, M. and Khan, M. A. (2011). Response of maize-legume intercropping system to different fertility sources under rainfed conditions. *Sarhad Journal of Agriculture* 27(4): 503-511.

Sarkar, S., Paramanick, M. and Goswami, S. B. (2007). Soil temperature, water use and yield of yellow sarson (Brassica napus L. var. glauca) in relation to tillage intensity and mulch management under rainfed lowland ecosystem in eastern India. *Soil and Tillage Research* 93: 94–101.

Saroa, G. S. and Lal, R. (2003). Soil restorative effects of mulching on aggregation and carbon sequestration in a Miamian soil in central Ohio. *Land Degradation and Development* 14(5): 481- 493.

Sayer, E. J., Heard, M. S., Grant, H. K., Marthews, T. R. and Tanner, E. V. (2011). Soil carbon release enhanced by increased tropical forest litterfall. *Nature Climate Change* 1(6): 304-307.

Six, J., Bossuyt, H., Degryze, S. and Denef, K. (2004). A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research* 79: 7 – 31.

Six, J., Elliott, E. T. and Paustian, K. (1999). Aggregate and soil organic matter dynamics under conventional and no-tillage systems. *Soil Science Society of America Journal* 63: 1350–1358.

Six, J., Feller, C., Denef, K., Ogle, S.M., Sa, J.C.M. and Albrecht, A. (2002). Soil organic matter, biota and aggregation in temperate and tropical soils - Effects of no-tillage. *Agronomie* 22: 755 – 775.

Six, J., Frey, S. D., Thiet, R. K. and Batten, K. M. (2006). Bacterial and fungal contributions to carbon sequestration in agroecosystems. *Soil Science Society of America Journal* 70(2): 555-569.

Snapp, S. S., Mafongoya, P. L. and Waddington, S. (1998). Organic matter technologies for integrated nutrient management in smallholder cropping systems of southern Africa. *Agriculture, Ecosystems and Environment* 71: 185 – 200.

Soil Survey Staff (1999). *Soil Taxonomy. A basic System of classification for marking and interpreting soil Survey. Second edition*. USD Natural Resources Conservation Service. Agricultural Handbook No. 436.

Sollins, P., Kramer, M. G., Swanston, C., Lajtha, K., Filley, T., Aufdenkampe, A. K., Wagai, R. and Bowden, R. D. (2009). Sequential density fractionation across soils of contrasting mineralogy: evidence for both microbial and mineral controlled soil organic matter stabilization. *Biogeochemistry* 96: 209-231.

Soudzilovskaia, N. A., van der Heijden, M. G., Cornelissen, J. H., Makarov, M. I., Onipchenko, V. G., Maslov, M. N., Akhmetzhanova, A. A. and van Bodegom, P. M. (2015). Quantitative assessment of the differential impacts of arbuscular and ectomycorrhiza on soil carbon cycling. *New Phytologist* 208(1): 280-293.

Stevenson, E. J. (1994). *Humus Chemistry: Genesis, Composition, Reactions*. 2^{nd} ed. John Wiley & Sons, New York. 512pp.

Tabatabai, M. A. (1994). Soil Enzymes. In: Weaver, R. W., Angle, J. S., Bottomley, P. S. (Eds.), *Methods of Soil Analysis: Microbiological and Biochemical Properties.* Part 2. SSSA Book Ser. 5. SSSA, Madison, W. I. pp. 775–833.

Tariq, M., Ali, H., Hussain, N., Nasim, W., Mubeen, M., Ahmad, S. and Hasanuzzaman, M. (2019). Fundamentals of crop rotation in agronomic management. In: *Agronomic Crops*. Springer, Singapore. pp. 545-559.

Tisdall, J. M. and Oades, J. M. (1982). Organic matter and water stable aggregates in soils. *Journal of Soil Science* 33: 141–163.

Treseder, K. K. and Allen, M. F. (2000). Mycorrhizal fungi have a potential role in soil carbon storage under elevated CO_2 and nitrogen deposition. *New Phytologist* 147: 189 – 200.

Turmel, M. S., Speratti, A., Baudron, F., Verhulst, N. and Govaerts, B. (2015). Crop residue management and soil health: A systems analysis. *Agricultural Systems* 134: 6-16.

Väisänen, R. K., Roberts, M. S., Garland, J. L., Frey, S. D. and Dawson, L. A. (2005). Physiological and molecular characterisation of microbial communities associated with different water-stable aggregate size classes. *Soil Biology and Biochemistry* 37(11): 2007-2016.

Vance, E. D., Brookes, P. C. and Jenkinson, D. S. (1987). An extraction method for measuring microbial biomass C. *Soil Biology and Biochemistry* 19: 703–707.

Vieira, F. C. B., Bayer, C., Zanatta, J. A., Mielniczuk, J. and Six, J. (2009). Building up organic matter in a subtropical Paleudult under legume cover-crop-based rotations. *Soil Science Society of America Journal* 73(5): 1699-1706.

Wagner, S., Cattle, S. R. and Scholten, T. (2007). Soil-aggregate formation as influenced by clay content and organic-matter amendment. *Journal of Plant Nutrition and Soil Science* 170(1): 173-180.

Wang, Q., Garrity, G. M., Tiedje, J. M. and Cole, J. R. (2007). Naive Bayesian classifier for rapid assignment of rRNA sequences into the new bacterial taxonomy. *Applied and Environmental Microbiology* 73: 5261–5267.

Wang, Q., Li, Y. and Alva, A. (2010). Cropping systems to improve carbon sequestration for mitigation of climate change. *Journal of Environmental Protection* 1 (03): 207.

West, T. O. and Post, W. M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation: A global data analysis. *Soil Science Society of America Journal* 66: 1930–1946.

Woomer, P. L., Martin, A., Albrecht, A., Resck, D. V. S. and Scharpenseel, H. W. (1994). The importance and management of soil organic matter in the tropics. *Biology management of tropical soils fertility. Chichester, UK: John Wiley and Sons*.

Xiao, L., Zhang, Y., Li, P., Xu, G.C., Shi, P. and Zhang, Y. (2019). Effects of freeze-thaw cycles on aggregate-associated organic carbon and glomalin-related soil protein in natural-succession grassland and Chinese pine forest on the Loess Plateau. *Geoderma* 334: 1–8.

Xu, S., Liu, L. L. and Sayer, E. J. (2013). Variability of above-ground litter inputs alters soil physicochemical and biological processes: A meta-analysis of litter fall manipulationexperiments. *Biogeosciences* 10: 7423–7433.

Yan, X., Zhou, H., Zhu, Q. H., Wang, X. F., Zhang, Y. Z., Yu, X. C. and Peng, X. (2013). Carbon sequestration efficiency in paddy soil and upland soil under long-term fertilization in southern China. *Soil and Tillage Research* 130: 42-51.

Yang, K., Zhu, J., Zhang, M., Yan, Q. and Sun, O. J. (2010). Soil microbial biomass carbon and nitrogen in forest ecosystems of Northeast China: a comparison between natural secondary forest and larch plantation. *Journal of Plant Ecology* 3(3): 175-182.

Zhang, C., Dong, Y., Tang, L., Zheng, Y., Makowski, D., Yu, Y., Zhang, F. and van der Werf, W. (2019). Intercropping cereals with faba bean reduces plant disease incidence regardless of fertilizer input; a meta-analysis. *European Journal of Plant Pathology* 154(4): 931-942.

Zhao, J., Chen, S., Hu, R. and Li, Y. (2017). Aggregate stability and size distribution of red soils under different land uses integrally regulated by soil organic matter, and iron and aluminum oxides. *Soil and Tillage Research* 167: 73-79.

Zhu, Y. G. and Miller, R. M. (2003). Carbon cycling by Arbuscular mycorrhizal fungi in soil-plant systems. *Trends in Plant Science* 8: 407–409.

CHAPTER TWO

2.0 PEDOLOGICAL CHARACTERIZATION AND CLASSIFICATION OF SELECTED SOILS OF MOROGORO AND MBEYA REGIONS OF TANZANIA

Abstract

This study was conducted in some selected soils of Morogoro (Magadu) and Mbeya (Uyole) regions of Tanzania to classify and characterize their properties. Two representative pedons (SUARAT-P1 and UYOLE-P1) were dug and described using FAO guidelines clarifying morphological features, physico-chemical properties and genesis. The representative pedons were geo-referenced using Global Positioning System (GPS) receiver. A total of nine (9) genetic soil horizons were identified from both sites and samples from each horizon collected for physical and chemical analyses. Soils from both sites were very deep and topsoil moist colors ranged from hue of 7.5YR to 10YR with chroma of less than 3 in SUARAT-P1 and UYOLE-P1 pedons. Soil structure ranged from strong fine crumbs in topsoils to medium coarse sub-angular blocks in subsoils of SUARAT-P1 while UYOLE-P1 had weak fine sub-angular blocks in topsoils and subsoils. The SUARAT-P1 had sandy clay (SC) texture in topsoil and clay texture in subsoil while UYOLE-P1 was sandy loam (SL) in topsoil and sand clay loam (SCL) in subsoil. Soil reaction were slightly acid to very strongly acid in SUARAT-P1 (pH 6.54 - 4.46) whereas UYOLE-P1 were slightly acid to neutral in the subsoil horizons (pH 6.35 – 7.32). Organic carbon ranged from very low to low (0.12- 0.95%) in SUARAT-P1 from 0-23 cm and medium (1.5%) from surface to 25 cm depth in UYOLE-P1. Nitrogen levels were very low to low (0.05 - 0.12%) in both sites, whereas available P ranged from low (0.30 mg kg^{-1}) to medium (8.55 mg kg^{-1}) in both pedons. The figures for soil OC and N will be used as baseline to forecast SOC and N sequestration potential in selected study sites. CEC of SUARAT-P1 was medium ranging from 12.4 to 23.2 cmol(c) kg^{-1}, whereas UYOLE-P1 was medium to high (15 – 34 cmol(c) kg^{-1}). The figures for soil OC and N will be set as baseline for SOC and N sequestration studies in the next chapters. In SUARAT-P1, topsoil BS was high (> 50%) and low (< 50%) in the subsoil while UYOLE-P1 registered high BS throughout its profile depth. As diagnostic horizons for soil classification, the SUARAT-P1 had an *ochric epipedon* overlying a *kandic horizon* and classified according to USDA Soil Taxonomy as *Typic Kandiustults*, while UYOLE-P1 had an *ochric epipedon* over a *cambic horizon* and was named as *Andic Dystrudepts* corresponding respectively to *Haplic Lixisols* and *Eutric Andic Cambisols* in the WRB for Soil Resources. The results have indicated that, studied soils are less fertile with possible reconstitution through land and crop management practices which include but not limited to no-tilling or conservation tillage, manuring and proper fertilizer application; residue retention, possible fallowing, liming for potential buffering of soil pH especially at SUARAT-P1 and crop rotation and intercropping with leguminous crops.

Keywords: Pedological Characterization, Soil Morphological Characteristics, Physico-chemical Properties, Soil Classification, Tanzania

2.1 Introduction

Soils are characteristically different in their level of fertility and other related chemical and physical aspects depending on locality and their natural evolution (Lufega *et al.*, 2017). For example soils originating from volcanic ash materials have high anion retention capacity and humus-rich horizons (Msanya *et al.*, 2007) while Kalala *et al.* (2017) reported other soils in Kilombero Valley which developed from alluvial materials deposited by floods during rainy seasons behaving differently.

Soil Taxonomy (ST) defines soil as “a natural body that is formed by solid particles (minerals and organic matter), natural gases and liquid materials that occur on the land surface, occupying space, and is portrayed by one or both of the following: layers and, or horizons, that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment (Juilleret *et al.,* 2016). Formation of soils is essentially contributed by several important factors: the native parent materials, climate, topography, biological components and time (Harrison and Strahm, 2008). Their influence on soil types varies accordingly from one location to another and depends on accumulated individual interaction of each factor (Moustakas and Georgoulias, 2005).

Composition of the upper part of soil and underground parent material are used to give general, site specific recommendations on soil fertility status, potential soil limitations and provides information on agro-ecologically supported crops (Kalala *et al.,* 2017). Therefore, information accruing from pedological characterization and classification of soils is of prime importance for agriculture activities (Tenga *et al.,* 2018).

Furthermore, systematic identification, grouping and delineation of various soil types is very important in interpretation, decision making on land use and management types on different crops and conservation activities (Msanya *et al.,* 2016; Shelukindo *et al.,* 2014). According to daily land uses, it is recommended that frequent observation of soils on different aspects of chemical and physical characteristics is important for current recommendations on sustainable crop production (Abitew and Kabebew, 2016). The Annual Agricultural Sample Survey (AASS) report of Tanzania of the year 2016/2017 (NBS, 2017) indicated that Mbeya and Morogoro among other regions, have had the highest grain yield reaching 3.7 Mg maize ha^{-1} and 4 Mg rice ha^{-1}, respectively.

Characterization and classification of the soils of the two regions was intended to generate important information on the morphological, physical and chemical properties of the soils thereby knowing their classification according to the United States Department of Agriculture (USDA) Soil Taxonomy (Soil Survey Staff, 2014) and the FAO World Reference Base (WRB) for Soil Resources (IUSS Working Group WRB, 2015). The specific site soil information is essential for future decision-making on the diversified soil management to enhance N and C sequestration and sustenance of agricultural production.

2.2 Materials and Methods

2.2.1 Description of the study areas

The study was conducted at Uyole and Magadu respectively in Mbeya and Morogoro Regions of Tanzania (Fig. 2.1).

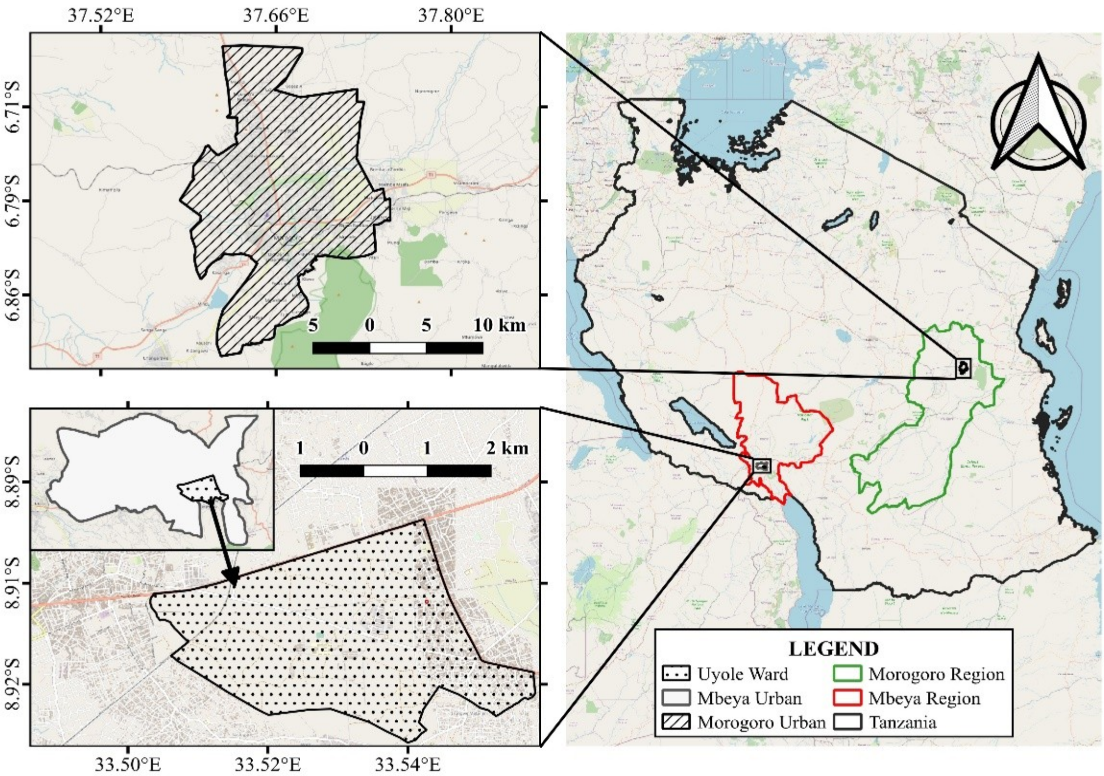

Figure 2.1: A map showing location of study areas in Mbeya and Morogoro regions

Mbeya Region is located in Southwest Tanzania and lies between latitude 06° 52′ 1″ S and 09° 43′ 14″ S and longitude 032° 58′ 40″ E and 034° 58′ 7″ E, with an altitude ranging from 1,700 m to 2,960 m above mean sea level.

The study site in Mbeya Region was Uyole Agricultural Research Station which is located at latitude 08° 54′ 4″ S and 08° 56′ 7″ S and 033° 30′ 11″ E and 033° 32′ 28″ E longitude with an altitude of 1,779 m above mean sea level. The site neighbors the volcanic Mbeya Mountains. Magadu site is located at latitude 06° 51′ 06″ to 06° 51′ 20″ S and longitude 37° 38′ 21″ to 37° 38′ 35″ E.

2.2.2 Climate

Morogoro Region has a tropical savanna climate experiencing a bimodal rainfall distribution pattern with two rainfall peaks per year, defining the short rain season starting from October through December and the long rain season from March to May (Fig. 2.2).

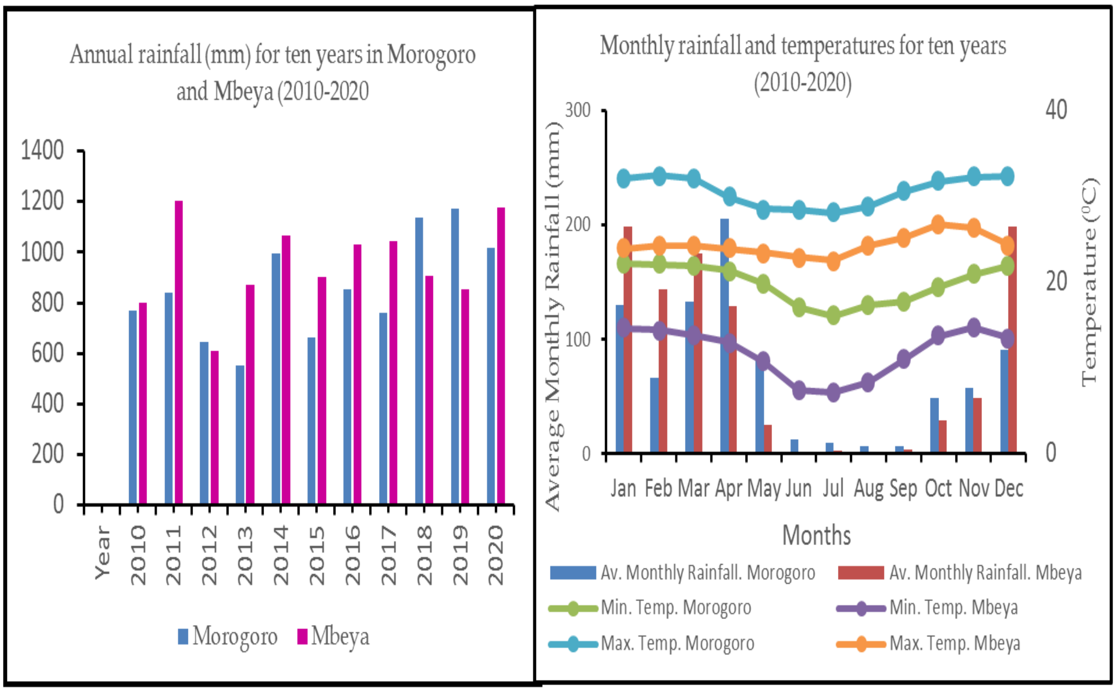

Figure 2.2: Annual and monthly rainfall, maximum and minimum temperature of Morogoro and Mbeya

At higher altitudes around Uluguru Mountains the rainfall is receiving up to 1,000 mm year^{-1} while at low altitude plains rainfall as low as 600 mm year^{-1} is recorded (Ojiyi *et al.,* 2015). Monthly mean maximum and minimum temperature recorded are respectively 30.1°C and 19.6°C (NBS, 2018).

Mbeya Region has a subtropical highland climate with a unimodal rainfall distribution pattern. The onset of the rains starts in late November and ends in early May with dry spells in between. The average annual minimum and maximum temperatures are 12.6 and 24.7°C respectively, with coldest temperatures recorded in the months of June and July reaching up to 7°C (NBS, 2018).

Table 2.1: Characteristics of the studied pedons at Magadu and Uyole sites, Tanzania

Attributes	**Description**	
	Magadu (SUARAT- P1)	**Uyole (UYOLE P1)**
Coordinates	37˚ 38´ 21˝ E to 37˚ 38´ 35˝ E and 06˚ 51´ 06˝ S to 06˚ 51´ 20˝ S	033˚ 30´ 11˝ E and 033˚ 32´ 28˝ E and 08˚ 54´ 4˝ S and 08˚ 56´ 7˝ S
Altitude (m.a.s.l)	541	1779
Landform	Plain; linear /straight	Flat or almost flat land
Parent material / Lithology	Colluvio-alluvium derived from the Uluguru Mountains consisting mainly of hornblende-pyroxene granulites, with plagioclase and quartz rich veins	Colluvio-alluvium derived from the Mbeya Volcanic Mountains
Slope %	4	2
Land use / Vegetation	Agriculture (maize, soybean, rice, cowpea and mixed crops) Research for rat mine detection	Agriculture (maize, soybean, beans, wheat, Irish potatoes)
Mean annual rainfall (mm)	600 – 1000 mm	1200 – 1730 mm
SMR	Ustic	Udic
Mean annual temperature °C		
STR	Isohyperthermic	Thermic

KEY: SMR= Soil moisture regime; STR = Soil temperature regime; m.a.s.l = above mean sea level

2.2.3 Field methods

Reconnaissance survey was done at Uyole Agricultural Research Station and Magadu (SUA) using transect walks and soil augering, sampling and descriptions to identify sampling areas. At each observation point, site data on landform, soil morphological features (soil color, texture, consistence, structure, porosity, and effective depth), parent material, natural vegetation, drainage, slope gradient, elevation, erosion and land use were recorded and filled in forms designed by the National Soil Service, Tanzania, adopted from the FAO Guidelines for Soil Description (FAO, 2006). Soil colour was determined using Munsell Color Charts (Munsell Color Company, 2000). Soil pits of 2.5 m length, 1.5 m width and 2 m depth were excavated in the representative sites. The locations of the study sites were recorded using Global Positioning System (GPS) model GARMIN (etrex 20). Disturbed (bulk) and undisturbed (core) soil samples were taken from each identified horizon from each site for physical and chemical analysis in the laboratory.

2.2.4 Laboratory methods

The disturbed soil samples were air dried for 2-3 days, mixed well and, after gentle crushing they were passed through a 2 mm sieve. The soil pH_{H2O} and pH_{KCl} were potentiometrically measured using a pH meter in a 1:2.5 soil: water and soil: 1 M KCl ratios, respectively (Okalebo *et al.,* 2002). Organic carbon (OC) of soil samples was determined by the wet oxidation method of Walkley-Black (Nelson and Sommers, 1982) and corresponding soil organic matter (SOM) was calculated by multiplying OC by a factor of 1.724 (Nelson and Sommers, 1982). Total nitrogen was determined by macro-Kjeldahl digestion distillation method (Moberg, 2000; Bremner and Yeomans, 1998).

Bulk density (BD) of undisturbed soil samples was determined by weighing soil cores after overnight oven drying at 105ºC (Okalebo *et al.,* 2002). Available phosphorus was extracted using the method of Bray and Kurtz (Olsen and Sommers, 1982; Bray and Kurtz, 1945) and determined by spectrophotometer at 884 nm wavelength following color developed by the molybdenum blue method (Okalebo *et al.,* 2002; Watanabe and Olsen, 1965). Particle size analysis was determined by hydrometer method after dispersion with 5% sodium hexametaphosphate (Moberg, 2000; NSS, 1990). Soil textural classes were determined using the USDA textural class triangle (FAO, 2006). Micronutrients (Cu, Fe, Zn, and Mn) were extracted by diethylenetriaminepentaacetic acid (DTPA) method and determined using atomic absorption spectrophotometer (Thomas, 1988).

Cation exchange capacity of soil (CECsoil) was determined by saturating soil with neutral 1M NH4OAc (ammonium acetate) and the adsorbed NH^{4+} were displaced by using 1M KCl and then determined by Kjeldahl distillation method for estimation of CEC of soil (Chapman, 1965). The exchangeable bases (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Al^{+3} and H+) were determined by Atomic Absorption spectrophotometer (AAS) (Anderson and Ingram, 1993). Total exchangeable bases (TEB) were calculated as sum of exchangeable bases Ca^{2+}, Mg^{2+}, Na^{+} and K+. Exchangeable Al^{3+} and H^{+} was used to predict total exchangeable acidity (TEA). Percent base saturation (PBS) was calculated by dividing the sum of the basic cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) by the CEC of the soil and multiplying by 100. Cation exchange capacity of clay (CECclay) was determined by the formula of Baize (1993) which corrects for the CEC contributed by organic matter as follows:

$$CECclay = ¿ \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Electrical conductivity (EC) was determined in a 1:2.5 soil: water suspension, using an electrical conductivity meter as described by Moberg (2000). Soil penetration resistance (PR) in each soil horizon was measured using pocket cone penetrometer (Daiki Rika Kogyo penetrometer Model DIK-5551) (Lowery and Morrison, 2002). Penetration resistance of soil is a measure of its strength to resist penetration, compactness or cohesiveness. The cone penetrometer is made up of a replaceable stainless steel cone structure of a tip of 30° angle and a rod base of 12.82 mm diameter (Hazelton and Murphy, 2016; Lowery and Morrison, 2002). The soil penetrability is measured as Cone Index (CI) and is expressed as force per unit cross-sectional area of the cone base (Lowery and Morrison, 2002). The measurements of penetration resistance (PR) were taken five times from each horizon. The mean penetrometer readings for each horizon in millimetre (mm) were converted to megaPascals (MPa) according to Massawe *et al.* (2017).

The penetration resistance was then calculated as follows:

$$\text{Penetration resistance (kg cm}^{-2}) = (100*X)/\ 0.7952(40\text{-}X)^2 \ldots\ldots\ldots\ldots\ldots \quad (2)$$

Where, X= penetrometer readings (mm) and 1 kg cm^{-2} = 0.09807 MPa

Total elemental composition of three selected horizons of the representative soil profiles was determined as follows using a swing mill pulverizer (Kalala *et al.,* 2017), soil samples were ground to the particle size of ≤ 177 µm diameter and then pressed into XRF cups and mounted with PANalytical B.V. X-Ray film-polyester PETP (Polyethylene Terephthalate Polyester). The elemental oxides were then measured by PANalytical, Minipal 4 Energy Dispersive X-Ray Fluorescence Spectrophotometer (ED-XRF) (Model PW4030/45B USA).

2.2.5 Soil classification

The collected field data (site characteristics, climate and soil morphological features) and data obtained from laboratory analyses (physical and chemical properties of the soils) were used to classify the soils to family level of the USDA Soil Taxonomy (Soil Survey Staff, 2014) and to tier-2 of the FAO World Reference Base for Soil Resources (IUSS Working Group WRB, 2015).

2.3 Results and Discussion

2.3.1 Soil morphological characteristics

The morphological characteristics of studied pedons are shown in Table 2.2. Both pedons were very deep (> 150 cm), with natural drainage classified as well to excessively well drained and well drained in Magadu and Uyole, respectively.

Table 2.2: Selected morphological features of soil pedons of Magadu and Uyole Sites, Tanzania

Profile	Horizon	Depth (cm)	Texture	Moist Colour[1]	Consistence[2]	Structure[3]	Pores[4]	Rock fragment[5]	Roots[6]	Cutans[7]	Horizon Boundary[8]
SUARAT-P1	Ah	0 - 5/8	SC	db (7.5YR3/2)	vfr, ss & p	sf & m, cr	mc & mm	-	cf, mm & fc	-	cw
	BA	5/8 - 23	SC	b (7.5YR4/4)	fr, s & p	mc & m, sbk	cc, mm, mf & mvf	-	cf & fc	ffc	ds
	Bt1	23 - 42	C	drb (5YR3/4)	fr, s & p	w-mc, sbk	fm, mf & mvf	-	fm, cc & cf	ffc	ds
	Bt2	42 - 88	C	yb (5YR4/6)	fr, s & p	w-mc & m, sbk	mf, mvf, cm & fc	-	fc & ff	ffc	ds
	Bt3	88 – 185+	C	yr (5YR5/8)	fr, s & p	sm, sbk	mf, mvf, cm & vfc	-	fm & cf	fdc	-
UYOLE-P1	Ap	0 - 19/25	SL	bl (10YR2/1)	fr, ss & sp	wf & m, sbk	cm, mf & mvf	cm, fa-p	mf	-	cw
	Bw1	19/25 - 60/86	SCL	db (10YR3/3)	fr, s & p	wf & vf, sbk	cm, mf & mvf	fm, fsa-p	cf	-	aw
	C	60/86 - 125/131	LS	lob (2.5Y 5/3)	-	sl-sgr	mm & mc	vf, ls-p,	cf & cvf	-	aw
	Ab/Bw2b	125/131 - 210+	SL	db (10YR3/3)	fr, s & p	w & mc, sbk	cm & cc, cf & cvf	-	fvf	-	-

Key::[1]Moist color: db = dark brown; b= brown; yb = yellowish brown; yr = yellowish red; drb= dark reddish brown; bl= black; lob= light olive brown; vdgb = very dark greyish brown; dyb = dark yellowish brown; vdb = very dark brown

[2]Consistence: vfr = very friable; fr = friable; s = sticky; ss = slightly sticky; sp = slightly plastic; ss-s = slightly sticky to sticky; sp-p= slightly plastic to plastic

[3]Structure: mf = moderate fine; sbk = subangular blocky; wf = weak fine; vf = very fine; m = medium; sf = strong fine; cr = crumby; c = coarse; mc = moderate coarse; w = weak; sm = strong medium; sl-sgr = structureless single grained; fc = few coarse; pmc = pumice; ands = andesite

[4]Pores: mm= many medium; fm = few medium; mc = many coarse; fc = few coarse; vfc = very few coarse; mf = many fine; mvf = many very fine; cvf = common very fine; cc = common coarse; cm = common medium; cf = common fine;

[5]Rock fragments: cm= common medium; fm= few medium; vf= very few; fa-p= friable angular pumices; fsa-p= friable subangular pumices; ls-p= loose pumices

[6]Roots: cf = common fine; ff = few fine; mf = many fine; vff = very few fine; mm = many medium; cc = common coarse; fc = few coarse; fm = few medium; cvf = common very fine; fvf = few very fine

[7]Cutans: ffc = few faint clay cutans; fdc = few distinct clay cutans

[8]Horizon boundary: cw =clear wavy; ds = diffuse smooth; aw = abrupt wavy

Pedon SUARAT-P1 had sandy clay topsoil overlying thick clayey subsoil extending to a depth of > 180 cm. Pedon UYOLE-P1 had a coarser texture characterized by sandy loam topsoil overlying sand clay loam to sandy loam/loamy sand subsoil. The topsoil color of pedon SUARAT-P1 ranged from dark brown to brown overlying dark red brown and yellowish red subsoil color. On the other hand pedon UYOLE-P1 had intense black topsoil color typical of volcanic materials and/or organic matter deposition overlying a subsoil with varied brown colors (Neswati *et al.*, 2019). Both SUARAT-P1 and UYOLE-P1 pedons had almost comparable consistence rated from very friable to friable consistence, indicating good water movement and root penetration (Peverill *et al.*, 1999). According to Peverill *et al.* (1999), soil consistence is generally used as a measure of soil permeability and root penetration; loose and soft (friable) consistence imply easy water movement but harder and more rigid consistence would imply less water movement and poorer root penetration.

The structure of pedon SUARAT-P1 was rated as strong fine crumby in the topsoil overlying moderate to weak coarse and medium subangular blocky subsoil. Pedon UYOLE-P1 had weak fine and medium subangular blocky structure in the topsoil overlying a subsoil with varying structures ranging from weak fine and very fine subangular blocky to structureless single-grained. Crumby and subangular blocky structures correlate with good aeration, root penetration and drainage (Brady and Weil, 2008). In both studied pedons the structures identified suggest good aeration, easy root penetration and smooth water movements.

Clay cutans were observed in the subsoil of pedon SUARAT-P1 indicating that the processes of eluviation and illuviation have been an active pedogenic processes in this pedon (Tenga *et al.*, 2018). Horizon boundaries in topsoils of both pedons were clear wavy, while subsoils of pedon SUARAT-P1 were diffuse smooth and those of pedon UYOLE-P1 abrupt wavy.

2.3.2 Soil physical characteristics

Results of soil physical properties are presented in Table 2.3.

Table 2.3: Some physical properties of studied areas of Magadu and Uyole sites, Tanzania

Profile	Horizon	Depth (cm)	Sand	Silt	Clay	Textural Class	Silt/ Clay ratio	BD g/cc	Porosity %	Penetration resistance (MPa)
SUARAT-P1	Ah	0 - 5/8	58.24	5.92	35.8	SC	0.17	1.02	61.51	0.37
	BA	5/8 - 23	46.24	4.92	48.8	SC	0.15	nd	nd	2.56
	Bt1	23 - 42	34.24	1.92	63.8	C	0.03	1.20	54.72	1.69
	Bt2	42 - 88	30.24	2.92	66.8	C	0.04	1.02	61.51	2.15
	Bt3	88 – 185+	28.24	2.92	68.8	C	0.04	nd	nd	1.94
UYOLE-P1	Ap	0 - 19/25	56.24	24.92	18.8	SL	1.33	0.86	67.55	2.83
	Bw1	19/25 - 60/86	48.24	22.92	28.8	SCL	0.80	0.97	63.40	2.38
	C	60/86 – 125/131	82.24	8.92	8.8	LS	1.01	0.47	82.26	0.60
	Ab/Bw2b	125/131 - 210+	68.24	16.92	14.8	SL	1.14	1.17	55.58	0.46

Note: Porosity = (1- [Bulk density/Particle density] x 100) assuming particle density of 2.65g/cm^3

2.3.2.1 Soil particle distribution (texture), silt/clay ratio and bulk density (BD)

Soil particle distribution is the relationship that shows different percentages of sand, silt and clay particles of certain soil (Hazelton and Murphy, 2016). Soil texture is one of the most stable and significant soil physical properties which have influence on other soil attributes including erodibility, water holding capacity, infiltration rate, nutrient retention, workability, soil consistence, soil aeration and fertility (Mukungurutse *et al.*, 2018; Tenga *et al.*, 2018).

The clay content of the SUARAT-P1 pedon distinctly increased with depth from 35.8% in topsoil to 68.8% in subsoil through the process of eluviation-illuviation as indicated by the presence of clay cutans in the subsoil (Table 2.3). On the other hand, sand content gradually decreased down the profile from 58.24% in topsoil to 28.24% in subsoil. The fineness of the texture in this pedon might suggest that the soil has high water retention and nutrient supply capacity. In the case of UYOLE-P1 pedon, the particle size distribution was quite different where by, the soil texture was generally coarser and showed no clear trend of change with depth. The highest clay content recorded was 28.8% in the B horizon while the least recorded was 8.8% in the C horizon.

There was dominance of sand fraction in all horizons, where the content ranged from 56.24% in topsoil and decreased to 48.24% in the B horizon and thereafter increased dramatically to 82.24% in the C horizon. The coarseness of the texture suggests that the soil has low water retention, poor physical stability and generally low fertility (Mukungurutse *et al.*, 2018; Shehu *et al.*, 2015). The silt/clay ratio of a given soil shows the extent of soil aging (Costantini *et al.*, 2002). According to Ribeiro (1976), silt to clay ratio of greater than 0.12 is an indication of less weathered and younger parent materials (Sharu *et al.*, 2013).

The silt/clay ratios of the two studied soils are relatively higher in topsoils than in subsoils indicating that subsoils are more weathered than topsoils. The subsoil of pedon SUARAT-P1 had silt/clay ratio much smaller than 0.12 implying that this pedon is highly weathered. In the case of pedon UYOLE-P1, all horizons had silt/clay ratios greater than 0.12 indicating that the pedon is genetically young in terms of weathering and development

(Kalala *et al.,* 2017; Msanya *et al.,* 2007).

Bulk density (BD) is a physical property of a soil that indicates compactness of soil particles, and their values indicate how well the aeration and root penetration are (Landon, 2014). Increase in BD values indicates reduction of water infiltration rate and consequently an increase in runoff (Landon, 2014). Bulk density of both studied sites are < 1.6 g cm^{-3} in all studied horizons which according to Landon (2014) and Arshad *et al.* (1996) do not pose any limitation to root growth, aeration and water movement.

2.3.2.2 Soil porosity

Total soil porosity is the percentage of the fraction of soil bulk density and particle density which reflects on the physical condition and the structure of the soil (Landon, 2014; Scrimgeour, 2008). An increase in bulk density would decrease soil porosity and consequently hamper aeration and restrict water infiltration rate. Pedons SUARAT-P1 and UYOLE-P1 have a normal and favorable range (40-70%) of total soil porosity in their topsoil and subsoil horizons (Landon, 2014; Scrimgeour, 2008) which indicate a good aeration and water infiltration. Thus the values of total porosity observed (Table 2.3) in the studied pedons pose no limitation to root penetration and water movement (Scrimgeour, 2008).

2.3.2.3 Soil penetration resistance

Penetration resistance (PR) is a measure of the soil strength, compactness or cohesiveness (Lowery and Morrison, 2002) which depends on the moisture of the soil and has some relationship with plant root growth (Hazleton and Murphy, 2016). In pedon SUARAT-P1 penetration resistance values showed an irregular pattern of change with depth from 0.37

MPa in topsoil to 2.56, 1.69, 2.15 and 1.94 MPa respectively in the BA, Bt1, Bt2 and Bt3 horizons.

On the other hand, penetration resistance values in pedon UYOLE-P1 showed a decreasing trend from 2.83 MPa in topsoil to 2.38, 0.60, and 0.46 MPa respectively in the subsoil horizons. Literature suggests that penetration resistance values of < 0.5 MPa are rated as loose, 0.5-1.25 MPa as medium, 1.25-2.0 MPa as dense, 2.00-3.00 MPa as very dense; and > 3.00 MPa as extremely dense. In terms of limitation to root growth such rating is translated as follows in the same order: root growth not affected, root growth of some cereal plants may be affected, cereal root growth badly affected, very few plant roots penetrate the soil, and root growth virtually ceases (Hazleton and Murphy, 2016). Therefore, root penetration at Magadu site (SUARAT-P1) in topsoil layer would be easy and development/growth of shallow-rooted plants is not impaired, whereas roots of deep-rooted plants might find it difficult to penetrate down the subsoil. In the case of Uyole site (UYOLE-P1), limitation to root growth can be rated as more severe than in pedon SUARAT-P1.

2.3.3 Soil chemical characteristics

Selected soil chemical properties of the studied pedons are shown in Table 2.4.

Table 2.4: Some chemical properties of Magadu and Uyole Sites, Tanzania

Profile	Horizon	Depth (cm)	pH		EC dSm^{-1}	OC	OM	TN	C/N ratio	Available P
			H_20	KCl			%			mg kg^{-1}
SUARAT-P1	Ah	0 - 5/8	6.54	6.03	0.34	0.12	0.21	0.11	1.1	2.56
	BA	5/8 – 23	4.56	3.90	0.10	0.95	1.64	0.10	9.5	1.48
	Bt1	23 – 42	4.79	3.79	0.06	0.53	0.91	0.11	4.8	7.14
	Bt2	42 – 88	4.46	3.91	0.08	0.27	0.47	0.08	3.4	2.56
	Bt3	88 – 185+	5.00	3.94	0.04	0.30	0.52	0.07	4.3	1.48
UYOLE-P1	Ap	0 - 19/25	6.35	5.56	0.06	1.50	2.59	0.12	12.5	7.14

Bw1	19/25 - 60/86	6.66	5.48	0.05	1.13	1.95	0.08	14.1	2.56
C	60/86 – 125/131	7.28	5.65	0.06	0.95	1.64	0.05	19.0	0.30
Ab/Bw2b	125/131 - 210+	5.65	5.65	0.05	0.47	0.81	0.06	7.8	8.55

2.3.3.1 Soil pH and electrical conductivity (EC)

Soil pH is a measure of the values of hydrogen ions (H+) and hydroxyl ions (OH-) present to indicate soil acidity or alkalinity (Hazleton and Murphy, 2016). The topsoil pH of both sites (Table 2.4) was slightly acidic, but pedon SUARAT-P1 subsoil abruptly changed to very strongly acidic (4.5-5.0) (Msanya *et al.,* 2001) while pedon UYOLE-P1 subsoil with pH values 6.66 and 7.28 in the subsoil horizons and were rated as having neutral pH while the last horizon with pH of 5.65 was rated as medium acidic. According to Ricardo and Yost (2006) soils with very strongly acidic conditions may cause Mn and / or Al toxicity or otherwise Ca and Mg deficiency would be observed in some crops like sorghum and soybean. Furthermore, micronutrient deficiencies of the likes of Zn or Fe are possible in high pH soils (Landon, 2014; Ricardo and Yost, 2006) in which Fe under high pH is changed to less soluble form (Landon, 2014).

Uyole site might be very suitable for most crops as the pH in topsoil and subsoil down to 135 cm are within pH ranges which support many crops (Msanya *et al.,* 2016). The Magadu site might be very suitable for shallow rooted crops within 8 cm (top horizon ends at 8 cm) while subsoils (starting at 8 – 23 cm) was very strongly acid, a condition which might impair availability of most nutrients to plants with deep roots. The pH_{KCl} values of both sites were lower than pH_{H2O} values and according to Msanya *et al.* (2016) and Ricardo and Yost (2006) such soils are said to have net negative charge and are cation exchangers.

In addition, electrical conductivity (EC) predicts the extent of salinity levels of a soil

(Hazelton and Murphy, 2016) in a soil:water suspension (1:2.5). Electrical conductivity of pedon SUARAT-P1 was 0.34 dS m^{-1} in topsoil and decreased with depth to very low levels down to 0.04 dSm^{-1} in the subsoil, indicating that the soil is not having salinity problem (< 1.7 dSm^{-1}) (Msanya *et al.*, 2001, Msanya *et al.*, 2016). Similarly, the UYOLE-P1 pedon had very low EC values < 1.7 dS m^{-1}. Thus, both pedons do not have a limitation of salinity that is likely to cause crop yield reduction.

2.3.3.2 Organic carbon and organic matter

The results on organic carbon (OC) and organic matter (OM) are shown in Table 2.4. Organic carbon (OC) and organic matter (OM) are inter-related entities, whereby OM is obtained by multiplying OC value by the factor of 1.724 (Nelson and Sommers, 1982). It is a very important chemical parameter which predicts states of soil fertility such as water and nutrient holding capacity, and cation exchange capacity (CEC) (Mtama e*t al.*, 2018b). The topsoil horizon of pedon SUARAT-P1 exhibited very low OC (0.12%) and OM (0.21%) contents, whereas pedon UYOLE-P1 had 1.50% OC and 2.59% OM in topsoil and was rated as medium (Msanya *et al.* (2001). The subsoil of pedon SUARAT-P1 had OC ranging from 0.27% (very low) to 0.95% (low) while the subsoil of pedon UYOLE-P1 had OC ranging from 0.47% (very low) to 1.13% (low). It was noted in this study that whereas OC and OM contents decreased regularly with depth in pedon UYOLE-P1, there was irregular change of OC and OM with depth in the case of pedon SUARAT-P1. On the basis of the values of OC and OM observed in this study, the soil fertility status of both study sites can generally be rated as poor to marginal.

2.3.3.3 Total Nitrogen, C:N ratio and available phosphorus

Nitrogen is one of the most limiting nutrients to many crops and is very important for plant growth and development. The results on total nitrogen (TN) levels are shown in Table 2.4. Pedon SUARAT-P1 had in the topsoil and in the subsequent two subsoil horizons TN levels rated as low (0.10 - 0.11%). The deeper subsoil with TN values of 0.08 and 0.07% were classified as very low (< 0.1%) (Msanya *et al.*, 2001). The UYOLE-P1 pedon had low level of TN in the topsoil (0.12%) and very low across the remaining subsoil horizons (with values of 0.08, 0.05 and 0.06%) (Table 2.4). The observed values of TN call for the need for reconstitution of both studied soils with amendments and /or management to enhance soil N for example through crop residue incorporation, no tilling and growing of leguminous cover crops.

The C:N ratio shows quality of organic matter in relation to nitrogen content (Hazelton and Murphy, 2016; Landon, 2014; Msanya *et al.,* 2001). It is an important parameter which shows the effect of mineralization of applied crop residues on soil nitrogen levels (Hazelton and Murphy, 2016). The C:N ratio of topsoil in SUARAT-P1 pedon was 1.09 which is an indication of high rate of decomposition or humification of SOM (Nicolardot *et al.,* 2001) while subsoil horizons had varied C:N ratios ranging from 9.5 in BA horizon reflecting good quality organic matter (C:N ratio 8 - 13) to C:N ratio of 3.4 (outside the good quality range of OM). On the other hand, UYOLE-P1 pedon had C:N ratio of 12.5 in topsoil as good quality OM (C:N ratio 8 - 13) implying high humification (Heathwaite and Göttlich, 1993) than in the two underlying subsoil horizons with C:N ratios of 14.1 and 19.0 implying moderate quality OM and C:N ratio of 7.8 in the deepest horizon reflecting good quality soil organic matter (Msanya *et al.,* 2001). According to Mtama *et al.* (2018a) the C:N ratio might not be a good parameter to evaluate soil fertility and therefore it is suggested in this regard to use separately the N and C values for more useful interpretation.

The available phosphorus contents in the studied pedons changed irregularly with depth. In pedon SUARAT-P1 levels of P ranged from 1.48 mg kg^{-1} (low) to 7.14 mg kg^{-1} (medium). A major part of the solum had P levels of < 7 mg kg^{-1} which means that pedon

SUARAT-P1 can generally be rated as having low levels of available P. The low levels of P in this pedon may be due to the very strong acid conditions (pH 4.5 – 5.0) causing fixation and unavailability of P. The topsoil of pedon UYOLE-P1 had medium levels of available P (7.14 mg P kg^{-1}) which may be sufficient for plant growth. However, with this amount of P and the fact that a major part of the subsoil below the topsoil had low available P (< 7.0 mg P kg^{-1}), P-deficiency is likely to occur in most crops (Tenga *et al.*, 2018). The unavailability of P in a major part of the subsoil of pedon UYOLE-P1 might be due to leaching and / or nature of the soil parent materials (Tenga *et al.*, 2018) or due to pH which exceeded 7.0 (Landon, 2014).

2.3.3.4 Exchangeable bases

The amounts of exchangeable bases in the studied pedons are presented in Table 2.5. The SUARAT-P1 pedon (clayey soil) had Ca levels varying from medium (5.1 - 10 Cmol(c) kg^{-1}) in topsoil to low (2.0 - 5.0 Cmol(c) kg^{-1}) and very low (< 2.0 Cmol(c) kg^{-1}) in subsoil horizons according to the rating by Msanya *et al*. (2001). The UYOLE-P1 pedon (loamy soil) on the other hand had very high levels of Ca (> 6.0 Cmol(c) kg^{-1}) in the upper two horizons and medium to high levels in the last two subsoil horizons respectively. The high Ca levels may likely diminish P availability in the soil (Landon, 2014) and therefore the soil might call for some management strategies to address this.

Table 2.5: Exchangeable bases and related properties of the studied pedons of Magadu and Uyole Sites, Tanzania

Profile	Horizon	Depth (cm)	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	Al^{3+}	H^{+}	TEB	CEC_{soil}	CEC_{clay}	PBS	ESP
			Cmol(c) kg^{-1}										
SUARAT-P1	Ah	0 - 5/8	7.9	2.99	2.62	0.13	0.00	0.04	13.64	14.60	39.61	93.42	0.89
	BA	5/8 – 23	2.35	1.17	0.61	0.06	2.00	1.24	4.19	13.20	20.37	31.70	0.45
	Bt1	23 – 42	2.96	1.11	0.37	0.06	1.95	1.46	4.50	13.40	18.15	33.58	0.45
	Bt2	42 – 88	2.04	1.15	0.14	0.10	2.00	1.58	3.43	12.40	17.19	27.66	0.81
	Bt3	88 – 185+	1.73	1.31	0.12	0.21	1.96	1.58	3.37	23.20	32.21	14.53	0.91
UYOLE-P1	Ap	0 - 19/25	6.67	2.11	2.37	0.49	0.00	0.12	11.76	21.00	108.94	55.43	2.33
	Bw1	19/25 - 60/86	8.21	1.87	6.39	1.16	0.00	0.08	17.71	34.00	104.58	51.85	3.41
	C	60/86 – 125/131	3.58	0.68	2.06	1.19	0.00	0.26	7.77	15.00	141.86	47.53	7.93

Ab/ Bw2b	125/131 - 210+	5.43	2.51	7.40	8.63	0.00	0.06	24.03	26.00	164.73	92.19	31.9

PBS = Percent base saturation ESP = Exchangeable sodium percent

Exchangeable Mg in SUARAT-P1 pedon (clayey soil) is rated as medium throughout the soil profile with Mg levels 1.1 - 3.0 Cmol(c) kg^{-1}, while in the UYOLE-P1 pedon (loamy soil) Mg was high in topsoil (2.11 Cmol(c) kg^{-1}) and in subsoil horizons Mg levels were rated as medium (1.87 Cmol(c) kg^{-1}), low (0.68C(c) kg^{-1}) and high (2.51 Cmol(c) kg^{-1}) in the last subsoil horizon. High amounts of Mg in topsoil of the pedon might be associated with less leaching of this element to subsoil horizons (Tenga *et al.*, 2018).

Exchangeable K levels decreased regularly with depth in pedon SUARAT-P1 while there was irregular change of K with depth in pedon UYOLE-P1. In pedon SUARAT-P1 (clayey) exchangeable K ranged from medium (0.61 Cmol(c) kg^{-1}) to very high (2.62 Cmol(c) kg^{-1}) in topsoil and ranged from very low (0.12 Cmol(c) kg^{-1}) to low (0.37 Cmol(c) kg^{-1}) in subsoil (Msanya *et al.*, 2001). In UYOLE-P1 pedon (loamy), the K levels ranged from 2.06 to 7.40 Ccmol(c) kg^{-1} and were rated as very high (> 1.35 Cmol(c) kg^{-1}) throughout the profile depth.

Exchangeable sodium (Na) at Magadu profile (SUARAT-P1) was rated as low throughout the profile with Na levels in between 0.10 - 0.30 Cmol(c) kg^{-1} (Msanya *et al.*, 2001). In UYOLE-P1 pedon Na levels ranged from 0.49 Cmol(c) kg^{-1} (medium) in topsoil to 1.19 Cmol(c) kg^{-1} (high) in the major part of the subsoil and then jumped to 8.63 Ccmol(c) kg^{-1} (very high) in the deeper subsoil. Sodium levels are important to forecast soil sodicity which is a more important parameter than the absolute level of exchangeable Na (Msanya *et al.*, 2001).

2.3.3.5 Cation exchange capacity

The cation exchange capacity (CEC) is the ability of the soil to hold on against leaching and exchange of cations (Hazelton and Murphy, 2016; Msanya *et al.*, 2001). CEC is very important in regulating/buffering pH in soils; the higher the CEC the lower the acidification. A soil with low CEC acidifies very quickly (Hazelton and Murphy, 2016) The CEC values of all horizons of SUARAT-P1 pedon were rated as medium (12.1 - 25 Cmol(c) kg^{-1}) (Msanya *et al.*, 2001). The highest CEC of 23.2 Cmol(c) kg^{-1} was observed in the illuvial *Bt3* horizon (the deepest) with the highest clay content. In the UYOLE-P1 pedon, the CEC was generally higher than in the SUARAT-P1 pedon with topsoil value of 21 Cmol(c) kg^{-1} (medium), then in the subsoil horizon Bw1 a value of 34 Cmol(c) kg^{-1} (high) was recorded, followed by a value of 15 Cmol(c) kg^{-1} (medium) in the C horizon and lastly a jump to 26 Cmol(c) kg^{-1} (high) in the deepest horizon. The levels of CEC observed in this study particularly for pedon SUARAT-P1 are not adequate and may need to be improved for sustainable crop production for example through organic matter addition (Hazelton and Murphy, 2016).

CEC_{clay} is an essential indicator of weathering development and the dominant clay mineral type in a soil (Kebeney *et al.,* 2015). The SUARAT-P1 pedon had in general lower CEC_{clay} values than the UYOLE-P1 pedon (Table 2.5). Similar trend was observed for CEC_{soil}. CEC_{clay} in SUARAT-P1 pedon ranged from 17.19 Cmol(c) kg^{-1} in the Bt2 horizon to 39.61 Cmol(c) kg^{-1} in the epipedon (Ah horizon). The values of CEC_{clay} observed in pedon SUARAT-P1 reflect a mixed clay mineralogy comprising dominantly kaolinite but may contain trace amounts of some 2:1 silicate clay minerals. The dominance of kaolinite (1:1 silicate clay mineral) in SUARAT-P1 pedon is typical of advanced weathering. The UYOLE-P1 pedon on other hand had high CEC_{clay} between 108.94 - 164.73 Cmol(c) kg^{-1} indicating the presence of 2:1 clay minerals most probably smectite (Msanya *et al.,* 2018;

Miranda-Trevino and Coles, 2003; Ma *et al.*, 1999; Ma, 1996). Smectite clay is formed from two tetrahedral silica and single octahedral alumina (2:1 clay) which according to Conklin (2013), occurs in younger and less weathered soils. The results in this study clearly indicate therefore that the SUARAT-P1 pedon has shown more advanced stage of weathering than UYOLE-P1 pedon by having both lower CEC_{soil} and CEC_{clay} values (Kebeney *et al.*, 2015).

2.3.3.6 Soil sodicity

Soil sodicity is a measure of amount of exchangeable sodium present in the soil and is calculated as amount of exchangeable sodium as a percentage of the cation exchange capacity (Hazelton and Murphy, 2016; Msanya *et al.*, 2001).

$$ESP = (\text{Exchangeable Na})/(\text{CEC}) \times 100 \qquad (3)$$

According to Hazelton and Murphy (2016), sodic soils may cause different soil problems including very low infiltration, very hard and dense subsoils, clay dispersion and vulnerability to soil tunnelling. All horizons of SUARAT-P1 pedon had ESP < 1 (Table 2.5) which is indicative of a non-sodic soil. In fact, according to Msanya *et al.* (2001) and Hazelton and Murphy (2016), all soils with ESP < 6 are categorized as non-sodic and these are suitable for crop production and do not have problems of soil dispersion. The UYOLE-P1 pedon is also rated as non-sodic in its epipedon and the underlying subsurface horizon (ESP 2.33 and 3.41%), respectively. However, the third and fourth horizons had ESP of 7.93 % and 31.9 % and were rated as slightly sodic and very strongly sodic, respectively. The results suggest that the soil can be used for crop production with no or very little impact on crop yield reduction (Msanya *et al.*, 2001). This is particularly so when considering the upper 60 cm or so of the profile which is non-sodic.

2.3.3.7 Base saturation

Base saturation (BS) refers to percentage ratio of sum of basic cations (Ca, Mg, K, and Na) to its cation exchange capacity (CEC) and is used as an indicator of soil fertility. Base saturation in topsoil of SUARAT-P1 pedon was 93.42% and was rated very high while in all the remaining horizons it was rated as low (Hazelton and Murphy, 2016) with all values <50%. In the UYOLE-P1 pedon, the upper three horizons can be rated as having medium levels of BS while the last horizon was rated as having very high BS (92.19%). According to Hazelton and Murphy (2016) in the SUARAT-P1 pedon, there must have been stronger leaching of the basic cations even beyond the profile depth than in the case of the UYOLE-P1 pedon.

2.3.3.8 Cation ratios and nutrient balance in the studied pedons

The relative proportions of the basic cations (Ca, Mg, K, and Na) are important in the availability of individual cations in the soil and plant uptake (Macedo and Bryant, 1987). Plant accessibility of one cation is not exclusively dependent on its availability but rather on the optimal proportion of other cations (Laekemariam *et al.*, 2018; Macedo and Bryant, 1987). The nutrient ratios in the studied pedons are presented in Table 2.6.

Table 2.6: Cation ratios and nutrient balance in the studied pedons of Magadu and Uyole sites, Tanzania

Profile	Horizon	Depth (cm)	Ca/Mg	Mg/K	Ca/TEB	% (K/TEB)
SUARAT-P1	Ah	0 - 5/8	2.64	1.14	0.58	19.15
	BA	5/8 - 23	2.01	1.92	0.32	8.21
	Bt1	23 – 42	2.67	3.00	0.37	4.68
	Bt2	42 – 88	1.77	8.21	0.29	2.00
	Bt3	88 - 185+	1.32	10.92	0.25	1.74
UYOLE-P1	Ap	0 - 19/25	3.16	0.89	0.57	20.15
	Bw1	19/25 - 60/86	4.39	0.29	0.46	36.08
	C	60/86 - 125/131	5.26	0.33	0.46	26.51
	Ab/Bw2b	125/131 - 210+	2.16	0.34	0.23	30.79

In pedon SUARAT-P1, the Ca/Mg ratios in the upper 40 cm of the pedon were favourable

(2 - 4) for plant growth (Msanya *et al.*, 2001). The last two horizons had Ca/Mg ratios of less than 2, and hence not favourable. In UYOLE-P1 pedon only the Ca/Mg ratios in topsoil and the last horizon were favorable for plant growth. The other two horizons had ratios higher than the optimal, implying that they will hinder Mg plant uptake (Tenga *et al.,* 2018). For example, when Ca/Mg ratio exceeds 5:1, it may cause Mg and P deficiency in plants (Landon, 2014). Considering topsoils, the Ca/Mg ratios in the two studied soils may not be a problem to crop growth and development.

The Mg/K ratios varied between 1.14 and 10.92 and increased down the profile in SUARAT-P1 pedon. According to Msanya *et al.* (2001) favourable range of Mg/K ratios for most crops range from 1 - 4. Considering the upper 40 cm of the soil, the Mg/K ratios are favourable for crop production. With regard to the UYOLE-P1 pedon, the Mg/K ratios were smaller than the prescribed optimal range of 1 – 4, suggesting that the soil will have a problem with K supply. The topsoil Ca/TEB ratios of both SUARAT-P1 and UYOLE-P1 pedons had values of 0.58 and 0.57, respectively. They were slightly > 0.5 which, according to Landon (2014), there will be a slight shortage of either Mg and / or K as Ca/TEB value exceeding 0.5 would signify difficulty in their uptake by plants. Percentage (K/TEB) values > 2.0% are favourable for most tropical crops according to Landon (2014). The % (K/TEB) values observed in both SUARAT-P1 and UYOLE-P1 pedons conform to this condition and hence the two pedons are favourable for most tropical crops.

2.3.3.9 Available micronutrients in the studied pedons

Micronutrients are very important for the growth of different crops (Fageria, *et al.,* 2002). Their availability in soils is affected by a number of factors including pH, soil texture, CEC, EC, OM, oxidation-reduction reactions, temperature, moisture and light (Landon, 2014; Fageria *et al.,* 2002; Sillanpää, 1982).

The results on essential micronutrients in the studied pedon are presented in Table 2.7. The micronutrient contents were in the order of Mn > Fe > Zn > Cu in SUARAT-P1 and UYOLE-P1 pedons as it appears in the general order in plant accumulation (Fageria *et al.*, 2002). The SUARAT-P1 pedon had copper (Cu) levels in topsoil and subsoil horizons between 0.48 - 1.33 mg kg^{-1} which were rated as medium and exceeded deficiency level (Merumba *et al.*, 2020; Sillanpää, 1982), while UYOLE-P1 pedon had Cu values between 0.16 - 0.37 mg kg^{-1} being rated medium in topsoil and low in subsoil.

Table 2.7: Some important extractable micro-nutrients of the studied pedons of Magadu and Uyole sites, Tanzania

Profile	Horizon	Depth (cm)	Cu	Zn	Mn	Fe
			mg kg^{-1}			
SUARAT-P1	Ah	0 - 5/8	1.33	3.24	94.17	41.15
	BA	5/8 - 23	1.65	0.48	71.83	62.47
	Bt1	23 - 42	1.12	0.15	35.14	23.49
	Bt2	42 - 88	1.01	0.15	19.18	11.92
	Bt3	88 – 185+	0.48	0.02	7.67	8.27
UYOLE-P1	Ap	0 - 19/25	0.37	7.29	119.70	91.70
	Bw1	19/25 - 60/86	0.16	7.21	134.10	111.19
	C	60/86– 125/131	0.16	3.16	39.93	26.54
	Ab/Bw2b	125/131 - 210+	0.16	6.5	30.35	56.38

According to Landon (2014), its availability among other things is controlled primarily by total soil Cu, high P and Zn. SUARAT-P1 topsoil registered high level of zinc (Zn) concentration while in subsoil horizons it ranged from 0.02 - 0.48 mg Zn kg^{-1} and was rated as low zinc concentration. On the other hand, topsoil and underlying horizons of UYOLE-P1 registered high level of zinc (Merumba *et al.*, 2020) exceeding the deficiency Zn levels (Landon, 2014). The high levels of Zn in UYOLE-P1 pedon might have been the reason for the observed low Cu concentrations (Landon, 2014).

Manganese (Mn) had higher concentration levels than all the other micronutrients in both sites with amounts exceeding the deficiency level of < 2 - 5 mg kg^{-1} soil (Sillanpää, 1982). In SUARAT-P1 pedon, Mn levels ranged from 7.67 - 94.17 mg Mn kg^{-1} with the highest amount in topsoil. The amounts showed a regular decreasing trend with depth. Similar trend was observed elsewhere by Merumba *et al.* (2020). In the case of UYOLE-P1 pedon, the highest Mn concentration of 134.1 mg kg^{-1} was observed in the *Bw* horizon while the least concentration of 30.35 mg kg^{-1} was observed in the deepest horizon. However, both sites were rated as having high levels of Mn in all horizons (Merumba *et al.,* 2020). Iron (Fe), similarly had higher values than the deficiency level of 2.5 - 4.5 mg kg^{-1} Landon (2014), and ranged between 8.27 - 62.47 mg kg^{-1} in SUARAT-P1 and between 26.54 - 111.19 mg kg^{-1} in UYOLE-P1 pedon.

Both pedons had sufficient amounts of the essential micro-elements, but as Landon (2014) cautioned, some cereal crops and vegetables are very sensitive to copper deficiency. Therefore, depending on specific critical levels of different crops, there might be need to add some copper in UYOLE soil depending on specific crop requirement for Cu.

2.3.3.10 Total elemental composition and weathering indices/ratios of the studied soils

The total elemental composition of the two soils is presented in Table 2.8. The most abundant elemental oxides were in the order of SiO_2> Fe_2O_3> Al_2O_3> TiO_2> P_2O_5> K_2O > CaO for SUARAT-P1 pedon and SiO_2> Al_2O_3> Fe_2O_3> K_2O > P_2O_5> TiO_2> CaO for UYOLE-P1 pedon.

Table 2.8: Total elemental composition and weathering indices in the studied pedons of Magadu and Uyole sites, Tanzania

			Total elemental composition %							Weathering Indices	
Profile	**Horizon**	**Depth (cm)**	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**K_2O**	**CaO**	**TiO_2**	**P_2O_5**	**SiO_2 /Al_2O_3**	**SiO_2/(Al_2O_3/Fe_2O_3)**
SUARAT-P1	Ah	0 - 5/8	71.5	10.32	10.65	0.35	0.26	1.37	0.50	6.93	3.41
	Bt1	23 - 42	72.01	10.71	11.64	0.25	0.19	1.56	0.65	6.72	3.22
	Bt3	88 – 185+	80.0	7.10	4.92	2.44	0.75	0.63	2.14	11.27	6.66
UYOLE-P1	Ap	0 - 19/25	74.24	8.32	5.26	2.02	0.53	0.76	1.87	8.92	5.47
	Bw1	19/25 - 60/86	80.7	7.13	3.76	2.33	0.59	0.51	0.97	11.32	7.41
	Ab/ Bw2b	125/131 - 210+	71.4	8.36	8.81	1.40	4.22	1.73	1.12	8.54	4.16

The amount of silica (SiO_2) in SUARAT-P1 pedon in the upper, middle and bottom horizons were 71.55, 72.01, 80.03%, respectively, increasing down the pedon, whereas in the UYOLE-P1 pedon, SiO_2 increased from 74.24% in the upper horizon to 80.71% in the middle horizon, and then decreased to 71.36% in the bottom horizon.. The high SiO_2 content of the B*w*1 horizon in the UYOLE-P1 pedon may be attributed to the large amount of pumice fragments found in the horizon (Gama-Castro *et al.*, 2000).

The Al_2O_3 content ranged from 7.13 to 10.32% in SUARAT-P1 pedon, while in UYOLE-P1 pedon, Al_2O_3 content ranged from 7.13 to 8.36%. Generally speaking, SUARAT-P1 pedon had higher content of Al_2O_3 than UYOLE-P1 pedon. The Fe_2O_3 content of SUARAT-P1 pedon ranged from 4.92 to 11.64% while that of UYOLE-P1 pedon ranged from 3.76 to 8.81%. Just like for Al_2O_3 content, SUARAT-P1 pedon had generally higher Fe_2O_3 content than UYOLE-P1 pedon. Higher content of both Al_2O_3 and Fe_2O_3 in SUARAT-P1 pedon than in UYOLE-P1 pedon is related to higher content of sesquioxides in the former pedon than in the latter pedon. SUARAT-P1 pedon was more highly weathered and hence had higher content of sesquioxides than UYOLE-P1 pedon.

The higher content of Al_2O_3 and Fe_2O_3 may have an effect in increasing soil acidity and limit availability of plant nutrients like phosphorus. For example, it is well known that higher content of Al and Fe causes P fixation in the soils (Landon, 2014) which may lead to P deficiency to crops grown in SUARAT-P1.

The other oxides, including, K_2O, CaO, TiO_2 and P_2O_5 detected in the two pedons, were as low as 5%, and the low levels may be due to their leaching out of the profile after weathering processes or may be due to the nature of the soil parent materials (Baba *et al.,* 2008). The SiO_2/Al_2O_3 ratio also known as Ruxton Ratio (RR) was introduced/suggested by Ruxton (1968), which assumed alumina and other sesquioxides to be immobile during the process of weathering. In the SUARAT-P1 pedon, the SiO_2/Al_2O_3 ratio in surface and middle horizons showed almost similar ratios (6.93 and 6.73) but the deepest horizon had value of 11.27 which was higher than that in upper horizons, implying that more weathering occurred in topsoils than in bottom soil horizons (Uwingabire *et al.,* 2016).

In the case of UYOLE-P1 pedon, the trend was different in which topsoil and bottom soils had almost similar ratio (8.92 and 8.54) while the middle horizons had higher ratio due to the presence of sizeable amounts of pumices weathering to more silicates minerals as proposed by Gama-Castro *et al.* (2000). The ratio of $SiO_2/(Fe_2O_3 + Al_2O_3)$ which is also known as silica- sesquioxide ratio in SUARAT-P1 pedon was 3.41, 3.22 and 6.66, respectively, in the top, middle and bottom horizons, showing higher ratios towards the bottom indicating more weathering in the top and less weathering in the bottom horizons. In UYOLE-P1 pedon, least weathering is observed in the middle horizon with a $SiO_2/(Fe_2O_3 + Al_2O_3)$ ratio of 7.41, whereas the top and middle horizons had ratios of, respectively, 5.47 and 4.16 insinuating more weathering in the bottom horizons than in the topsoils (Merumba *et al.,* 2020; Uwingabire *et al.,* 2016; Tan and Troth, 1982).

Simultaneous decreases of both SiO_2/Al_2O_3 and $SiO_2/(Fe_2O_3 + Al_2O_3)$ ratios down the profile as revealed by SUARAT-P1 pedon is assumed to be caused by clay and / or Al and Fe movements down the profile; as opposed to their increase down the profile (from topsoil to middle horizons) as shown in UYOLEP-1 pedon, which may suggest the shifting of silicate minerals to lower horizons (Tan and Troth, 1982).

Results on both SiO_2/Al_2O_3 and $SiO_2/(Fe_2O_3 + Al_2O_3)$ weathering indices of the studied pedons, SUARAT-P1 pedon showed more advanced weathering of its soil minerals than in UYOLE-P1 pedon, with lesser degree of weathering observed in UYOLE-P1 pedon which is had higher SiO_2/Al_2O_3 ratio (Merumba *et al.*, 2020; Uwingabire *et al.*, 2016).

2.3.4 Soil classification in the studied area

Soil classification was done accordingly to USDA Soil Taxonomy (Soil Survey Staff, 2014) and correlated with the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015) based on the results obtained in the laboratory and properties observed and described in the field. Soil diagnostic horizons and features were identified and appropriate names given following the keys provided by the two systems of classification (Tables 2.9 and 2.10).

The soil of studied area at Magadu (SUARAT-P1) as described by the USDA Soil Taxonomy was named as "*Very deep, clayey, slightly acid to very strong acid, very gently sloping, ustic, isohyperthermic, Typic Kandiustults*" matching in the World Reference Base for Soil Resources (WRB) with "*Haplic Lixisols (Clayic, Cutanic, Ochric, Profondic)*", and the Uyole pedon (UYOLE-P1) was classified as *"Very deep, loamy, slightly acid to neutral, very gently sloping, Udic, Thermic, Andic Dystrudepts"* in the USDA Soil Taxonomy and as *"Eutric Andic Cambisols (Loamic, Colluvic, Humic)"* in the WRB.

Table 2.9: Diagnostic features and classification of the studied pedons of Magadu and Uyole sites, Tanzania

Pedon	Diagnostic horizon(s)	Other diagnostic features	Order	Suborder	Greatgroup	Subgroup	Family
SUARAT-P1	Ochric epipedon; Kandic Horizon	Very deep, clayey, slightly acid to very strong acid, very gently sloping, ustic SMR1, Isohyperthermic STR2	Ultisols	Ustults	Kandiustults	Typic Kandiustults	Very deep, clayey, slightly acid to very strong acid, very gently sloping, ustic, isohyperthermic, Typic Kandiustults
UYOLE-P1	Ochric epipedon; Cambic horizon	Very deep, loamy, slightly acid to neutral, very gently sloping, Udic SMR1, Thermic STR2	Inceptisols	Udepts	Dystrudepts	Andic Dystrudepts	Very deep, loamy, slightly acid to neutral, very gently sloping, udic, thermic, Andic Dystrudepts

1 =SMR = Soil moisture regime, 2 =STR = Soil temperature regime

Table 2.10: Diagnostic horizons and features, and classification of the studied soils of Magadu and Uyole Sites, Tanzania

Pedon No	Diagnostic horizon	Reference Soil Group (RSG) - TIER1	Principal Qualifiers	Supplementary Qualifiers	WRB soil name - TIER 2
SUARAT-P1	Ochric horizon; Argic horizon	Lixisols	Haplic	Clayic, Cutanic, Ochric, Profondic	Haplic Lixisols (Clayic, Cutanic, Ochric, Profondic)
UYOLE-P1	Cambic horizon	Cambisols	Andic, Eutric	Loamic, Colluvic, Humic,	Eutric Andic Cambisols (Loamic, Colluvic, Humic)

2.3.5 Conclusions and Recommendations

2.3.5.1 Conclusions

1. The SUARAT-P1 pedon is a very deep, acidic, Clay soil, classified in the USDA Taxonomy as an Ultisol (*Typic Kandiustults*) which correspond respectively to Haplic Lixisols in the WRB for soil resources.
2. The silt/clay ratio and CEC_{clay} has indicated that the soil is highly weathered.
3. The bulk density (BD) of less than 1.6 Mg m^{-3} favours good root penetration and water movement.
4. The soil has been rated as low in organic matter, total nitrogen, and available phosphorus.
5. The cation exchange capacity (CEC), electrical conductivity (EC), and basic nutrient balance are rated only as fair and favorable

Generally the soil of Magadu has poor fertility and needs significant management.

1. The UYOLE-P1 pedon is very deep soil but with slightly acidic to neutral reaction and dominantly Loamy textural class.
2. The pedon has been classified in USDA Taxonomy as Inceptisols (*Andic Dystrudepts*) which correspond respectively to *Eutric Andic Cambisols* in the WRB for Soil Resources.
3. Soil has favourable bulk density (BD) throughout its profile depth offering easy root penetration and water movement.
4. Soil has medium OM and low N, medium P and very high K
5. The site has medium to high CEC and BS

The soil is likely to offer moderately favorable soil conditions for crop production.

NB: The obtained values for soil OC and N are baseline for the proposed studies in SOC and N sequestration.

2.3.5.2 Recommendation

Good management practices (GMP) should be invested to assure sustainable use of the soil resource for crop production and other land uses which may include residue incorporation and mulching amendment, use of manure, crop rotation and intercropping.

References

Abitew, M. and Kebebew, S. (2016). Soil Fertility Status of Some Soil Orders and NuMaSS Fertilizer Recommendation at Bench-Maji Zone, South West, Ethiopia. *Canadian Journal of Agriculture and Crops* 1(2): 70-82.

Anderson, J. M. and Ingram, J. S. I. (1993). A handbook of methods. CAB International, Wallingford, Oxfordshire. 221pp.

Arshad, M. A, Lowery, B. and Grossman, B. (1996). Physical tests for monitoring soil quality. In: *Methods for Assessing Soil Quality*; Doran, J. W., Jones, A. J., Eds, Soil Science Society of America: Madison, WI, USA. pp. 123-142.

Baba, M., Hennie, F. W., Soehady, E., Sanudin, T. (2008). Geochemical characterization of volcanic soils from Tawau, Sabah. *Bulletin of the Geological Society of Malaysia* 54: 33-36.

Baize, D. (1993). *Soil Science Analysis.* A guide to correct use. John Wiley and Sons Ltd. West Sussex. 192pp.

Brady, N. C. and Weil, R. R. (2008). *The Nature and Properties of Soils*, 12th edition. Prentice-Hall, Inc., Upper Saddle River, NJ, USA. 881pp.

Bray, R. H. and Kurtz, L. T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science* 59: 39-45.

Bremner, J. R. and Yeomans, J. C. (1998). Laboratory techniques in J. R. Wilson (Ed) Advance in nitrogen cycling in agriculture ecosystem C. A. B Int. Willing, England. [www.sciencepublishinggroup.com › journal › paperinfo › j.ijnrem.202106...] site visited on 15/08/2018.

Chapman, H. D. (1965). “Cation Exchange Capacity.” In: *Methods of Soil Analysis.* Part 1, 1st edition, Agronomy Monograph no. 6, (Edited by C.A. Black), American Society of Agronomy, Madison, Wisconsin, vol. 9, pp. 891- 901.

Costantini, E. A., Angelone, M. and Damiani, D. (2002). Physical, geochemical and mineralogical indicators of aging in Quaternary soils of Central Italy. In: *17th World Congress of Soil Science, Transactions: International Union of Soil Sciences* 599: 1-9.

Conklin, A. R. (2013). Introduction to soil chemistry: Analysis and instrumentation. John Wiley and Sons. 376pp.

Fageria, N. K., Baligar, V. C. and Clark, R. B. (2002). Micronutrients in crop production. *Advances in agronomy* 77: 185-268.

FAO (2006). *Guidelines for Soil Description*. 4th Edn. Food and Agriculture Organization of the United Nations, Rome. 110pp.

Gama-Castro, J. E., Solleiro-Rebolledo, E. and Vallejo-Gomez, E. (2000). Weathered pumice influence on selected alluvial soil properties in west Nayarit, Mexico. *Soil and Tillage Research* 55: 143-165.

Hailu, H., Mamo, T., Keskinen, R., Karltun, E., Gebrekidan, H. and Bekele, T. (2015). Soil fertility status and wheat nutrient content in Vertisol cropping systems of central highlands of Ethiopia. *Agriculture and Food Security* 4(1): 1-10.

Hazelton, P. and Murphy, B. (2016). *Interpreting soil test results: What do all the numbers mean?* CSIRO publishing.

Heathwaite, A. L. and Göttlich, K. (1993). Mires Process, Exploitation and Conservation, John Wiley and Sons Ltd, London.

IUSS Working Group WRB. (2015). World Reference Base for Soil Resources 2014, update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106. FAO, Rome.

Juilleret, J., Dondeyne, S., Vancampenhout, K., Deckers, J. and Hissler, C. (2016). Mind the gap: A classification system for integrating the *subsolum* into soil surveys. *Geoderma* 264: 332–339.

Kalala, A. M., Msanya, B. M., Nyambilila, A. and Semoka, J. M. R. (2017). Pedological characterization of some typical alluvial soils of Kilombero District, Tanzania, *American Journal of Agriculture and Forestry* 5(1): 1-11.

Kebeney, S. J., Msanya, B. M., Ng'etich, W. K., Semoka, J. M. R., Serrem, C. K. (2015). Pedological characterization of some typical soils of Busia County, Western Kenya: Soil morphology, physico-chemical properties, classification and fertility trends. *International Journal of Plant and Soil Science* 4: 29-44.

Laekemariam, F., Kibret, K. and Shiferaw, H. (2018). Potassium (K)-to-magnesium (Mg) ratio, its spatial variability and implications to potential Mg-induced K deficiency in Nitisols of Southern Ethiopia. *Agriculture and Food Security* 7(1): 1-10.

Landon, J. R. (2014). Booker Tropical Soil Manual: A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics. In: 2000 Symposium: Sugarcane: Research towards Efficient and Sustainable Production, Routledge, London, pp. 237-240.

Lowery, B. and Morrison, J. E. (2002). Soil penetrometers and penetrability. In; Methods of Soil Analysis Part 4, Physical Method*s* (Eds Dane, J. H. and Topp, G. C.). Soil Science Society of America: Madison, WI, USA. pp. 363–388.

Lufega, S. M. and Msanya, B. M. (2017). Pedological characterization and soil classification of selected soil units of Morogoro District, Tanzania. *International Journal of Plant and Soil Science* 16(1): 1-12.

Ma, C. (1996). *The ultra -structure of kaolin*. Ph.D. Thesis for Award Degree at, Australian National University, Canberra, Australia. 343pp.

Ma, C., Richard, A. and Eggleton, A. (1999). Cation exchange capacity of kaolinite. *Clays and Clay Mineral* 47: 174–180.

Macedo, J. and Bryant, R. B. (1987). Morphology, mineralogy, and genesis of a hydrosequence of Oxisols in Brazil. *Soil Science Society of American Journal* 51: 690–698.

Massawe, I. H., Msanya, B. M. and Rwehumbiza, F. B. (2017). Pedological characterization and fertility evaluation of paddy soils of Mvumi village, Kilosa district, Tanzania. *International Journal of Current Research in Biosciences and Plant Biology* 4(4): 49-60.

Miranda-Trevino, J. C. and Coles, C. A. (2003). Kaolinite properties, structure and influence of metal retention on pH. *Applied Clay Science* 23: 133–139.

Moberg, J. (2001). *Soil and Plant Analysis Manual*. (Revised Edition). The Royal Veterinary and Agricultural University Chemistry Department, Copenhagen, Denmark. 133pp.

Moustakas, N. K. and Georgoulias, F. (2005). Soils developed on volcanic materials in the island of Thera, Greece. *Geoderma* 129: 125-138.

Msanya, B. M., Kimaro, D. N., Kileo, E. P., Kimbi, G. G. and Munisi, A. I. M. (2001). Land Resources Inventory and Suitability Assessment for the Production of the Major Crops in the Eastern Part of Morogoro Rural District, Tanzania. Soils and Land Resources of Morogoro Rural and Urban Districts, Vol. 3. Department of Soil Science, Faculty of Agriculture, Sokoine University of Agriculture, Morogoro, Tanzania. 69pp.

Msanya, B. M., Mwasyika, T. A., Amuri, N., Semu, E. and Mhoro, L. (2018). Pedological characterization of typical soils of Dodoma Capital City District, Tanzania: soil morphology, physico-chemical properties, classification and soil fertility trends. *Annals of Advanced Agricultural Science*s 2(4): 59-73.

Msanya, B. M., Munishi, J. A., Amuri, N., Semu, E., Mhoro, L. and Malley, Z. (2016). Morphology, genesis, physico-chemical properties, classification and potential of soils derived from volcanic parent materials in selected Districts of Mbeya Region, Tanzania. *International Journal of Plant and Soil Science* 10(4): 1-19.

Msanya, B. M., Otsuka, H., Araki, S. and Fujitake, N. (2007). Characterization of volcanic ash soils in southwestern Tanzania: Morphology, physicochemical properties, and classification. *African Study Monographs* 34: 39-55.

Mtama, J. G., Msanya, B. M. and Burras, C. L. (2018a). Pedology at four representative sites of Southern Highland Zone of Tanzania. *American Journal of Agriculture and Forestry* 6(5): 111-121.

Mtama, J. G., Burras, C. L. and Msanya, B. M. (2018b). Pedotransfer functions for cation exchange capacity, available water holding capacity and soil organic carbon for representative soils of southern highland zone of Tanzania. *International Journal of Agriculture and Biological Sciences* 2018b: 26-42.

Mukungurutse, C. S., Nyapwere, N., Manyanga, A. M. and Mhaka, L. (2018). Pedological characterization and classification of typical soils of Lupane District, Zimbabwe. *International Journal of Plant and Soil Science* 22(3): 1-12.

Merumba, S. M., Msanya, B. M., Semu, E. and Semoka, J. M. (2020). Pedological Characterization and Suitability Assessment for Cassava Production in Bukoba, Missenyi and Biharamulo Districts, Tanzania. *American Journal of Agriculture and Forestry* 8(4): 144-166.

National Bureau of statistics (NBS) (2019). Tanzania in figures 2018 [https://www.nbs.go.tz/index.php/en/tanzania-in-figures/422-tanzania-in-figures-2018] site visited on 15/08/2018.

National Bureau of Statistics (NBS). Annual Agricultural Sample Survey (AASS) 2016-2017 [https://www.nbs.go.tz/index.php/en/census-surveys/agriculture-statistics/57-2016-17-annual-agriculture-sample-survey-crop-and-livestock-final-report] site visited on 15/08/2018.

National Soil Service (1990). *Laboratory Procedures for Routine Analysis.* 3rd edition, Agricultural Research Institute, Mlingano Tanga, Tanzania. 169pp.

Nelson, D. W. and Sommers, L. E. (1982). Total organic carbon. In: L. A. Page, R. H. Miller, and D. R. Keeney (Eds.) *Methods of Soil Analysis*, *Part 2* (2nd Ed.) Agronomy Monograph No. 9. American Society of Agronomy and Soil Science Society of America, Madison, WI. pp. 539-579.

Neswati, R., Lopulisa, C. and Basir, A. (2019). Characteristics and Classification of Soil Formed from Banda Recent Volcanic Ash on Various Topographic Positions. In IOP Conference Series: *Earth and Environmental Science* 280(1): 1-27.

Nicolardot, B., Recous, S. and Mary, B. (2001). Simulation of C and N mineralisation during crop residue decomposition: a simple dynamic model based on the C: N ratio of the residues. *Plant and Soil* 228(1): 83-103.

Ojoyi, M. M., Antwi-Agyei P., Mutanga O., Odindi J. and Abdel-Rahman E. M. (2015). An analysis of ecosystem vulnerability and management interventions in the Morogoro region landscapes, Tanzania. *Tropical Conservation Science* 8(3): 662- 680.

Okalebo, J. R., Gathua, K. W. and Woomer, P. L. (2002). *Laboratory Methods of Soil and Plant Analysis*: *A Working Manual* 2nd edition. Sacred Africa, Nairobi. 128pp.

Peverill, K. I., Sparrow, L. A. and Reuter, D. J. (Eds.). (1999). ‘Soil analysis: an interpretation manual.’ (CSIRO publishing: Melbourne).

Ribeiro, L. (1976). Introducao ao estudo da mineralogia dos solos de Ibitiara, BA, in Ana ´is do de´cimo quinto congresso Sociedade Brasileiro de Cieˆncia do solo. ociedade Brasileira de Ciencia do Solo, Campinas, SP, Brazil, pp. 423–427.

Ricardo, M. M. and Yost, R. (2006). A survey of soil fertility status of four agroecological zones of Mozambique. *Soil Science* 171(11): 902-914.

Ruxton, B. P. (1968). Measures of the degree of chemical weathering of rocks. *The Journal of Geology* 76(5): 518-527.

Sillanpää, M. (1982). Micronutrients and the nutrient status of soils: a global study (Vol. 48). Food and Agriculture Organization.

Scrimgeour, C. (2008). Soil Sampling and Methods of Analysis. Edited by MR Carter and EG Gregorich. Boca Raton, Fl, USA: CRC. *Experimental Agriculture* 44(3): 437-437.

Sharu, M. B., Yakubu, M., Noma, S. S. and Tsafe, A. I. (2013). Characterization and classification of soils on agricultural landscape in Dingyadi District, Sokoto State, Nigeria. *Nigerian Journal of Basic and Applied Sciences* 21(2): 137-147.

Shehu, B. M., Jibrin, J. M. and Samndi, A.M. (2015). Fertility Status of Selected Soils in the Sudan Savanna Biome of Northern Nigeria. *International Journal of Soil Science* 10(2): 74-83.

Shelukindo, H. B., Msanya, B. M., Semu, E., Mwango, S. B., Singh, B. R. and Munishi, P. (2014). Characterization of some typical soils of the miombo woodland ecosystem of kitonga forest reserve, Iringa, Tanzania: Physico-chemical properties and classification. *Journal of Agricultural Science and Technology* 4: 224-234.

Soil Survey Staff, (2014). *Keys to Soil Taxonomy. United States Department of Agriculture*, 12th ed., Natural Resource Conservation Service, Washington, DC. 187pp.

Harrison, R. B. and Strahm, B. D. (2008). Soil formation. *Encyclopaedia of Ecology* 2008: 3291-3295.

Thomas, G. W. (1988). Exchangeable cations. In: A. I, Page (Ed). *Methods of soil analysis, part 2.Chemical and microbiological propertie*s 2nd edition. American Society of Agronomy, Soil Science Society of America, Madison, Wl. pp159-165.

Tenga, J. J., Msanya, B. M., Semoka, J. M., Semu, E. and Mwango, S. B. (2018). Pedological Characterization and Classification of Some Typical Soils in Three Agro-Ecological Settings of South-Eastern Tanzania. *International Journal of Scientific and Engineering Research* 9(2): 692-702.

Uwingabire, S., Msanya, B. M., Mtakwa, P. W., Uwitonze, P. and Sirikare, S. N. (2016). Pedological characterization of soils developed on gneissic - Granites in the Congo Nile watershed divide and central plateau zones, Rwanda. *International Journal of Current Research* 8 (9): 39489-39501.

Watanabe, F. S. and Olsen, S. R. (1965). Test of an ascorbic acid method for determining phosphorus in Central Illinois. Midwest Friends of the Pleistocene 26th Field Conf., Campaign, IL Illinois Geological Survey Guidebook 13, pp.129-134.

CHAPTER THREE

3.0 INFLUENCE OF MAIZE - SOYBEAN CROPPING SYSTEMS ON SOIL NITROGEN, SOIL ORGANIC CARBON, AND CROP YIELDS IN SELECTED SOILS OF TANZANIA

Abstract

The main objective of the study was to evaluate effect of different cropping systems (monocropping, intercropping and/or rotation) on crop yield, soil organic carbon (SOC) and gains in soil nitrogen (N). Crop residues of maize and soybean yield were determined from the intercropped or mono-cropping systems prior to residue incorporation into the soil. Soil was collected and SOC and, soil N were determined. There were no significant ($p < 0.05$) differences between cropping systems on the SOC and N sequestration for three seasons in Magadu, and two seasons in Suluti and Uyole sites. The SOC sequestration among cropping systems in the Magadu site was insignificantly ($p < 0.05$) greater in the continuous maize amended with inorganic N fertilizer (80 kg N ha^{-1}). The trend of SOC slightly decreased in all three sites. Meanwhile the trend of soil N in Magadu appeared to maintain almost the same soil N values, increased values in both Suluti and Uyole were observed. Maize grain yield in Magadu did not significantly ($p < 0.05$) differ between cropping systems one year after residue retention, however, significantly ($p < 0.05$) higher soybean grain yield in the sole soybean were observed than in the intercropped plots. The maize grain yield in the Suluti was significantly ($p < 0.05$) higher in fertilized maize (80 kg N ha^{-1}) treatments in the first year (1.34 Mg ha^{-1}), and significantly ($p < 0.05$) higher in the intercropping (2.5 Mg ha^{-1}) in second year. In the Uyole site, the intercropped and the inorganic fertilized maize (80 kg N ha^{-1}) plots had highest yield reaching 1.5 Mg ha^{-1} in the first year, and significantly ($p < 0.05$) higher in the fertilized maize (80 kg N ha^{-1}) plot in the second year (2.54 Mg ha^{-1}) than other cropping systems. The above ground biomass in Magadu ranged from 14.05 Mg ha^{-1} in the maize (80 kg N ha^{-1}) and 5.7 Mg ha^{-1} in sole maize and rotation in the first year but decreased in the third year to 2.41 Mg ha^{-1} in the maize (80 kg N ha^{-1}) and 1.04 Mg ha^{-1} 1.29 Mg ha^{-1} in sole maize and rotation, respectively. Maize biomass yield in Uyole site was 11.3 - 12.96 Mg ha^{-1} in the first season, and ranged from 6.96 Mg ha^{-1} in intercrop, 8.82 Mg ha^{-1} in sole maize, and 12.33 Mg ha^{-1} in the maize (80 kg N ha^{-1}). The result point out that SOC, N, and the crop yield were not significantly enhanced in a three and two years under intercropping, rotation or monocropping, however, the grain and biomass yield was greatly influenced in the fertilized maize and intercropping. The C and N sequestration under these cropping systems may need more time to achieve potential SOM increment under this management.

Keywords: intercropping, rotation, carbon sequestration, grain yield, biomass yield, cropping system

3.1 Introduction

Soil management is essential to ensure increased crop production (Liao *et al.,* 2015; Poffenbarger *et al.,* 2017). Moreover, productivity is the integral function of healthy physical and chemical properties of soils, which are governed by many factors such as high levels SOM and its conservation, properly balanced nutrient and soil moisture regimes, and good soil management, among others (Cong *et al.,* 2015; Das *et al.,* 2013). Inappropriate use of inorganic fertilizers and other agrochemicals deteriorates soil quality and health for sustainable crop production (Anantha *et al.,* 2018; Vance, 2001).

Intercropping and crop rotation are famous cropping systems with several advantages, including improving soil biological, physico-chemical properties coupled with enhanced crop yields (Borase *et al.*, 2020; Poffenbarger *et al.*, 2017; Yang *et al.*, 2017; Wang *et al.*, 2014). These two systems have several advantages that include enhancing soil properties, crop yield, pest, and weed management. For example, Cong *et al*. (2014) has reported an increased plant diversity and functional complementarity, relatively higher yields per unit land area/ land use efficiency (Wang *et al.*, 2014) reduction of incidence of pests (Li *et al.*, 2009) from prolonged host absence and weed suppression (Corre-Hellou *et al.*, 2011).

The legume-cereal intercropping and or rotation has better C input in root system as in sole crops (Borase *et al.*, 2020; Yang *et al.*, 2010; Ghosh *et al.*, 2006; Li *et al.*, 2001). In addition, legume–cereal rotation also increased SOC and SON reserves through microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN), coupled with significant increases in enzymatic activities, particularly dehydrogenase, arylsulfatase, and acid phosphatase enzymes (Borase *et al.*, 2020).

Legumes contribute the bulk of high-quality SOM in soils due to the low C: N ratios of their plant residues (Dhakal *et al.*, 2016), whereby N is readily available for plants after microbial decomposition of the residues.

Maintenance of soil fertility in most developing countries of Sub-Saharan Africa, is hampered by little knowledge of most of smallholder farmers on soil management (Zingore *et al*., 2015), multiple uses of crop residues besides soil fertility improvement (Batidzirai *et al.*, 2016; Turmel *et al.*, 2015), and unfavourable weather conditions in tropical countries (Srinivasarao *et al.*, 2012).

There are knowledge gaps, however, as to how these cropping systems can enhance sequestration of C and N in such soils, coupled with increased crop yields. Therefore, this research aimed at investigating different cropping systems of maize and soybean which might have positive influence on the SOC, soil N, and grain and biomass yields.

3.2 Materials and Methods

3.2.1 Description of research sites

The research was established in three different locations to study the influence of maize – soybean cropping systems on SOC, N, and crop yields. The experiments were established at Morogoro (Magadu), Mbeya (Uyole), and Ruvuma (Suluti) in Tanzania.

The Morogoro site is located at Magadu site (SUA) which is located at latitude 06° 51′ 06″ to 06° 51′ 20″ S and longitude 37° 38′ 21″ to 37° 38′ 35″ E in Morogoro municipality, in Magadu ward, at the Sokoine University of Agriculture rat research (APOPO) site. The soil type was classified according to USDA Soil Taxonomy as *Typic Kandiustults*. The research site plot at ARI – Uyole was on the outskirts of Mbeya city, and 08° 54′ 4″ S and 08° 56′ 7″ S to 033° 30′ 11″ E to 033° 32′ 28″ E, at 1,779 metres above sea level (m.a.s.l), with soil classified as Inceptisols. The experimental study site in Namtumbo district at Suluti village was located at latitude 10º 34′ 32″ S to 10º 35′ 2″ and longitude 036° 7′ 36″ E to 036° 8′ 3″ E. Some data on weather at the site are presented in the Fig. 3.1. The data shows that sites are suitable for crop plant growth in terms of rainfall and temperature.

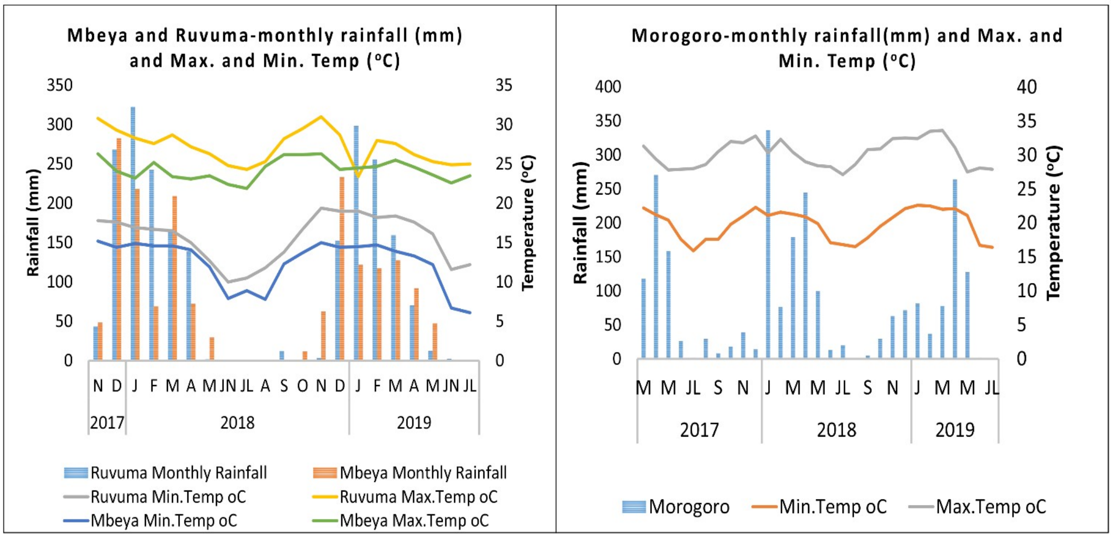

Figure 3.1: Monthly rainfall (mm) maximum and minimum temperature (°C) variation in Morogoro, Mbeya, and Ruvuma

3.2.2 Experimental design

This research was established on experimental plots in Magadu, Suluti and Uyole on land fallowed for between three to four years. Experimental plots in Magadu were established in March 2017 and the experimental plots were initiated at ARI-Uyole and Suluti in December 2017. The experiments comprised six treatments with a total of four different cropping systems. The treatments were maize monocropping, maize – soybean rotation, maize - soybean intercropping, soybean monocropping, maize + inorganic fertilizer (N) at 80 kg N ha^{-1}, and the absolute control in which no seed was planted. The experimental design was the randomized complete block design (RCBD), with each treatment replicated three times. Plot size was 9 square meters per plot (3x3 metres).

The field was ploughed using a hand hoe as practiced by smallholder farmers before planting. Plant spacing was 75 cm x 30 cm and 50 cm x 10 cm for maize and soybean, respectively, giving populations of 44,444 for maize and 200,000 for soybeans per hectare for the monoculture crops. In maize - soybean intercropping, soybeans were planted in between maize rows.

In the Magadu-SUA site in Morogoro region the plots were planted in March or early April and harvested in July while in planting and harvesting at Uyole and Suluti were done in December-January and July, respectively. During harvesting, maize and soybean plants were harvested from an area of 3.6 m^2 (1.5 m x 2.4 m) while soybean in intercropped plots was harvested from an area of 1.8 m^2 (0.75 m x 2.4 m) leaving the exterior part of the original plot. Following a method used by Al-Kaisi *et al.* (2005), grains were dried to adjust moisture content to 15.5 and 13 % for maize and soybean, respectively, before yield calculations were done. After harvesting, the dry biomass in the field was chopped into small pieces of 5-10 cm and incorporated into the soil using a hand hoe.

3.2.3 Soil sampling after harvesting

At harvesting, soil samples were randomly collected diagonally in each plot at the depth 0 - 30 cm for physicochemical analysis. The soil surface was cleaned of plant debris or other residues prior to sampling. Collected soil sample were passed through a 2 mm sieve and subsequently air-dried for three days before being subjected to physicochemical analysis as described below.

3.2.4 Chemical analysis

3.2.4.1 SOC

Soil organic carbon was determined by the wet oxidation method of Walkley and Black (Nelson and Sommers, 1982). Accordingly, one gram of the sample soil was weighed and placed into a 500 ml conical flask. Ten ml of 1 M potassium dichromate was subsequently added, followed by the addition of 20 ml of concentrated sulfuric acid under a fume hood. The mixture was left for 30 min and then 100 ml of distilled water was added followed by 10 ml of 85 % phosphoric acid. The solution was titrated against 0.5 M. $(NH_4)_2Fe(SO_4)_2.6H_2O$ (ammonium ferrous sulfate).

3.2.4.2 Nitrogen

Total nitrogen was determined by the micro-Kjeldahl digestion and distillation method (Bremner and Yeomans, 1998). One gram of the sample soil was weighed and placed into a Kjeldahl digestion tube. The soil in the tube was mixed with 10 ml of concentrated sulfuric acid and two grams of mixed catalyst (Potassium sulfate, Selenium, and Copper II Sulfate) prior to incubation of the resultant mixture at 360 ^{o}C for two hours to allow digestion of the contents. After two hours of digestion, the contents of each tube were mixed with 50 ml of distilled water followed by 50 ml of 40 % NaOH before Kjeldahl distillation. The ammonium collected from the distillation process was reacted with 25 ml of 4 % boric acid mixed with an indicator in a conical flask. Finally, the reacted solution was titrated against 0.05 N H_2SO_4.

3.2.4.3 Biomass yield

The above ground biomass of maize and soybean in the field were collected in a two square metres from their respective plots during harvesting and weighed using a field scale.

3.2.5 Data analysis

The data were subjected to analysis of variance (ANOVA) using GENSTAT 15th Edition Statistical Package. When significance at $p < 0.05$ was found, means were compared using to Duncan Multiple Range Test (DMRT) at $p < 0.05$.

3.3 Results and Discussion

3.3.1 Influence of cropping system on soil organic carbon

The soil organic carbon (SOC) in different cropping systems over three years at Magadu, Suluti and Uyole are shown in Tables 3.1 and 3.2. There were no significant differences ($p < 0.05$) in SOC among all cropping systems.

Table 3.1: Influence of cropping system and residue incorporation on soil organic carbon (SOC) for three years at Magadu, Morogoro

Treatment	Year 1	Year 2	Year 3
	Organic carbon (%)		
Absolute Control	1.36	1.28	1.30
Sole maize	1.25	1.15	1.18
Intercropping	1.38	1.28	1.21
Rotation	1.31	1.32	1.15
Sole soybean	1.14	1.27	1.12
Maize (80 kg N ha^{-1})	1.37	1.40	1.26
	NS	NS	NS

NS= not significant at $p \leq 0.05$

Table 3.2: Organic carbon for two years at Suluti (Ruvuma) and Uyole (Mbeya)

Treatments	Suluti		Uyole	
	Organic Carbon %			
	Year 1	Year 2	Year 1	Year 2
Absolute Control	1.3	1.24	1.70	1.60
Sole maize	1.28	1.16	1.75	1.61
Intercropping	1.38	1.13	1.71	1.62
Rotation	1.22	1.10	1.83	1.65
Sole soybean	1.21	1.13	1.69	1.61
Maize (80 kg N ha^{-1})	1.33	1.13	1.76	1.65
	NS	NS	NS	NS

NS= not significant at $p \leq 0.05$

However, SOC decreased slightly in the sole maize and in the sole soybean treatments, in all years, relative to the other treatments. In the treatments other than the absolute control, the expectation would be that it increased SOC following incorporation into soil of the plant biomass generated in the various treatments. In year 1, this might not be expected because soil sampling at the end of the cropping season was done before incorporation of the biomass. Any increase in SOC would be observed at the beginning of the following season, that is, one year after incorporation of biomass into soil. However, this did not happen in year 2 or year 3.

There were no significant ($p < 0.05$) differences in SOC between years and among the treatments although, as mentioned above, slight changes (increase and decrease) were observed in some treatments. The slight changes indicated a little insignificant increase in SOC in the intercropping and rotation treatments relative to maize monocropping. Cong *et al.* (2014) and Wang *et al.* (2014) also showed increased SOC after seven and two years, respectively, under intercropping as compared to monocropping.

Cong *et al.* (2014, 2015), and Li *et al.* (2013) postulated that upon incorporation into soil of residues containing leguminous plants in addition to non-legume plants, the overall C:N ratio of the combined residues becomes narrower than that in maize residues. This narrow C:N ratio enhances decomposition of the combined residues and, consequently, increases in SOC. Therefore, compared to observations by Cong *et al*. (2014) that SOC increase was observed after seven years of practice, it is plausible to suggest in the present study that the lack of significant increase in SOC in the second and third year calls for longer-term studies in the soils of Morogoro, Ruvuma and Mbeya used for the current study. Perhaps the presently insignificant ($p < 0.05$) increases in SOC under intercropping, rotational cropping and use of high level of N fertilizer after two or three years (Table 3.1 and 3.2) could add up to significant ($p \leq 0.05$) increases in SOC in the longer term, as observed by Cong *et al.* (2014) and Wang *et al.*(2014). This underscores the need for this type of experiments to be essentially long – term.

The addition of crop residues is characterized by higher CO_2-C efflux which appears to be quickly established at the very initial stage following application of the residue (Hall, *et al.,* 2019; Qiu *et al.,* 2016). For example, Qiu *et al.* (2016) reported 2.702 mg C kg^{-1} of soil and only 9 - 12 % of the initial CO_2-C efflux was observed on the 15th day of incubation but further concluded that 94 - 96 % of the total CO_2-C efflux was accounted in the first six months (190 days). Another research on soil incubation of maize residue revealed that residue retention in soil significantly enhanced CO_2-C emission as compared to when N fertilizer alone was used (Qiu *et al.,* 2016). A similar study undertaken for two-years showed that maize residue contributed CO_2-C flux of up to 0.67 Mg C ha^{-1} y^{-1}, doubling that of soybean residue which produced 0.32 Mg C ha^{-1} y^{-1} (Mazzilli *et al*., 2014). The return of residues of different quality to the soil may contribute to SOC loss in agricultural soils when residues are used as means of soil amendment, thus accounting for the non-increase of SOC in the soil at least in the short term, as observed in the current study.

The SOC sequestration is also influenced by some weather conditions like soil temperature, precipitation, and other physical soil properties (clay, silt, and rate of SOC occlusion in soil aggregates) (Mazzilli *et al*., 2014; Amanullah *et al.,* 2009). For example, Davidson and Janssens (2006) reported that most soil microbes require temperatures between 10 - 35 ^{o}C for their optimum performance, while Broadbent (2015) reported that temperatures in the range of 2 to 38 ^{o}C increases the rates of SOM decomposition, which may increase rate of C loss through respiration (CO_2-C efflux). A separate study revealed that the effect of higher temperature across years reduced the SOC by 126 g C m^{-2} $year^{-1}$ (Cheng *et al.,* 2017). The slight decreases of SOC (Tables 3.1 and 3.2) in the present study may have been due, in part to the high temperature experienced in the trial sites (Fig. 3.1). The slight decrease trends in SOC in some treatments might have also been contributed by enhanced microbial decomposition of soil organic matter (SOM) and applied fresh crop biomass to CO_2 (Yang *et al.,* 2009). Thus, high temperatures in the long term will be counterproductive to increased C sequestration in these soils.

Also, the effect of residue diversity (litter mixture) in intercropping might have hastened SOC decomposition caused by the legumes in narrowing of the C:N ratio of the overall mixture (Cardinale *et al.,* 2011).

The carbon sequestration buildup in the present study was very slow, suggesting that in the three years of this study were too short to realize the effect thus requiring more long - term study at least six years to start observing significant SOC increases (Al-Kaisi *et al.*, 2005).

3.3.2 Effect of cropping system and residues incorporation on soil nitrogen

Results of the effect of cropping system and residues incorporation on soil N are presented in Tables 3.3 and 3.4 for Magadu, Suluti and Uyole sites.

There were generally no significant ($p < 0.05$) differences in soil total N among cropping treatments.

Table 3.3: Soil nitrogen influenced by different cropping systems for three years at Magadu (Morogoro)

Treatment	Nitrogen (%)		
	Year1	Year2	Year3
Absolute Control	0.14	0.12	0.13
Sole maize	0.12	0.12	0.13
Intercropping	0.15	0.10	0.13
Rotation	0.13	0.11	0.12
Sole soybean	0.13	0.11	0.12
Maize (80 kg N ha^{-1})	0.15	0.12	0.14
	NS	NS	NS

NS= not significant at $p \leq 0.05$

The trends of soil N changes over years among treatments, were insignificant, and were similar to the trends of SOC changes (as a reflection to SOM changes) between the treatments as discussed above (section 3.3.1). The same reasoning could well apply here explaining for soil N.

Table 3.4: Soil nitrogen as influenced by different cropping systems for two years in Suluti (Ruvuma) and Uyole (Mbeya)

Treatment	Suluti		Uyole	
	N %			
	Year1	Year2	Year1	Year2

Absolute Control	0.08	0.11	0.11	0.14
Sole maize	0.08	0.11	0.12	0.15
Intercropping	0.09	0.09	0.12	0.14
Rotation	0.08	0.11	0.11	0.13
Sole soybean	0.06	0.11	0.11	0.14
Maize (80 kg N ha^{-1})	0.07	0.10	0.11	0.15
	NS	NS	NS	NS

NS = not significant at $p \leq 0.05$

Table 3.4 presents results on the effects of intercropping and/or rotation on soil N at Suluti and Uyole following two years of experiment. The first and second year in Suluti showed no significant ($p > 0.05$) differences between treatments.

There were generally insignificant ($p > 0.05$) changes in soil N in all treatments from first to the second year. The lack of soil N increase in the sole soybean could be attributed to the narrow C:N ratio of soybean residues, leading to greater decomposition and net mineralization of N that subsequently became lost from soil. The observed trend of soil N changes were similar to trends of SOC changes because N is a constituent of SOM.

The Uyole plots showed no significant ($p > 0.05$) differences in the first and second-year treatments (Table 3.4). However, after one year of crop residue management soil N showed insignificant ($p > 0.05$) increment in the second harvesting year in all treatments (Table 3.4). This observation is similar to those made by Shafi *et al.* (2007) who showed that residue incorporation in two years resulted in soil N increase. This observation of some increases in N overtime give credibility to the suggestion given above (section 3.3.1) that long term study might eventually show some significant increases in SOM and hence soil N. Thus long term execution of practices that increases soil OC will lead also to significantly increased soil N.

3.3.3 Effect of cropping systems and residue retention on maize and soybean grain yield

3.3.3.1 Maize yield

Tables 3.5 and 3.6 show the grain yield data for the Magadu, Suluti and Uyole experimental sites.

Table 3.5: Maize and soybean grain yield for three years at Magadu, Morogoro

Treatments	Maize	Soybean	Maize	Soybean	Maize	Soybean
	(Mg/ha)					
	Year 1		Year 2		Year 3	
Absolute Control						
Sole maize	0.412a		0.544ns		0.094ns	
Intercropping	0.739a	0.192a	0.653ns	0.121a	0.142ns	0.063a
Rotation	0.691a			0.351b	0.225ns	
Sole soybean		0.997b		0.327b		0.260b
Maize (80 kg N ha^{-1})	2.347b		0.670ns		0.767ns	

Means within a column followed by different letter(s) are significantly different at p≤0.05 according to DMRT. Maize (80 kg N ha^{-1}) maize plot supplied with 80 kg of N per hectare, ns= not significant at p≤0.05

Table 3.6: Maize and soybean grain yield for two years at Suluti, Ruvuma and Uyole, Mbeya

Cropping system	Suluti				Uyole			
	Maize	Soybean	Maize	Soybean	Maize	Soybean	Maize	Soybean
	Year 1 (2018)		Year 2 (2019)		Year 1 (2018)		Year 2 (2019)	
Absolute Control								
Sole maize	0.289a		1.125a		1.113a		1.454b	
Intercropping	0.335a	0.55ns	2.513b	0.276a	1.558b	0.532a	0.916a	0.825a
Rotation	0.335a			0.786b	1.329ab			1.514ab
Sole soybean		0.57ns		0.86b		2.263b		1.583b
Maize (80 kg N ha^{-1})	1.34b		2.331b		1.51b		2.543c	

Means within a column followed by different letter(s) are significantly different at p≤0.05 according to New D.M.R.T, Maize ((80 kg N ha^{-1}) - maize plot supplied with 80 kg of N per hectare, ns =not significant at p <0.05.

There were significantly higher ($p \leq 0.05$) maize yields only in MZ (80 kg N ha^{-1}) treatment plot. Grain yields of sole maize, intercropped maize, and maize rotation were not significantly ($p < 0.05$) different amongst them. In the first cropping year, the effect of residue incorporation was not expected because crop residues were applied at the end of the season after harvest. The low levels of yields under the biomass incorporation may imply that the biomass could not supply enough N for higher maize yields. Logah *et al.*

(2011) also found significantly higher maize yield after the use of N fertilizer over an un-amended maize plot.

The retention of biomass obtained from previous years in Magadu could not enhance yield performance in the third year, rather there was further decline compared to the previous two seasons (2017-2018) in the sole maize, intercropping, and rotated plots but a slight increase of 0.09 Mg ha^{-1} in the MZ (80 kg N ha^{-1}) plots probably due to access by crops to the added N fertilizer (Poffenbarger *et al.*, 2017).

Yield response to residues retention depends on the quality and even quantity of residues applied (Mohammed *et al.,* 2013) as well as favorable weather conditions such as temperature and soil moisture content (Mohammed *et al.*, 2014). Declining yield trends in the first four years of rotation and/or intercropping have been reported before. Agyare *et al.* (2006) showed, for example, that indeed there was a decline in yield before gains due to intercropping and/or rotation could be realized. In some cases, researchers have reported a lack of gains in yield in a maize-legume rotation for up to over seven years of practice (Al-Kaisi *et al.,* 2005; Agyare *et al.,* 2006).

As observed in the present study, the SOM levels were not significantly enhanced even after residue retention in three or two years. The decline in grain yields could be due to low soil fertility levels due to competition for nutrients in the intercropping (Lv *et al.,* 2014).

3.3.3.2 Soybean grain yield

Magadu soybean grain yields (Table 3.5) in the first season were 5.19 times (0.805 Mg ha^{-1}) higher ($p \leq 0.05$) in the sole soybean than intercropping, similarly, Uyole site also had

4.25 times higher (1.73 Mg ha^{-1}) soybean grain yield in the sole soybean than intercropped plots in the first season due to population difference in which sole soybean have more than twice number of soybean plants. The soybean yields in the Suluti site in the first year were not significantly ($p < 0.05$) different in the intercropped plots and sole soybean (Table 3.6), both had a grain yield of 0.5 Mg ha^{-1}.

There were no yield differences in soybean between the rotation and sole soybean treatments in the season two at Magadu (Table 3.5), yet their yields were more than twofold higher than under intercropping. The same trend was observed in the Suluti site (Table 3.6) in second year cropping, and the yields under rotation with soybean crop and sole soybean were higher than under intercropping. Furthermore, sole soybean was observed to have reduced yield performance by three- and two-folds, respectively, in Magadu, relative to the first season.

In Uyole, the intercropped plots had an increase of 0.293 Mg ha^{-1} of soybean grain while the sole soybean grain yield was higher than under intercropping but not significantly so compared to the rotated soybean. Results of the present study correspond to the study by Wang *et al.* (2020) which also showed that monocrop soybean exceeded the yields of intercropped soybean by more than 2 times.

In addition, it is reported that soybean grain yield performance under intercropping is affected by the planting pattern (Wang *et al.*, 2020; Zhang *et al.*, 2015) and the shading effect of the dominant partner crop (Liu *et al.*, 2018; Yang *et al.*, 2017; Tsubo and Walker, 2004). Liu *et al.* (2018) and Yang *et al.* (2017) reported that maize shading affected soybean crop in the seedling stages and the reproductive stage under intercropping and may have significantly lowered yield in the soybean-maize intercropping system as compared to sole soybean in the present experiments. Similarly, Tsubo and Walker (2004), found that the decrease in grain yields in common bean was also due to effect of shading. The effect of shading may have operated in the present study.

3.3.4 Effect of cropping systems and residue retention on biomass yields

3.3.4.1 Maize biomass yield

The maize and soybean biomass yields in Magadu are presented in Table 3.7.

Table 3.7: Maize and soybean biomass yields for three years at Magadu (Morogoro)

	MZ Biomass	SB Biomass	MZ Biomass	SB Biomass	MZ Biomass	SB Biomass
	Year 1 (2017)		Year 2 (2018)		Year 3 (2019)	
	(Mg/ha)					
Absolute Control						
Sole maize	5.37a		1.46ns		1.04a	
Intercropping	7.32a	0.29a	1.63ns	0.15a	1.80ab	0.13a
Rotation	5.37a			0.44b	1.29a	
Sole soybean		1.31b		0.39b		0.48b
Maize (80 kg N ha^{-1})	14.07b		1.65ns		2.41b	

Means within a column followed by different letter(s) are not significantly different at p≤0.05 according to New DMRT, Maize ((80 kg N ha^{-1}) - maize plot supplied with 80 kg of N per hectare, ns =not significant at p <0.05.

The maize with N fertilizer (MZ (80 kg N ha^{-1}) in Magadu produced significantly ($p < 0.05$) higher maize biomass than in the intercropping, sole maize and rotation, respectively. The above result was due to positively influence of fertilizer N as compared to other treatment on biomass yields. Biswas and Ma (2016) also reported increased in biomass yield with an increase in fertilizer N. Besides, plant biomass retention after successful decomposition increased the levels of SOC and N stocks (Lal, 2009; Peoples *et al.*, 2009) with quality of residue, amount (Campos *et al.*, 2011; Maobe *et al.*, 2011) and soil type (Chivenge *et al.*, 2007), alluding to the potential in SOC and N sequestration.

In the second growing season, the maize biomass yields had no significant ($p < 0.05$) differences between cropping systems at Magadu site. Geren *et al.* (2008) reported that intercropping overall enhances biomass yields than monocropping, and Cong *et al.* (2014) reported 13 % to 23 % greater biomass in intercrops than in monocrops. The biomass yields were decreased in the second year by 3.68, 4.49, and 8.53 times in sole maize, intercropping and MZ (80 kg N ha^{-1}), respectively, signifying that crops might have missed potential nutrients for proper growth (Amanullah *et al.,* 2009). Nitrogen was low in the Magadu site (Table 3.3), and this could have been the major nutrient contributing to the overall low biomass yield at the site.

Sole maize, intercropping, and rotation showed no significant ($p \leq 0.05$) maize biomass yields in the third season. However, soil amended with inorganic fertilizer (MZ (80 kg N ha^{-1}) produced significantly ($p \leq 0.05$) higher biomass than sole maize and rotation, in addition to showing an improved yield in the third year by 0.76 Mg ha^{-1} as compared to the second year. In the same season, soybean biomass was 3.69 times in sole soybean than in intercropping; however, the average yield was less than 0.5 Mg ha^{-1} in both systems.

On the other hand, maize biomass yields in Suluti (Table 3.8) showed no statistically significant ($p < 0.05$) difference in season one in all cropping systems, but it had increased in the second cropping year by 3.73, 3.57, and 4.76 fold in sole maize, MZ (80 kg N ha^{-1}) and intercropping, respectively, as compared to the first season. The observed yield increase might be attributed to the effect of intercropping whereby maize benefited N from soybean biomass (Zhang *et al.,* 2015; Hauggaard-Nielsen *et al.,* 2003) and the effects from N fertilizer treatment that enhanced biomass yield (Amanullah *et al.*, 2009).

Table 3.8: Maize and soybean biomass yield for two years at Suluti, Ruvuma and Uyole, Mbeya

Treatments	**Suluti**				**Uyole**			
Cropping system	**MZ Biomass^{ns}**	**SB Biomass**	**MZ Biomass**	**SB Biomass**	**MZ Biomass^{ns}**	**SB Biomass**	**MZ Biomass^{ns}**	**SB Biomass**
	Year 1 (2018)		**Year 2 (2019)**		**Year 1 (2018)**		**Year 2 (2019)**	
	(Mg/ha)							
Absolute Control								
Sole maize	2.04		7.6a		12.04		8.82	
Intercropping	1.85	0.22a	8.81ab	0.46a	12.96	0.56a	6.96	0.67a
Rotation	1.22			1.19b	11.85			2.44b
Sole soybean		0.67b		1.22b		1.48b		2.89b
Maize(80 kg N ha^{-1})	2.67		9.52b		11.3		12.33	

Maize ((80 kg N ha^{-1}) maize plot supplied with 80 kg of N per hectare, ns =not significant at $p < 0.05$, means within a column followed by different letter(s) are significantly different at $p \leq 0.05$ according to DMRT

In the first year, large amounts of maize biomass yields (11.3 - 12.96 Mg ha^{-1}) were observed in the Uyole site (Table 3.8) with no significant ($p < 0.05$) yield differences between cropping systems, which implied that enough N was accumulated in soil that was fallowed for some time (section 3.2.1) before the first cropping season of this study.

Meanwhile, in the second cropping year, the sole maize decreased by 3.22 Mg maize residue ha^{-1} (26.74%) while the intercropping was reduced by 6 Mg maize residue ha^{-1} (46.3%). This may be attributed to higher utilization in the first year of the accumulated nutrients from previous years and low supply of nutrients from decomposition of the residues incorporated at the end of the first year to restore the consumed nutrients. However, maize biomass in MZ (80 kg N ha^{-1}) treatment increased 1.03 Mg maize residue ha^{-1} due to ample supply of inorganic N from fertilizer (Amanullah *et al.,* 2009). This proves that inorganic N fertilizer, properly used, always result in higher crop/maize yield.

3.3.4.2 Soybean biomass yield

The sole soybean in Magadu in the first season (Table 3.7) had significantly ($p \leq 0.05$) higher residue biomass weight of 1.3 Mg ha^{-1} as compared to 0.3 Mg ha^{-1} in the intercropping due to higher soybean population than in intercropping. Moreover, the sole soybean and the rotation had more than twice the biomass as in intercropping in the second season (2018), but the yield difference between sole soybean and rotation were not significant ($p \leq 0.05$) probably due to same plant populations. In the third year Magadu had soybean biomass yield of in the intercropping significantly ($p \leq 0.05$) less than in the sole soybean.

On the other hand, Suluti soybean biomass in the intercropping was only 32.8 % of sole soybean for the first cropping season, which was significantly ($P \leq 0.05$) higher than in the intercropping (Table 3.8). In the second year both sole and intercropped soybean increased yield almost twice as compared to first season. However, the rotation and sole soybean had significantly ($p \leq 0.05$) higher residues than intercropping, but not significantly ($p \leq 0.05$) different among themselves (i.e rotation and sole soybean).

The soybean biomass yields in Uyole in the first season were greater in sole soybean by 0.92 Mg ha^{-1}, equivalent to 264.29 % (Table 3.8) as compared to the intercropping, and increased almost twice in the second season. The resulting residue input returned in the first year probably increased somewhat enough nutrients to enhance biomass yields in the second year. The biomass yield in the rotation was approximately the same as sole soybean a trend similar to that observed at the Magadu (Table 3.7) and Suluti (Table 3.8) sites in the second cropping season.

The observed lesser biomass yield in the intercrops as compared to sole cropping can be attributed to the influence of maize shading effect to soybean and planting pattern under intercropping which gave half of the crop population as in the sole crop and as in grain yield (Wang *et al.,* 2020; Liu *et al.,* 2018; Yang *et al.,* 2017; Zhang *et al.,* 2015; Tsubo and Walker, 2004).

There were different yield levels observed under the same cropping systems/treatments across the three different localities of Magadu, Suluti, and Uyole. These differences might be due to different soil types as also reported by Erick (2019) leading to the observed differences in SOC and soil N across locations. However, the yield trends between cropping treatments were consistent between the sites.

3.3.5 Conclusions and recommendations

3.3.5.1 Conclusions

1. The study shows that different cropping systems namely monocropping, rotation, and intercropping did not significantly enhance the SOC (soil C sequestration) after three years in Magadu and two years each in Suluti and Uyole. Therefore, this indicates that for the current practice these interventions could not result in increased C sequestration in three or two years, and that significant increment may require long periods of time to accumulate.
2. The total soil N was not significantly enhanced by cropping systems, and that total soil N did not increase in the two or three years.
3. Generally, inorganic N fertilizer coupled with residue incorporation insignificantly elevated grain and total biomass yield.

3.3.5.2 Recommendations

Based on the above conclusions, this study leads to the following recommendations:

1. In order to maximize crop yields, and to increase SOC and N sequestration, the interventions (cropping system and residue retention) should be undertaken on a long term basis as other studies have also indicated.
2. Use of inorganic N fertilizer should be encouraged since it could enhance SOC, soil N, in addition to increasing grain and biomass yields.

References

Agyare, W. A., Clottey, V. A., Mercer-Quarshie, H. and Kombiok, J. M. (2006). Maize yield response in a long-term rotation and intercropping systems in the Guinea Savannah zone of Northern Ghana. *Journal of Agronomy* 5: 232-238.

Al-Kaisi, M. M., Yin, X., and Licht, M. A. (2005). Soil carbon and nitrogen changes as affected by tillage system and crop biomass in a corn–soybean rotation. *Applied Soil Ecology* 30(3): 174-191.

Amanullah, M. K., Marwat, K. B., Shah, P., Maula, N. and Arifullah, S. (2009). Nitrogen levels and its time of application influence leaf area, height and biomass of maize planted at low and high density. *Pakistan Journal of Botany* 41(2): 761-768.

Anantha, K. C., Majumder, S. P., Padhan, D., Badole, S., Datta, A., Mandal, B. and Gade, K.R. (2018). Carbon dynamics, potential and cost of carbon sequestration in double rice cropping system in semi-arid southern India. *Journal of Soil Science and Plant Nutrition* 18(2): 418-434.

Batidzirai, B., Valk, M., Wicke, B., Junginger, M., Daioglou, V., Euler, W. and Faaij, A. P. C. (2016). Current and future technical, economic and environmental feasibility of maize and wheat residues supply for biomass energy application: Illustrated for South Africa. *Biomass and Bioenergy* 92: 106-129.

Biswas, D. K. and Ma, B. L. (2016). Effect of nitrogen rate and fertilizer nitrogen source on physiology yield, grain quality, and nitrogen use efficiency in corn. *Canadian Journal of Plant Science* 96: 392- 403.

Borase, D. N., C. P. Nath, K. K. Hazra, M. Senthilkumar, S. S. Singh, C. S. Praharaj, U. Singh, and N. Kumar. (2020). Long-term impact of diversified crop rotations and nutrient management practices on soil microbial functions and soil enzymes activity. *Ecological Indicators* 114: 106322.

Bremner, J. R. and Yeomans, J. C. (1998). ‘’Laboratory techniques’’ In: J.R Wilson (Ed) Advance in nitrogen cycling in agriculture ecosystem C.A.B Int. Willing, England. [www.sciencepublishinggroup.com › journal › paperinfo › j.ijnrem.202106...] site visited on 15/08/2018.

Broadbent, F. E. (2015). Soil organic matter. *Sustainable Options in Land Management*. 2: 34–38.

Campos, B. C., Amado, T. J. C., Bayer, C., Nicoloso, R. S. and Fiorin, J. E. (2011). Carbon stock and its compartments in a subtropical oxisol under long-term tillage and cropping systems. *Revista Brasileira de Ciência do Solo* 35: 805-817.

Cardinale, B. J., Matulich, K. L., Hooper, D. U., Byrnes, J. E., Duffy, E., Gamfeldt, L., Balvanera, P., O'connor, M. I. and Gonzalez, A. (2011). The functional role of producer diversity in ecosystems. *American Journal of Botany* 98(3): 572-592.

Cheng, L., Zhang, N., Yuan, M., Xiao, J., Qin, Y., Deng, Y.E., Tu, Q., Xue, K., Van Nostrand, J. D., Wu, L. and He, Z. (2017). Warming enhances old organic carbon decomposition through altering functional microbial communities. *The ISME Journal* 11(8): 1825-1835.

Chivenge, P. P., Murwira, H. K., Giller, K. E., Mapfumo, P. and Six, J. (2007). Long-term impact of reduced tillage and residue management on soil carbon stabilization: Implications for conservation agriculture on contrasting soils. *Soil and Tillage* 94(2): 328-337.

Cong, W. F., Hoffland, E., Li, L., Janssen, B. H., and van der Werf, W. (2015). Intercropping affects the rate of decomposition of soil organic matter and root litter. *Plant and Soil* 391(1-2): 399-411.

Cong, Wen-Feng, Ellis Hoffland, Long Li, Johan Six, Jian-Hao Sun, Xing-Guo Bao, Fu-Suo Zhang, and Wopke Van Der Werf. (2014). Intercropping enhances soil carbon and nitrogen. *Global Change Biology* 21(4): 1715-1726.

Corre-Hellou, G., Dibet, A., Hauggaard-Nielsen, H., Crozat, Y., Gooding, M., Ambus, P., Dahlmann, C., Von Fragstein, P., Pristeri, A., Monti, M., Jensen, E.S. (2011). The competitive ability of pea–barley intercrops against weeds and the interactions with crop productivity and soil N availability. *Field Crops Research* 122: 264–272.

Das, T. K., Bhattacharyya, R., Sharma, A. R., Das, S., Saad, A. A., Pathak, H. (2013). Impacts of conservation agriculture on total soil organic carbon retention potential under an rrigated agro-ecosystem of the western Indo-Gangetic Plains. *European Journal of Agronomy* 51: 34–42.

Dhakal, Y., Meena, R. S. and Kumar, S. (2016). Effect of INM on nodulation, yield, quality and available nutrient status in soil after harvest of green gram. *Legume Research* 39(4): 590–594.

Erick, S. (2019). Maize Field Biomass Yield and Land Equivalent Ratio under the Influence of Different Management Practices and Location. *Asian Journal of Crop Science* 11: 25-31.

Geren, H., Avcioglu, R., Soya, H. and Kir, B. (2008). Intercropping of corn with cowpea and bean: Biomass yield and silage quality. *Africa Journal of Biotechnology* 7: 4100-4102.

Ghosh, P. K., Mohanty, M., Bandyopadhyay, K. K., Painuli, D. K. and Misra, A. K. (2006). Growth, competition, yields advantage and economics in soybean/pigeonpea intercropping system in semi-arid tropics of India: II. Effect of nutrient management. *Field Crops Research* 96(1): 90-97.

Hall, S. J., Russell, A. E. and A'lece, R. M. (2019). Do corn-soybean rotations enhance decomposition of soil organic matter? *Plant and Soil* 444(1): 27-442.

Hauggaard-Nielsen, H., Ambus, P. and Jensen, E. S. (2003). The comparison of nitrogen use and leaching in sole cropped versus intercropped pea and barley. *Nutrient Cycling in Agroecosystems* 65(3): 289-300.

Lal, R. (2009). Challenges and opportunities in soil organic matter research. *European Journal of Soil Science* 60(2): 158-169.

Li, C., He, X., Zhu, S., Zhou, H., Wang, Y., Li, Y., Yang, J., Fan, J., Yang, J., Wang, G. and Long, Y. (2009). Crop diversity for yield increase. *PLoS One* 4 (11): e8049.

Li, L., Sun, J., Zhang, F., Li, X., Rengel, Z. and Yang, S. (2001). Wheat/maize or wheat/soybean strip intercropping: II. Recovery or compensation of maize and soybean after wheat harvesting. *Field Crops Research* 71(3): 173-181.

Li, L. J., Han, X. Z., You, M.Y., Yuan, Y. R., Ding, X. L. and Qiao, Y. F. (2013). Carbon and nitrogen mineralization patterns of two contrasting crop residues in a Mollisol: Effects of residue type and placement in soils. *European Journal of Soil Biology* 54: 1-6.

Liao, Y., Wu, W. L., Meng, F. Q., Smith, P., and Lal, R. (2015). Increase in soil organic carbon by agricultural intensification in northern China. *Biogeosciences* 12: 1403–1413.

Liu, X., Rahman, T., Song, C., Yang, F., Su, B., Cui, L., Bu, W. and Yang, W. (2018). Relationships among light distribution, radiation use efficiency and land equivalent ratio in maize-soybean strip intercropping. *Field Crop Research* 224: 91–101.

Logah, V., Ewusi-Mensah, N. and Tetteh, F. M. (2011). Soil organic carbon and crop yield under different soil amendments and cropping systems in the semi-deciduous Forest Zone of Ghana. *Journal of Plant Science* 6: 165-173.

Lv, Y., Francis, C., Wu, P.T., Chen, X.L. and Zhao, X.N. (2014). Maize-soybean intercropping interactions above and below ground. *Crop Science* 54: 914-922.

Maobe, S. N., Akundabweni, L. S. M., Mburu, M. W. K., Ndufa, J. K., Mureithi, J. G., Gachene, C. K. K., Okello, J. J. and Makini, F. W. (2011). Effect of mucuna green manure application rate on decomposition and soil available nitrogen under field conditions: I. During season of incorporation. *World Journal of Agricultural Sciences* 7(4): 430-438.

Mazzilli, S. R., Kemanian, A. R., Ernst, O. R., Jackson, R. B. and Pineiro, G. (2015). Greater humification of belowground than aboveground biomass carbon into particulate soil organic matter in no-till corn and soybean crops. *Soil Biology and Biochemistry* 85: 22-30.

Mohammed, A. M., Nartey, E., Naab, J. B., Adiku, S. G. K. (2013). A simple model for predicting plant residue decomposition based upon their C/N ratio and soil moisture content. *African Journal of Agricultural Research* 8: 2153–2159.

Mohammed, A. M., Nartey, E., Naab, J. B. and Adiku, S. G. K. (2014). Carbon mineralization from plant residue-amended soils under varying moisture conditions. *Journal Experimental Biology and Agricultural Science* 1: 491–498.

National Bureau of statistics (NBS). (2018). Tanzania in figures. pp. 112, [https://www.nbs.go.tz/index.php/en/tanzania-in-figures/422-tanzania-in-figures-2018]. Site visited on 12/08/2019.

Nelson, D. W. and Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. *Methods of soil analysis: Part 3 Chemical methods, 5,* pp. 961-1010.

Partey, S. T., Preziosi, R. F. and Robson, G. D. (2014). Improving maize residue use in soil fertility restoration by mixing with residues of low C-to-N ratio: effects on C and N mineralization and soil microbial biomass. *Journal of Soil Science and Plant Nutrition* 14(3): 518-531.

Peoples, M. B., Unkovich, M. J. and Herridge, D. F. (2009). Measuring symbiotic nitrogen fixation by legumes. *Nitrogen Fixation in Crop Production* 52: 125-170.

Poffenbarger, H. J., Barker, D. W., Helmers, M. J., Miguez, F. E., Olk, D. C., Sawyer, J. E., Six, J. and Castellano, M. J. (2017). Maximum soil organic carbon storage in Midwest US cropping systems when crops are optimally nitrogen-fertilized, *PLoS One* 12(3): e0172293.

Qiu, Q., Wu, L., Ouyang, Z., Li, B., Xu, Y., Wu, S. and Gregorich, E. G. (2016). Priming effect of maize residue and urea N on soil organic matter changes with time. *Applied Soil Ecology* 100: 65-74.

Shafi, M., Bakht, J., Jan, M.T. and Shah, Z. (2007). Soil C and N dynamics and maize (Zea may L.) yield as affected by cropping systems and residue management in North-western Pakistan. *Soil and Tillage Research* 94(2): 520-529.

Srinivasarao, Ch., Deshpande, A. N., Venkateswarlu, B., Lal, R., Singh, A. K., Kundu, S., Vittal, K. P. R., Mishra, P. K., Prasad, J. V. N. S., Mandal, U. K. and Sharma, K. L. (2012). Grain yield and carbon sequestration potential of post monsoon sorghum cultivation in Vertisols in the semi-arid tropics of central India. *Geoderma* 175–176: 90–97.

Tsubo, M. and Walker, S. (2004). Shade effects on *Phaseolus vulgaris* L. with *Zea mays* L. under well-watered conditions. *Journal of Agronomy and Crop Science* 190: 168-176.

Turmel, M. S., Speratti, A., Baudron, F., Verhulst, N. and Govaerts, B. (2015). Crop residue management and soil health: A systems analysis. *Agricultural Systems* 134: 6-16.

Vance, C. P. (2001). Symbiotic nitrogen fixation and phosphorus acquisition: plant nutrition in a world of declining renewable resources. *Plant Physiology* 127: 390–397.

Wang, X., Wu, X., Ding, G., Yang, F., Yong, T., Wang, X. and Yang, W. (2020). Analysis of Grain Yield Differences among Soybean Cultivars under Maize–Soybean Intercropping. *Agronomy* 10(1): 110.

Wang, Z. G., Jin, X., Bao, X. G., Li, X. F., Zhao, J. H., Sun, J. H., Christie, P. and Li, L. (2014). Intercropping enhances productivity and maintains the most soil fertility properties relative to sole cropping. *PloS One* 9(12): e113984.

Yang, C. H., Chai, Q. and Huang, G. B. (2010). Root distribution and yield responses of wheat/maize intercropping to alternate irrigation in the arid areas of northwest China. *Plant, Soil and Environment* 56(6): 253-262.

Yang, F., Liao, D., Wu, X., Gao, R., Fan, Y., Raza, M.A., Wang, X., Yong, T., Liu, W., Liu, J. and Du, J. (2017). Effect of aboveground and belowground interactions on the intercrop yields in maize-soybean relay intercropping systems. *Field Crops Research* 203: 16-23.

Yang, Y., Guo, J., Chen, G., Yin, Y., Gao, R. and Lin, C. (2009). Effects of forest conversion on soil labile organic carbon fractions and aggregate stability in subtropical China. *Plant and Soil* 323(1-2): 153-162.

Zhang, Y., Liu, J., Zhang, J., Liu, H., Liu, S., Zhai, L., Wang, H., Lei, Q., Ren, T. and Yin, C. (2015). Row ratios of intercropping maize and soybean can affect agronomic efficiency of the system and subsequent wheat. *PloS One* 10(6): e0129245.

Zingore, S., Mutegi, J., Agesa, B., Tamene, L. and Kihara, J. (2015). Soil degradation in sub-Saharan Africa and crop production options for soil rehabilitation. *Better Crops* 99(1): 24-26.

CHAPTER FOUR

4.0 EFFECTS OF MAIZE - SOYBEAN CROPPING SYSTEMS AND CROP RESIDUE RETENTION ON WATER EXTRACTABLE ORGANIC CARBON AND WATER STABLE SOIL AGGREGATES

Abstract

Effects of maize-soybean intercropping, rotation and continuous monocropping with residue incorporation on enhancing water extractable organic carbon (WEOC) and water stable aggregates (WSA) in three different locations of Tanzania were investigated. Results showed no significant ($p < 0.05$) differences in each cropping year on the WEOC as a result of the differences in cropping systems in Magadu, Suluti and Uyole. Generally CWEOC value increased in the last year in Magadu and Suluti except in the intercrops, however, some cropping systems decreased or increased the CWEOC in Uyole site. Meanwhile, the hot water extractable organic carbon (HWEOC) in Magadu were in the range of 41.6 – 100.2 mg kg^{-1} in the first year, increased in the third year to 128.7 - 180.2 mg kg^{-1} as a result of intervention. However, there were noticeable value decline in HWEOC at Uyole site from 182.4 – 78.3 mg kg^{-1} in the first year to 90.5 – 51.7 mg kg^{-1} in the second year. The ratio of water extractable organic carbon (WEOC) to total organic carbon (TOC) were different between Magadu, Suluti and Uyole sites. The relative percentage contribution of CWEOC/TOC was highest in the fertilized maize (80 kg N ha^{-1}) (0.90%) at the Uyole site and HWEOC/TOC was highest (1.25%) in intercropping in Magadu. There were no significant ($p < 0.05$) differences between different cropping systems on the distribution of individual aggregate sizes of macroaggregates (>2.00 mm), mesoaggregates (2.00 - 0.5 mm) and microaggregates (< 0.25 mm) in each cropping year. The Magadu and Suluti sites exhibited a higher proportion of macroaggregates in the range of 40 – 58 % and 39 – 55 %, respectively, and lower range in Uyole site (9.8 – 23 %) in the last cropping year. The Magadu and Uyole slightly showed a decline in the macroaggregates sizes across cropping years, while Suluti increased the macroaggregate proportion in all cropping systems in the last year. Different cropping systems together with residue incorporation improved WEOC and soil aggregate in some soils and therefore, can be recommended as management strategy for the future.

Keywords: aggregate stability, water extractable organic carbon, hot water extractable organic carbon, intercropping, rotation

4.1 Introduction

Water extractable organic carbon (WEOC) pool represents very little fraction of the total SOC (Hamkalo and Bedernichek, 2014; Corvasce *et al.*, 2006; Chantigny, 2003), yet it is very important in the soil biogeochemical cycle (Haynes, 2000). It serves as an early indicator to soil management than total OC (Geraei *et al.*, 2016). The WEOC is the readily available carbon for microbial consumption (Zhao *et al.*, 2008). It consists of two components, which are cold water extractable organic carbon (CWEOC) and hot water extractable organic carbon (HWEOC) (Ghani *et al.*, 2003).

The WEOC is a small proportion of dissolved organic matter (DOC) passing through the 0.45 µm pore size membrane following agitation with water (cold or hot). This differs from particulate organic matter (POM), which is retained on the 0.45 µm pore size filter (Silveira, 2005). Despite the very little concentration of WEOC, it is involved in such soil processes as podsolization (Buurman and Jongmans, 2005) and soil weathering. Due to its solubility and easy movement, it is responsible in heavy metal and organic acid transportation (Williams *et al.*, 2000) and in the supply to microorganisms of the C necessary for OM and aggregate stability formation (Silveira, 2005).

The HWEOC, which appears to have less recalcitrance in soil than CWEOC fraction, contains more of carbohydrates, phenols and lignin monomers (Gadja *et al.*, 2020), the carbohydrates being susceptible to microbial consumption as compared to the other constituents (Zhao *et al.*, 2008). In addition, the HWEOC part of WEOC is responsible for stabilization of aggregates in the soil because of the presence of extracellular polysaccharides (Haynes *et al.*, 1991; Haynes and Swift, 1990).

Land use changes have a great impact on the dynamics of WEOC in which forest land occurs to have greater WEOC than arable lands (Ćirić et *al.*, 2016; Hamkalo and Bedernichek, 2014; Chantigny, 2003). However, Zhang *et al.* (2019) obtained no differences in the top soil's WEOC in different land uses.

Meanwhile, soil aggregate stability is one of the important soil physical properties which correlate with soil organic C (Blanco-Canqui *et al.*, 2014, Tisdall and Oades, 1982). The ability of the soil to reserve C is measured through conservation of aggregates from dismantling to smaller aggregates mediated by water and or wind erosion and other physical activities which may disrupt aggregates and unveil C available for mineralization (Tisdall and Oades, 1982).

Adequate SOM in the soil system is important for the binding of aggregates in soil particles (Six *et al.*, 2002). In turn, soil aggregates not only have an important effect on the conservation of SOC stocks (Hazra *et al.,* 2019; Nath *et al.,* 2019) but also on other soil properties such as aeration, water holding capacity, and bulk density (Olujobi, 2016; Lal, 2015). Soil macroaggregates and microaggregates hold most of the soil carbon through different binding mechanisms, which retain carbon for a few to several years in soil (Hazra *et al.,* 2019; Nath *et al.,* 2019; Simansky *et al.,* 2016).

Therefore, this study was undertaken to assess the effects of intercropping, rotation and respective monoculture of maize and soybean on enhancement of water extractable organic carbon and water stable aggregates of selected sites of Magadu in Morogoro, Uyole in Mbeya and Suluti in Ruvuma.

4.2 Materials and Methods

4.2.1 Description of research area

The experiments were established at Magadu (Morogoro), Uyole (Mbeya) Suluti and (Ruvuma) regions of Tanzania. The experimental site in Morogoro municipality is located at latitude 06˚ 51´ 06˝ to 06˚ 51´ 20˝ S and longitude 37˚ 38´ 21˝ to 37˚ 38´ 35˝ E within Edward Moringe campus of the Sokoine University of Agriculture. The research plot in Uyole (Mbeya) is located at latitude 08˚ 54´ 4˝ S and 08˚ 56´ 7˝ S and a longitude of 033˚ 30´ 11˝ E and 033˚ 32´ 28˝ E which is 1779 m.a.s.l.

The-Suluti site is located at latitude 10º 34´ 32˝ S and 10º 35´ 2˝ and a longitude of 036˚ 7´ 36˝ E and 036˚ 8´ 3˝ E in Ruvuma region, within Namtumbo district. Other details about the experimental site are given in chapter 3.

4.2.2 Treatment details and experimental design

The research was set up on experimental plots previously fallowed for 3 to 4 years in the Magadu, Uyole and Suluti sites. The experimental plots in all three sites comprised six treatments having four different cropping systems namely maize monocropping (MZ-SL), maize – soybean rotation (MZ/SB), maize- soybean intercropping (MZ+SB), soybean monocropping (SB-SL), maize - inorganic fertilizer (N) at 80 kg N ha^{-1} (MZ80 kg N ha^{-1}) and absolute control (ABSLT CNTRL) in which no crop was planted. The experiment was laid in the Randomized Complete Block Design (RCBD), replicated three times.

4.2.3 Data collection and analysis

4.2.3.1 Soil sampling after harvesting

Soil samples were collected after harvesting; the soil samples were randomly collected diagonally using a spade in different spots in each plot from 0 - 30 cm deep for soil aggregate (physical) and chemical analysis (WEOC). The soil surface was cleaned of plant and other debris before sampling. Samples were packed and carefully transported to ensure no disturbance of soil aggregates from field to laboratory. The soil samples were air dried in a greenhouse for three days for aggregate stability tests. For chemical analysis, the soil samples were passed through a 2 mm sieve and subsequently air-dried for three days.

4.2.3.2 Water extractable organic carbon

The water extractable organic carbon (WEOC) was determined according to the method of Haynes and Francis (1993), modified by Ghani *et al.* (2003), which consists of a two-step water-based OC-extraction process. For the first step, 3 g of air-dried soil were placed into a 50 ml falcon centrifuge tube and 30 ml of distilled water were added. The tube was put on an end-over-end shaker at 30 r.p.m. and 20 ºC for 30 min. The resultant soil-water suspension was centrifuged at 3500 r.p.m. for 20 min followed by filtration of the supernatant through a glass membrane filter of 0.45 μm pore diameter. Then, a 5 ml portion of the obtained filtrate was placed into a conical flask and evaporated at 60 ºC to dryness. The dried filtrate in the conical flask was then analyzed for the cold water extractable organic carbon (CWEOC) fraction by the wet oxidation method of Walkley and Black (Nelson and Sommers, 1982). The same falcon tubes with soil were kept for the second step extraction of hot water extractable organic carbon (HWEOC) extraction.

The second step for hot water extractable organic carbon (HWEOC) was done immediately after centrifugation of filtrate for CWEOC by adding 20 ml of distilled water to the same falcon tubes. Then 10 ml of distilled water were added to wash the same filters used in the previous step to reach 30 ml of soil –water suspension. The tube was hand shaken vigorously for 10 seconds and placed in an oven at 80 ºC for 16 h. The tubes were then shaken for 10 s to ensure complete extraction of HWEOC from SOM. The soil – water suspension was centrifuged, filtered and evaporated to dryness as previously mentioned in step one. The HWEOC was also determined by the wet oxidation method of Walkley and Black (Nelson and Sommers, 1982).

4.2.3.3 Water stable aggregates

An air dried soil sample was passed through a nested pair of sieves of 8 mm (top) and 6.5 mm (bottom) mesh sizes. The retained aggregates in the 6.5 mm sieve were cleaned of roots and other plant materials/ debris. Each sample was weighed to 20 g in duplicate; one for water content correction and the other one for the actual water stable aggregate determination. Wet – sieving of stable aggregate was done using a method similar to the modified approach of Kemper and Chepil (1965) using Yoder's sieve shaker (Yoder, 1936). Sieves of mesh diameters of 4.75, 2, 1, 0.5, and 0.212 mm were stacked, in descending sequence, with the 4.75 mm sieve on top and immersed in water in a plastic container. The aggregates were gently placed on the top sieve (4.75 mm) and then aggregates were allowed to pre-wet for 10 minutes. The apparatus was switched on to run up-and-down movements of approximately 3.6 cm within the water, at a frequency of 30 times per minute for 10 minutes. Water level was enough to ensure that the sample on the top sieve was covered with water during the upstroke movement. Aggregates remaining after sieving, on individual sieves, were gently collected to respective labelled containers for air drying, and their weights were recorded.

The sand fraction was determined in each sample by mixing and shaking the sample with a 2 g / L sodium hexametaphosphate as recommended by Kemper and Rosenau (1986). The sand was oven dried and its weight was recorded. The amount of water stable aggregates was calculated as a percentage wet aggregate stability by the formula by Kemper (1966) as follows:

$$WSA\left(\%\, soil > 250\ \mu m\right) = \frac{wt.\, of\ stable\, aggregates \wedge sand - wt.\, of\ sand}{wt.\, of\ sample\, soil - wt.\, of\ sand} * 100 \ldots\ldots\ldots\ldots\ldots\ldots$$

(1)

where, WSA= water stable aggregates, where "sand" is sand particle larger than 0.25 mm. diameter.

The mean weight diameter was calculated from the formula developed by van Bavel (1949):

$$MWDw = \sum_{i=1}^{n} Xi \, . \, Wi \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

where, ***Xi*** is the mean diameter of the *i*th sieve, and ***Wi*** is the total aggregates in *i*th fraction.

Geometric Mean Diameter was calculated form the formula developed by Mazurk (1950).

$$GMD = \exp\left[\frac{\sum_{i=1}^{n} wi \log xi}{\sum_{i=1}^{n} wi}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

where, ***xi*** is the mean diameter of each size fraction, ***wi*** is the proportion of the total sample weight occurring in the size *i*th fraction and $\sum_{i=1}^{n} wi$ is total weight of the sample (Kemper and Rosenau, 1986).

4.2.4 Statistical analysis of data

The data were subjected to analysis of variance (ANOVA) using GENSTAT 15th Edition Statistical Package. When significance at $p < 0.05$ was found, means were compared using Duncan Multiple Range Test (DMRT) at $p < 0.05$.

4.3 Results and Discussion

4.3.1 Cold water extractable organic carbon

4.3.1.1 Cold water extractable organic carbon in Magadu

The Cold water extractable organic carbon (CWEOC) values in Magadu, Morogoro site, are presented in Table 4.1.

Table 4.1: Cold water extractable organic carbon (WEOC) and hot water extractable organic carbon (HWEOC) in Magadu, Morogoro soil

	CWEOC ($mg\ kg^{-1}$)	HWEOC ($mg\ kg^{-1}$)

Treatment	Year1	Year2	Year3	Year1	Year2	Year3
ABS CNTRL	63.8	78.39	63.7	50.80	164	141.6
SL-MZ	107.3	91.26	114.7	48.10	227.4	128.7
MZ+SB	78.60	91.39	63.7	100.2	201.8	167.3
MZ/SB	56.80	104.4	76.5	41.60	227.2	180.2
SL-SB	82.50	91.50	89.2	73.0	189.7	167.3
MZ(80 kg N ha^{-1})	48.95	130.7	89.2	97.1	214.5	135.1
	NS	NS	NS	NS	NS	NS

NB: ABS CNTRL= Absolute control, **SL-MZ**= Sole maize, **MZ+SB**= Maize and Soybean intercropping, **MZ/SB**= Maize rotated with soybean, **SL-SB**= Sole soybean and MZ (80 kg N ha^{-1}) = Maize supplied with 80 kg N ha^{-1} of inorganic fertilizer, NS=not significant at p≤0.05

The CWEOC in Magadu site exhibited no significant ($p < 0.05$) differences between cropping systems in each year; however, there were value slight differences.

CWEOC was in the range of 48.95 - 107.3 mg kg^{-1}, 78.39 -130.7 mg kg^{-1}, and 63.7 - 114.7 mg kg^{-1} in the first, second and third year of study, respectively. The range of CWEOC values of this study are smaller compared to other studies by Hamkalo and Bedernichek (2014) and Zhang *et al.* (2019) who reported excess of 200 mg kg^{-1} and 300 mg kg^{-1} in crop lands, respectively, but lower than those by Malobane *et al.* (2020) who reported a CWEOC of 38.28 mg kg^{-1} in no-till and 22.4 mg kg^{-1} in a conventional tillage.

There was generally an increasing trend from the first to second year, followed by a slight decrease in the third year, except under the maize monocropping (SL-MZ) in which CWEOC decreased in the second but increased in third year. These trends may be due to the fact that in the maize monocropping plot the residue added a wide C:N ratio and high lignin (Grebliunas *et al.* 2016) and may have resulted in a large fraction of humic component into the soil, with greater recalcitrance, to suppress microbial activities, leaving much of the WEOC intact.

Inorganic N fertilizer and crop residue incorporation was reported to increase cold WEOC, albeit significantly as a result of microbial biomass addition and the resulting narrow residue C:N ratio which, in turn, enhanced residue decomposition (Sharma *et al.*, 2020; Ghani *et al.*, 2003). This reasoning may explain the numerical increase, though not significant ($p < 0.05$), of CWEOC in the second year in Magadu (Table 4.1) in the MZ(80 kg N ha^{-1}) plot.

Meanwhile, the observed decline in the third year might be due to increased microbial biomass because a microbial population might have thrived from previously available C (Sharma *et al.*, 2020) thus enhancing microbial function (CO_2 and dinitrogen efflux) and/ or C leaching to underground horizons and soil water table (Grebliunas *et al.*, 2016).

4.3.1.2 Cold water extractable organic carbon in Suluti

At the Suluti site, the differences of the contents of CWEOC between treatments were not statistically significant ($p < 0.05$) (Table 4.2) between cropping systems as was also observed in Magadu (section 4.1.1). There were small numerical increases in other cropping systems in the CWEOC in the second year except in the intercropping (MZ+SB) (Table 4.2). The less CWEOC in the intercropping could have been due to high microbial activities which may have rapidly consumed most of CWEOC released (Malobane *et al.*, 2020; Angers *et al.*, 2006; Boyer and Groffman, 1995).

Table 4.2: Cold water extractable organic carbon (WEOC) and hot water extractable organic carbon (HWEOC) in Suluti, Ruvuma and Uyole, Mbeya

Treatments	Suluti				Uyole			
	CWEOC		HWEOC		CWEOC		HWEOC	
	mg kg^{-1}				mg kg^{-1}			
	Year1	Year2	Year1	Year2	Year1	Year2	Year1	Year2
ABS CNTRL	99.08	86.22	104.4	126.8	169	192.1	104.4	77.6
SL-MZ	49.78	66.33	169.4	139.5	195	64.0	169.4	90.5
MZ+SB	62.46	59.69	78.30	82.40	156	89.7	78.30	51.7
MZ/SB	73.24	92.86	130.4	107.8	104	140.9	130.4	90.5
SL-SB	48.83	72.96	129.5	76.10	195	76.8	129.5	64.7

MZ(80 kg N ha^{-1})	61.03	92.86	182.4	69.80	143	166.5	182.4	90.5
	NS	NS	NS	NS	NS	NS	NS	NS

NB: ABS CNTRL= Absolute control, **SL-MZ**= Sole maize, **MZ+SB**= Maize and Soybean intercropping, **MZ/SB**= Maize rotated with soybean, **SL-SB**= Sole soybean and MZ (80 kg N ha^{-1}) = Maize supplied with 80 kg N ha^{-1} of inorganic fertilizer, NS=not significant at $p \leq 0.05$

4.3.1.3 Cold water extractable organic carbon in Uyole

Results in Table 4.2 show, further, that there were no significant ($p < 0.05$) differences in CWEOC between cropping systems, with no systematic trends. The increase and/ or decreasing values of CWEOC in Uyole site (Table 4.2) in different cropping systems from first to second season were also observed as was in the other sites, above. The WEOC variability between treatments is presumed to be caused by characteristic effect of WEOC to strongly adsorb into clay, Fe and Al hydroxide surfaces, and/ or differences in soil water content of different cropping systems (Angers *et al.,* 2006).

4.3.2 Hot water extractable organic carbon

4.3.2.1 Hot water extractable organic carbon in Magadu

The HWEOC from all treatments in Magadu showed no significant ($p < 0.05$) differences between cropping systems (Table 4.1). The values generally increased from the first to the second year’s harvesting season whereby rotation (MZ/SB) and maize monocropping (SL-MZ) plots accounted for highest percentage rise in HWEOC (446.2 % and 372.8%, respectively, in rotation and sole maize).

In the third year, the amount of HWEOC decreased in all treatments, which might be explained by appearance of different aromatic and humic substances providing different WEOC stability (Zhang *et al.,* 2019) and so, different biodegradability of WEOC (Boyer and Groffman, 1996). For example, Xu *et al.* (2013) reported only 12.5 % bioavailable WEOC in annual and 22 % in perennial legumes after 30 days of incubation. Higher values in second year could have led to higher microbial activities. Malobane *et al.* (2020) observed positive correlation between HWEOC and MBC which, therefore, suggests increased HWEOC content consumption in third season as a result of increased microbial activities in the second season (Malobane *et al.,* 2020; Chantigny, 2003).

4.3.2.2 Hot water extractable organic carbon in Suluti

There were no differences ($p < 0.05$) in HWEOC contents between the treatments (Table 4.2). In the second year, decline in HWEOC values was observed much more in sole soybean as compared to sole maize and in the rotation treatment with a slight increase in the intercropping. According Ghani *et al.* (2003) and Boyer and Groffman, (1996) under N fertilizer and residues addition the microbial biomass turnover is high which in turn takes advantage of available HWEOC to assimilate C in microbial cells.

4.3.2.3 Hot water extractable organic carbon in Uyole

The HWEOC values observed at Uyole (Table 4.2) had no significant ($p < 0.05$) differences among treatments in year one and year two. However, the fertilized maize (80 kg N ha^{-1}) had the HWEOC value decreased in the second season. This result suggests that HWEOC is lost through CO_2 efflux and microbial assimilation (Ghani *et al.,* 3003).

Losing a vast amount of C was observed by Embacher *et al.* (2007) in arable land due to different seasons of the year, resulting in different extents of humification and biodegradability of the WEOC. The absolute control (ABS CNTRL) and intercropping were the only plots where the HWEOC increased somewhat. The increased value in absolute control might be contributed to root exudates of some grasses and natural vegetation that thrived in those plots (Šeremešić *et al.,* 2013).

4.3.3 Relative contribution of WEOC to total SOC

It is revealed from the result in Magadu (Table 4.3), Suluti and Uyole (Table 4.4) that CWEOC values occupy only a small proportion of TOC which did not exceed one percent (< 1%) except for the control (ABS CNTRL) plot in Uyole site. According to Ghani *et al*. (2003) the CWEOC constitute a small fraction, most labile and highly variable C pool than HWEOC.

Table 4.3: Relative contribution of the CWEOC and HWEOC to the total soil organic carbon in Magadu

Treatments	TOC	CWEOC	HWEOC	CWEOC/ TOC	HWEOC/TOC
		(g kg^{-1})		**(%)**	
ABS CNTRL	13.03	0.07	0.12	0.53	0.91
SL-MZ	11.96	0.10	0.15	0.87	1.23
MZ+SB	12.89	0.08	0.16	0.60	1.25
MZ/SB	12.60	0.08	0.15	0.63	1.15
SL-SB	11.74	0.09	0.13	0.75	1.11
MZ(80 kg N ha-1)	13.55	0.09	0.15	0.66	1.10

NB: ABS CNTRL= Absolute control, **SL-MZ**= Sole maize, **MZ+SB**= Maize and Soybean intercropping, **MZ/SB**= Maize rotated with soybean, **SL-SB**= Sole soybean and MZ (80 kg N ha^{-1}) = Maize supplied with 80 kg N ha^{-1} of inorganic fertilizer

Table 4.4: Relative contribution of the cold and hot water extractable organic carbon to the total soil organic carbon in Suluti and Uyole

	Suluti					**Uyole**				
Treatments	TOC	CW	HW	CW in TOC	HW/TOC	TOC	CW	HW	CW/TOC	HW/TOC
	g/kg			%		g/kg			%	
ABS CNTRL	12.71	0.09	0.12	0.73	0.91	16.47	0.18	0.09	1.10	0.55
SL-MZ	12.20	0.06	0.15	0.48	1.27	16.81	0.13	0.13	0.77	0.77
MZ+SB	12.52	0.06	0.08	0.49	0.64	16.63	0.12	0.07	0.74	0.39
MZ/SB	11.62	0.08	0.12	0.72	1.03	17.43	0.12	0.11	0.70	0.63
SL-SB	11.68	0.06	0.10	0.52	0.88	16.50	0.14	0.10	0.82	0.59
MZ(80 kg N ha-1)	12.33	0.08	0.13	0.62	1.02	17.06	0.15	0.14	0.91	0.80

NB: ABS CNTRL= Absolute control, **SL-MZ**= Sole maize, **MZ+SB**= Maize and Soybean intercropping, **MZ/SB**= Maize rotated with soybean, **SL-SB**= Sole soybean and MZ (80 kg N ha^{-1}) = Maize supplied with 80 kg N ha^{-1} of inorganic fertilizer, **TOC**=Total organic carbon, **CW**=cold water extractable organic carbon, **HW**= Hot water extractable organic carbon

The CWEOC/TOC and HWEOC/TOC is an indicator of labile C to total soil carbon (Šeremešić *et al.,* 2013). Their fraction differs according to land uses (e.g. forest versus arable), soil management and also to soil type (Ćirić et *al.*, 2016) and, therefore, it is an important indicator of the soil management.

The HWEOC fraction of total soil organic carbon (TOC) in Magadu was only up to 1.25% (Table 4.3) and 1.27% in Suluti (Table 4.4) matching the range of 1.1 to 1.7 % obtained by Šeremešić *et al.* (2013), yet the values in our present study appear to be less than those reported by Ćirić et *al.* (2016) and Hamkalo and Bedernichek (2014) in arable land.

The Uyole site exhibited lower HWEOC/TOC percentage than CWEOC/TOC fraction as compared to other sites, and this might be due to the fact that HWEOC could have been quickly consumed by microorganism before sampling processes or during storage before WEOC analysis. For example, Šeremešić *et al.* (2020) found significant variability of HWEOC levels during different sampling times. Furthermore, Kalbitz *at al.* (2000) reported 10 – 40 % of dissolved organic carbon (DOC) was utilized in some days or few months and Zhao *et al.* (2008) found 55 – 82 % WEOC were consumed in the laboratory incubation in just 35 days.

4.3.4 Water Stable Aggregates (WSA)

4.3.4.1 Macroaggregates (> 2.00 mm) distribution in soil of Magadu, Suluti and Uyole

Results of macroaggregates distribution in Magadu, Suluti and Uyole are presented in Tables 4.5, 4.6 and 4.7. There were no significant ($p < 0.05$) differences in macroaggregate size distribution between all treatments in all years in the Magadu, Suluti and Uyole. The aggregate size distribution is important in the fact that they give important information on soil C sequestration potential (Nath *et al.*, 2019) by providing C allocations in different sizes and thus evaluates its persistence.

The larger aggregates (macro and meso aggregates) hold most of the soil carbon than smaller size aggregates (microaggregates) (Nath *et al.*, 2019). Thus, building up larger aggregate sizes by SOM through different soil managements is crucial for higher C sequestration and stabilization (Gale *et al.*, 2000). The larger aggregates (macro and meso aggregates) hold most of the soil carbon than smaller size aggregates (microaggregates) (Nath *et al.*, 2019).

Table 4.5: Percentage aggregate size distribution for three seasons at Magadu

Year	Cropping system	Macroaggregates (>2.0 mm)	Mesoaggregates (2.0-0.5 mm)	Microaggregates (<0.250 mm)	MWD(mm)	GMD(mm)
				%		
Year1	ABS CNTRL	66.43	12.81	16.12	3.46	1.009
	SL-MZ	63.31	20.73	15.96	4.00	1.011
	MZ+SB	69.57	13.72	16.71	3.75	1.010
	MZ/SB	77.73	9.89	12.38	4.20	1.012
	SL-SB	67.83	14.54	17.62	4.12	1.012
	MZ(80 kg N ha^{-1})	77.01	9.93	13.05	3.79	1.010
Year2	ABS CNTRL	65.86	12.51	21.63	3.62	1.021
	SL-MZ	56.10	16.83	27.06	3.91	1.024
	MZ+SB	61.94	15.82	22.24	3.38	1.015
	MZ/SB	62.07	13.56	24.37	3.89	1.025

	SL-SB	62.42	14.05	23.53	4.00	1.028
	MZ(80 kg N ha^{-1})	65.66	12.73	21.62	3.65	1.022
Year3	ABS CNTRL	56.74	20.47	22.79	3.57	1.027
	SL-MZ	58.34	27.10	23.62	3.24	1.023
	MZ+SB	47.85	24.06	28.09	3.13	1.018
	MZ/SB	40.93	27.72	31.35	2.78	1.011
	SL-SB	43.95	27.40	28.66	3.01	1.017
	MZ(80 kg N ha^{-1})	51.98	22.05	25.97	3.34	1.023
		NS	NS	NS	NS	NS

NB: ABS CNTRL= Absolute control, **SL-MZ**= Sole maize, **MZ+SB**= Maize and Soybean intercropping, **MZ/SB**= Maize rotated with soybean, **SL-SB**= Sole soybean and MZ (80 kg N ha^{-1}) = Maize supplied with 80 kg N ha^{-1} of inorganic fertilizer **MWD**= Mean weight Diameter, **GMD**= Geometric mean Diameter, **NS**= Not significant at $p \leq 0.05$

Table 4.6: Percentage aggregate size distribution of each year in two seasons in Suluti

Year	Cropping system	Macroaggregates (>2.0 mm)	Mesoaggregates (2.0-0.5 mm)	Microaggregates (<0.250 mm)	MWD(mm)	GMD(mm)
				%		
Year1	ABS CNTRL	52.25	31.30	16.45	3.50	1.029
	SL-MZ	45.47	36.32	18.21	3.26	1.025
	MZ+SB	37.58	41.25	21.17	2.93	1.020
	MZ/SB	31.05	35.8	33.15	2.49	1.006
	SL-SB	28.57	48.28	23.15	2.61	1.014
	MZ(80 kg N ha^{-1})	33.69	46.58	19.73	2.88	1.020
Year2	ABS CNTRL	56.39	22.18	21.43	3.58	1.039
	SL-MZ	53.04	29.83	17.14	3.54	1.040
	MZ+SB	39.28	36.90	23.82	2.83	1.022
	MZ/SB	39.09	39.02	21.89	2.86	1.024
	SL-SB	50.23	33.01	16.76	3.36	1.036
	MZ(80 kg N ha^{-1})	55.57	26.87	17.56	3.62	1.042
		NS	NS	NS	NS	NS

NB: ABS CNTRL= Absolute control, **SL-MZ**= Sole maize, **MZ+SB**= Maize and Soybean intercropping, **MZ/SB**= Maize rotated with soybean, **SL-SB**= Sole soybean and MZ (80 kg N ha^{-1}) = Maize supplied with 80 kg N ha^{-1} of inorganic fertilizer, **MWD**= Mean weight Diameter, **GMD**= Geometric mean Diameter, **NS**= Not significant at $p \leq 0.05$

Table 4.7: Aggregate size distribution of each year in different sieve sizes for two seasons in Uyole

Year	Cropping system	Macroaggregates (> 2.0 mm)	Mesoaggregates (2.0-0.5 mm)	Microaggregates (< 0.250 mm)	MWD	GMD
			%		mm	
Year1	ABS CNTRL	21.25	52.45	26.30	2.10	1.007
	SL-MZ	17.90	53.31	28.79	2.01	1.003
	MZ+SB	29.17	48.48	22.35	2.56	1.015
	MZ/SB	21.44	49.52	29.04	2.10	1.002
	SL-SB	29.08	47.55	23.37	2.63	1.015
	MZ(80 kg N ha^{-1})	29.17	48.54	22.29	2.62	1.017
Year2	ABS CNTRL	9.80	52.51	37.69	1.56	0.993
	SL-MZ	23.24	51.90	24.86	2.31	1.010s
	MZ+SB	12.60	64.87	22.53	1.89	1.006
	MZ/SB	15.70	49.50	34.80	1.78	0.994
	SL-SB	13.06	53.61	33.33	1.74	0.998
	MZ(80 kg N ha^{-1})	22.23	51.18	26.58	2.21	1.006
		NS	NS	NS	NS	NS

NB: ABS CNTRL= Absolute control, **SL-MZ**= Sole maize, **MZ+SB**= Maize and Soybean intercropping, **MZ/SB**= Maize rotated with soybean, **SL-SB**= Sole soybean and MZ (80 kg N ha^{-1}) = Maize supplied with 80 kg N ha^{-1} of inorganic fertilizer, **MWD**= Mean weight Diameter, **GMD**= Geometric mean Diameter, **NS**= Not significant at $p \leq 0.05$

Thus, building up larger aggregate sizes by SOM through different soil managements is crucial for higher C sequestration and stabilization (Gale *et al.*, 2000).

The range of macroaggregates in Magadu were 63.31 - 77.73 %, 56.10 - 61.94 %, 40.93 – 58.34 %, respectively, in the first, second and third seasons while the range of macroaggregates in the Uyole was 17.9 - 29.17 % in the first season and 9.8 - 23.24 % in second season. The percentage of macroaggregates in both sites (Magadu and Uyole) seemed to decrease in value progressively in every season. It could be due to little soil disturbance in the soils during planting and harvesting which have caused a decrease in macroaggregates (>2.0 mm) fraction. The same situation was observed by Mikha and Rice (2004) in which minimum soil disturbances reduced the macroaggregates fraction. Consequently, depending on the chemical recalcitrance of SOM in the macroaggregates, disturbances reduce cohesion between microaggregates and breakdown the macroaggregates and, thus, increase soil aeration and enhances more CO_2 efflux (respiration) which have an impact on SOC dynamics (Tobiašová *et al.*, 2016; Tian *et al.*, 2015).

On the contrary, the Suluti site showed increased percentage values from 31.08 – 52.25 %, in the first year to the range of 39.09 – 56.39 % in the second year. The addition of residue may have contributed positively to the slight enhancement in aggregation (Sandoval-Estrada *et al.*, 2008).

4.3.4.2 Mesoaggregates (2.00 - 0.5 mm) distribution in Magadu, Suluti and Uyole

In all three sites, there were no significant ($p < 0.05$) differences in contents of the mesoaggregate size distribution between cropping treatments. In the Magadu site (Table 4.5), the mesoaggregates (2.0 - 0.5 mm) ranged between 20.73% in the sole maize and 13.72 % in the intercropping in the first year. Meanwhile in the second year the proportion declined; the maximum was 16.83% in sole maize and minimum of 12.51% in the absolute control showing no significant ($p < 0.05$) difference among cropping system. However, in the third year the crop rotation system had 27.72% and a minimum of 20.47% in the absolute control. The increases in proportion of the mesoaggregates were a result of macroaggregates breakdown and lessening of microaggregates proportion which reconstitute mesoaggregates and macroaggregates.

The mesoaggregates fraction in Suluti site ranged from 31.3 – 48.28 % in the first year to 22.18 - 39.02 %. The fertilized maize (80 kg N ha^{-1}) plots appeared to lose more mesoaggregates (2.00 mm - 0.5 mm) by 43.3 % to higher aggregates size (macroaggregates) as indication of positive response. Apparently, fertilization and residue retention enhanced aggregation percentage. This observation is supported by previous research in which addition of crop residues resulted in an increase in aggregate stability (Blanco – Canqui *et al.*, 2014; Zhang *et al.*, 2014).

Uyole site had no significant ($p < 0.05$) differences in mesoaggregates distribution between treatments. It has a range from 47.55 – 53.31 % in the first year, which increased to 51.18 – 64.87 % in the second year. Intercropped plots showed more aggregation (64.87 %) over control, sole maize or rotation since the quality of residue (mixed of maize and soybean) incorporated into soil amended has great influence in aggregates turnover of the soil; slowing down the C decomposition due to their wider C:N ratios (Chivenge *et al.*, 2011).

4.3.4.3 Microaggregates (< 0.25 mm) distribution in Magadu, Suluti and Uyole

The microaggregates (< 0.250 mm) in the Magadu showed no significant ($p < 0.05$) differences between treatments in the first, second and third years. The microaggregates values were slightly higher in sole soybean (17.62 %) and minimum in the fertilized maize (13.05 %) in the first year. After three years of cultivation, the rotation contained somewhat high values of microaggregate fraction (31.35 %) and lowest in the control (22.79 %). This decrease is attributed to loss of larger aggregates fraction (Johnson *et al.*, 2016). Another studies by Castro Filho *et al.* (2002) also found no influence of soybean rotation to the aggregate stability. Besides, the high quality residues, with soybean as an example of narrow C:N ratio, enhance C mineralization in macroaggregates thus leading to loss of SOC and thus, to less stability due to collapse of microaggregates (Six *et al.*, 2001). The microaggregates in Suluti site as well showed no significant ($p < 0.05$) differences between treatments in the first and second year. There was a slightly higher content of microaggregates (33.15 %) in the crop rotation system in the first year, but its content was reduced in the second year (21.19 %) and seems to enhance larger aggregate sizes.

Meanwhile, in the Uyole, microaggregates (< 0.250 mm) were insignificantly higher ($p < 0.05$) in the rotation treatment in the first year, and generally increased value in the second year, which indicates more collapse of the larger aggregates.

4.3.5 Mean weight diameter and Geometric mean diameter aggregate stability indices in Magadu, Suluti and Uyole

The mean weight diameter (MWD) and Geometric mean diameter (GMD) are the soil structure indices which show stability of the soil aggregates. The Magadu site showed no significant ($p < 0.05$) difference among cropping systems in the MWD and GMD values (Table 4.5). The range of MWD was between 4.20 mm in rotation and the lowest was 3.46 mm in the absolute control plot in the first season. Except for the absolute control plot, the MWD of all cropping systems decreased in their content in the second and third years and minimum loss were recorded in the fertilized maize (80 kg N ha^{-1}) with respect to initial MWD in the first year.

The declining in MWD means soil contains more of the smaller sized aggregates classes and this leads to loss in structural stability of macroaggregates and envisages the declining in SOC (Johnson *et al.*, 2016; Piccolo *et al.*, 1997). Nevertheless, it seems over time length, the fertilized maize (80 kg N ha^{-1}) plot gave structural resistance against soil disturbances as compared to other cropping systems probably due to quick crop residue decomposition enhanced by N supply which lead to SOM increase. This observation corresponds to Blanco-Canqui *et al.* (2014) who also reported minimized aggregates breakdown under 80 kg N ha^{-1}.

On the other hand, the rotation plots lost a slightly higher proportion of macroaggregates in the third year by 47.3% (77.7% to 40.93%), which simultaneously caused the loss in MWD value in the third year due to strong correlation of macroaggregates and MWD values (Kubar *et al.*, 2018; Castro Filho *et al.*, 2002). Blanco – Canqui *et al.* (2014) and

Castro Filho *et al.* (2002) also reported weak stability indices of MWD in maize soybean rotation as a result of less SOC accumulation over a period of study time.

The mean weight diameter (MWD) and geometric mean diameter (GMD) in the Suluti were not significantly ($p < 0.05$) different between treatments. The slightly higher MWD was in the control plots followed by the sole maize, and the lowest was in the rotation in the first year. In the second year the highest value of MWD was in fertilized maize (80 kg N ha^{-1}) in Magadu followed by the sole maize which was also reported by Blanco – Canqui *et al.* (2014).

Similarly, in Uyole, there were no significant ($p < 0.05$) differences in MWD for the first season, however, in the second season all other treatments were greater than the control plot. The slightly higher MWD was in fertilized maize (80 kg N ha^{-1}) as in Magadu and Suluti, and the lowest was in sole maize in the first year, while in the second year higher MWD was in the sole maize and lowest were in the control plots. The higher values of MWD stability indices observed in all three sites in the continuous maize cropping is attributed to the recalcitrant nature of the maize residue with wide C:N ratio (Drury *et al.*, 2004), which is resistant to quick microbial decomposition and, therefore, resistant to aggregates breakdown.

4.3.6 Distribution of aggregate size classes in Magadu, Suluti and Uyole sites

4.3.6.1 Aggregate size classes in Magadu

The aggregate size distribution in Magadu is shown in the Table 4.8, for each cropping system in each year. The macroaggregates in the first year was shown to be significantly ($p < 0.05$) higher and dominant in all cropping systems than mesoaggregate and microaggregates. This indicated that most of the C stock was associated with larger aggregates (> 2.00 mm). But mesoaggregates and microaggregates were not significantly ($p < 0.05$) different.

In the second year, the trend was as in the first year. It was only in the sole soybean treatment that the microaggregates were significantly ($p \leq 0.05$) higher than mesoaggregates. This may be a result of macroaggregate breakdown due to soil disturbance during land preparations since the mesoaggregates retained same fraction (14 %) as in first season. Mikha and Rice (2004) also observed increase in microaggregates as a result of decline of larger aggregates.

Table 4.8: Effect of cropping system on the proportion of macroaggregates, mesoaggregates, and microaggregates in Magadu

Year	Aggregate sizes	Treatments					
		Absolute Control	**Sole Maize**	**Intercropping**	**Rotation**	**Sole Soybean**	**Maize (80 kg N ha^{-1})**
		%					
Year 1	Macroaggregates	66.43 b	63.31 b	77.73 b	69.57 b	67.83 b	77.01 b
	Mesoaggregates	12.81 a	15.96 a	9.89 a	13.72 a	14.54 a	9.93 a
	Microaggregates	16.12 a	20.73 a	12.38 a	16.71 a	17.62 a	13.05 a
	s.e.m	4.009	1.91	1.28	3.98	3.62	3.448
	cv%	21.8	9.9	6.6	20.7	18.8	17.9
Year 2	Macroaggregates	65.86 b	56.10 b	61.94 b	62.07 b	62.42 c	65.66 b
	Mesoaggregates	12.51 a	16.83 a	15.82 a	13.56 a	14.05 a	12.73 a
	Microaggregates	21.63 a	27.06 a	22.24 a	24.37 ab	23.53 b	21.62 a
	s.e.m	3.72	3.4	2.52	9.61	2.38	5.97
	cv%	19.3	17.7	13.1	49.9	12.4	31
Year 3	Macroaggregates	56.74 b	58.34 b	47.85	40.93	43.95	51.98
	Mesoaggregates	20.47 a	27.10 a	24.06	27.72	27.40	22.05
	Microaggregates	22.79 a	23.62 a	28.09	31.35	28.66	25.97
	s.e.m	5.44	6.12	NS	NS	NS	NS
	cv%	28.3	29.2				

NS= Not significant at $p \leq 0.05$,
Means followed by different latter (s) in the same column in separate year are significantly different at $p \leq 0.05$ using New Duncan Multiple Range Test (DMRT)

In the third season, only absolute control and sole maize have had significantly ($p \leq 0.05$) higher proportion of macroaggregates than mesoaggregates and microaggregates. Intercropping, rotation, sole soybean and maize with 80 kg N ha^{-1} resulted in no significant ($p < 0.05$) differences between aggregate types, but the proportion of mesoaggregates and microaggregates increased.

Declined proportion of the macroaggregates to meso and microaggregates in the third year could have been caused by soil disturbances during land preparation which may have released intra-aggregate C and enhanced SOC decomposition to result in less SOM to cement small aggregates into larger aggregates (Grandy and Robertson, 2007).

4.3.6.2 Aggregate size classes in Suluti

Table 4.9 presents the percentage aggregate size distribution in the Suluti site. There were significantly ($p \leq 0.05$) higher macroaggregates than microaggregates in only sole maize in the first year while other cropping systems had no significant ($p < 0.05$) differences between aggregates types (macroaggregates, mesoaggregates and microaggregates). In the second year, only in absolute control, sole maize, and sole soybean plots had macroaggregates significantly higher ($p \leq 0.05$) than microaggregates.

The sole maize cropping system in Suluti site showed higher distributions of macroaggregates due to its C recalcitrance which was the reason for better aggregation in the sole maize cropping system. Similar observations were reported by Drury *et al.* (2004), suggesting less significant CO_2 efflux in the continuous maize, which means more SOC to bind aggregates.

4.3.6.3 Aggregate size classes in Uyole

Except in intercropping, the Uyole site the mesoaggregates were significantly ($p \leq 0.05$) higher than macroaggregates and microaggregates sizes in all cropping systems (Table 4.10) in the first year. In the second year the mesoaggregates in the different treatments were significantly ($p \leq 0.05$) higher than macroaggregates and microaggregates except in the rotation treatments.

Table 4.9: Effect of cropping system on the proportion of macroaggregates, mesoaggregates, and microaggregates in Suluti

Year	Aggregate sizes	Treatments					
		Absolute Control	Sole Maize	Intercropping	Rotation	Sole Soybean	Maize (80 kg N ha^{-1})
		%					
Year 1	Macroaggregates	52.25	45.47 b	37.58	31.05	28.57	33.69
	Mesoaggregates	31.30	36.32 b	41.25	35.80	48.28	46.58
	Microaggregates	16.45	18.21 a	21.17	33.15	23.15	19.73
	s.e.m	NS	4.03	NS	NS	NS	NS
	cv%		21				
Year 2	Macroaggregates	56.39 b	53.04 b	39.28	39.09	50.23 b	55.57
	Mesoaggregates	22.18 a	29.83 ab	36.90	39.02	33.01 ab	26.87
	Microaggregates	21.43 a	17.14 a	23.82	21.89	16.76 a	17.56
	s.e.m	2.14	7.4	NS	NS	7.67	NS
	cv%	11.1	38.4			39.8	

NS= Not significant at $p \leq 0.05$, Means followed by different latter (s) in the same column in separate year are significantly different at $p \leq 0.05$ using New Duncan Multiple Range Test (DMRT)

The significant ($p < 0.05$) increase in microaggregates and mesoaggregates in the second year was a result of decrease in the macroaggregates.

Table 4.10: Effect of cropping system on the proportion of macroaggregates, mesoaggregates, and microaggregates in Uyole

Year	Aggregate sizes	Treatments					
		Absolute Control	Sole Maize	Intercropping	Rotation	Sole Soybean	Maize (80 kg N ha^{-1})
		%					
Year 1	Macroaggregates	21.25 a	17.90 a	29.17	21.44 a	29.08 a	29.17 a
	Mesoaggregates	52.45 b	53.31 b	48.48	49.52 b	47.55 b	48.54 b
	Microaggregates	26.30 a	28.79 a	22.35	29.04 ab	23.37 a	22.29 a
	s.e.m	4.4	3.5	NS	5.3	3.56	4.06
	cv%	22.5	18.1		27.5	18.5	21.1
Year 2	Macroaggregates	9.80 a	23.24 a	12.60 a	15.70	13.06 a	22.23 a
	Mesoaggregates	52.51 c	51.90 b	64.87 b	49.50	53.61 c	51.18 b
	Microaggregates	37.69 b	24.86 a	22.53 a	34.80	33.33 b	26.58 a
	s.e.m	5.58	5.9	5.51	NS	5.01	4.31
	cv%	29	30.7	28.6		26.5	22.4

NS= Not significant at p≤0.05, Means followed by different small latter (s) in the same column in separate year are significantly different at p ≤ 0.05 using New Duncan Multiple Range Test (DMRT)

The loss of macroaggregates in favour of microaggregates formation may indicate that in Uyole site the SOC which binds the macroaggregates were easily consumed by microbes since macroaggregates are stabilized by young and labile organic carbon (Jastrow *et al.*, 1996) which leads to SOC loss upon their decomposition (Cambardella and Elliot, 1993), and consequently, loss of structural stability of the resulting aggregates (Ashagrie *et al.*, 2007).

4.4 Conclusions and Recommendation

4.4.1 Conclusions

Cropping systems coupled with residue retention practices in three or two years did not result in significant differences in the water extractable organic carbon of CWEOC and HWEOC in all cropping years in Magadu, Suluti and Uyole.

Cropping practice caused the declined of larger aggregates season after season in Magadu site (70 % in year 1 to 50 % in year 3) even after amending soils with crop residues. Insignificant increase in macroaggregate fractions was observed in Suluti site which indicated site responded positively.

Larger macroaggregate fractions were mostly retained than other aggregate size classes (meso and microagregates) in Magadu and Suluti, suggesting a good structural stability against soil disturbances as indication of good soil attribute for SOC stock conservation than in Uyole site.

4.4.2 Recommendation

The results of a two or three year study have not been very consistent. Therefore, it is recommended that this type of study be undertaken on a longer term basis in the hope that consistent trends will be observed.

References

Alhameid, A., Singh, J., Sekaran, U., Kumar, S. and Singh, S. (2019). Soil biological health: influence of crop rotational diversity and tillage on soil microbial properties. *Soil Science Society of America Journal* 83(5):1431-1442.

Angers, D. A., Chantigny, M. H., Rochette, P. and Gagnon, B. (2006). Dynamics of soil water-extractable organic C following application of dairy cattle manures. *Canadian Journal of Soil Science* 86(5): 851-858.

Ashagrie, Y., Zech, W., Guggenberger, G. and Mamo, T. (2007). Soil aggregation, and total and particulate organic matter following conversion of native forests to continuous cultivation in Ethiopia. *Soil and Tillage Research* 94:101-108.

Blanco-Canqui, H., Ferguson, R. B., Shapiro, C.A., Drijber, R. A. and Walters. D. T. (2014). Does Inorganic Nitrogen Fertilization Improve Soil Aggregation? Insights from Two Long-Term Tillage Experiments. *Journal of Environmental Quality* 43: 993-1003.

Boyer, J. N. and Groffman, P. M. (1996). Bioavailability of water extractable organic carbon fractions in forest and agricultural soil profiles. *Soil Biology and Biochemistry* 28: 783 – 790.

Breulmann, M. (2011). Functional soil organic matter pools and soil organic carbon stocks in grasslands: an ecosystem perspective [dissertation]. Leipzig: UFZ. 116pp.

Buurman, P. and Jongmans, A. G. (2005). Podzolisation and soil organic matter dynamics. *Geoderma* 125: 71–83.

Cambardella, C. A. and Elliott, E. T. (1993). Carbon and Nitrogen Distribution in Aggregates from Cultivated and Native Grassland Soils. *Soil Science Society of America Journal* 3(57): 1071-1076.

Castro Filho, C. D., Lourenço, A., Guimarães, M. D. F. and Fonseca, I. C. B. (2002). Aggregate stability under different soil management systems in a red latosol in the state of Parana, Brazil. *Soil and Tillage Research* 65(1): 45-51.

Chantigny, M. H. (2003). Dissolved and water-extractable organic matter in soils: a review on the influence of land use and management practices. *Geoderma* 113: 357– 380.

Chivenge, P., Vanlauwe, B., Gentile, R. and Six, J. (2011). Comparison of organic versus mineral resource effects on short-term aggregate carbon and nitrogen dynamics in a sandy soil versus a fine textured soil. *Agriculture, Ecosystems and Environment* 140: 361–371.

Chu, J., Zhang, T., Chang, W., Zhang, D., Zulfiqar, S., Fu, A. and Hao, Y. (2016). Impacts of cropping systems on aggregates associated organic carbon and nitrogen in a semiarid highland agroecosystem. *Plos One* 11(10): e0165018.

Ćirić, V., Belić, M., Nešić, L., Šeremešić, S., Pejić, B., Bezdan, A. and Manojlović, M. (2016). The sensitivity of water extractable soil organic carbon fractions to land use in three soil types. *Archives of Agronomy and Soil Science* 62(12): 1654-1664.

Corvasce, M., Zsolnay, A., D'Orazio, V., Lopez R. and Miano, T. M. (2006). Characterization of water extractable organic matter in a deep soil profile. *Chemosphere* 62: 1583–1590.

Coulter, J. A., Nafziger, E. D. and Wander, M. M. (2009). Soil organic matter response to cropping system and nitrogen fertilization. *Agronomy Journal* 101(3): 592-599.

Drury, C. F., Yang, X. M., Reynolds, W. D. and Tan, C. S. (2004). Influence of crop rotation and aggregate size on carbon dioxide production and denitrification. *Soil and Tillage Research* 79: 87–100.

Embacher, A., Zsolnay, A., Gattinger, A. and Munch, J. C. (2008). The dynamics of water extractable organic matter (WEOM) in common arable topsoils: II. Influence of mineral and combined mineral and manure fertilization in a Haplic Chernozem. *Geoderma* 148(1): 63-69.

Gajda, A. M., Czyż, E. A. and Ukalska-Jaruga, A. (2020). Comparison of the Effects of Different Crop Production Systems on Soil Physico-Chemical Properties and Microbial Activity under Winter Wheat. *Agronomy* 10(8): 1130.

Gale, J., Cambardella, C. A. and Bailey, T. B. (2000). Root–derived carbon and the formation and stabilization of aggregates. *Soil Science Society of America Journal* 64: 201–207.

Geraei, D. S., Hojati, S., Landi, A. and Cano, A. F. (2016). Total and labile forms of soil organic carbon as affected by land use change in southwestern Iran. *Geoderma Regional* 7(1): 29-37.

Ghani, A., Dexter, M. and Perrott, K. W. (2003). Hot-water extractable carbon in soils; a sensitive measurement for determining impacts of fertilization, grazing and cultivation. *Soil Biology and Biochemistry* 35(9): 1231–1243.

Grebliunas, B. D., Armstrong, S. D. and Perry, W. L. (2016). Changes in water-extractable organic carbon with cover crop planting under continuous corn silage production. *Air, Soil and Water Research 9*: ASWR-S30708.

Gregorich, E. G., Beare, M. H., Stoklas, U. and St Georges. P. (2003). Biodegradability of soluble organic matter in maize-cropped soils. *Geoderma* 113: 237-252.

Hamkalo, Z. and Bedernichek, T. (2014). Total, cold and hot water extractable organic carbon in soil profile: impact of land use change. *Zemdirbyste-Agriculture* 101(2): 125–132.

Haynes, R. J., Swift, R. S. and Stephen, R. C. (1991). Influence of mixed cropping rotations (pasture-arable) on organic matter content, water stable aggregation and clod porosity in a group of soils. *Soil and Tillage Research* 19: 77-87.

Haynes, R. J. and Francis, G. S. (1993). Changes in microbial biomass C, soil carbohydrate composition and aggregate stability induced by growth of selected crop and forage species under field conditions. *Journal of Soil Science* 44: 665-675.

Haynes, R. J. and Swift R. S. (1990). Stability of soil aggregates in relation to organic constituents and soil water content. *Journal of Soil Science* 41: 73-83.

Haynes, R. J. (2000). Labile organic matter as an indicator of organic matter quality in arable and pastoral soils in New Zealand. *Soil Biology and Biochemistry* 32: 211-219.

Haynes, R. J. and Naidu. R. (1998). Influence of lime, fertilizer, and manure applications on soil organic matter content and soil physical conditions: A review. *Nutrient Cycling in Agroecosystems* 51: 123–137.

Hazra, K. K., Nath, C. P., Singh, U., Praharaj, C. S., Kumar, N., Singh, S. S. and Singh, N. P. (2019). Diversification of maize-wheat cropping system with legumes and integrated nutrient management increases soil aggregation and carbon sequestration. *Geoderma* 353: 308-319.

Jastrow, J. T., Boutton, T. W. and Miller, R. (1996). Carbon dynamics of aggregate-associated organic matter estimated by carbon-13 natural abundance. *Soil Science Society of America Journal* 60: 801-807.

Johnson, J. M., Strock, J. S., Tallaksen, J. E. and Reese, M. (2016). Corn stover harvest changes soil hydrology and soil aggregation. *Soil and Tillage Research* 161: 106-115.

Kalbitz, K., Solinger, S. and Park, J. H. (2000). Controls on the dynamics of dissolved organic matter in soils: a review. *Soil Science* 165: 277-304.

Khan, S. A., Mulvaney, R. L., Ellsworth, T. R. and Boast, C. W. (2007). The myth of nitrogen fertilization for soil carbon sequestration. *Journal of Environmental Quality* 36(6): 1821-1832.

Kubar, K. A., Huang, L., Lu, J., Li, X., Xue, B. and Yin, Z. (2018). Integrative effects of no-tillage and straw returning on soil organic carbon and water stable aggregation under rice-rape rotation. *Chilean Journal of Agricultural Research* 78(2): 205-215.

Lu, M., Zhou, X., Luo, Y., Yang, Y., Fang, C., Chen, J. and Li, B. (2011). Minor stimulation of soil carbon storage by nitrogen addition: a meta-analysis. *Agriculture, Ecosystems and Environment* 140(1-2): 234-244.

Malobane, M. E., Nciizah, A. D., Mudau, F. N. and Wakindiki, I. I. C. (2020). Soil Organic Carbon and Labile Carbon Pools Attributed by Tillage, Crop Residue and Crop Rotation Management in Sweet Sorghum Cropping System. *Sustainability* 12(22): 1-10.

Mikha, M. M. and Rice, C. W. (2004). Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. *Soil Science Society of America Journal* 68: 809 -816.

Nath, C. P., Hazra, K. K., Kumar, N., Praharaj, C. S., Singh, S. S., Singh, U. and Singh, N. P. (2019). Including grain legume in rice–wheat cropping system improves soil organic carbon pools over time. *Ecological Engineering* 129: 144-153.

Olujobi, O. J. (2016). Comparative effect of selected tree legumes on physico-chemical properties of an alfisol in Ekiti State. *ARPN Journal of Agricultural and Biological Science* 11: 82-87.

Piccolo, A., Pietramellara, G. and Mbagwu, J. (1997). Use of humic substances as soil conditioners to increase aggregate stability. *Geoderma* 75: 267-277.

Šeremešić, S., Milošev, D., Sekulić, P., Nešić, L. and Ćirić, V. (2013). Total and hot-water extractable carbon relationship in Chernozem soil under different cropping systems and land use. *Journal of Central European Agriculture* 14: 1496 – 1504.

Šeremešić, S., Nešić, L., Ćirić, V. I., Vasin, J., Đalović, I., Marinković, J. and Vojnov, B. (2020). Soil organic carbon fractions in different land use systems of Chernozem soil. *Zbornik Matice Srpske za Prirodne Nauke* 2020(138): 31-39.

Sharma, S., Singh, P. and Kumar, S. (2020). Responses of soil carbon pools, enzymatic activity and crop yields to nitrogen and straw incorporation in a rice-wheat cropping system in north-western India. *Frontiers in Sustainable Food Systems* 4: 532704.

Silveira, M. L. A. (2005). Dissolved organic carbon and bioavailability of N and P as indicators of soil quality. *Scientia Agricola* 62(5): 502-508.

Šimanský, V. (2011). Chemical Properties, soil structure and organic matter in different soil managements and their relationships with carbon sequestration in water-stable aggregates. *Research Journal of Agricultural Science* 43: 138–149.

Šimanský, V. and Bajčan, D. (2014). Stability of soil aggregates and their ability of carbon sequestration. *Soil and Water Research* 9: 111–118.

Šimanský, V., Balashov, E. and Horák, J. (2016). Water stability of soil aggregates and their ability to sequester carbon in soils of vineyards in Slovakia. *Archives of Agronomy and Soil Science* 62(2): 177-197.

Six, J., Carpentier, A., van Kessel, C., Merckx, R., Harris, D., Horwath, W.R. and Luscher, A. (2001). Impact of elevated CO_2 on soil organic matter dynamics as related to changes in aggregate turnover and residue quality. *Plant and Soil* 234: 27–36.

Six, J., Conant, R. T., Paul, E. A. and Paustian, K. (2002). Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant and Soil* 241(2): 155-176.

Tisdall, J. M. and Oades, J. M. (1982). Organic matter and water stable aggregates in soils. *Journal of Soil Science* 33: 141–163.

Tobiašová, E., Barančíková, G., Gömöryová, E., Makovnikova, J., Skalský, R., Halas, J., Koco, Š., Tarasovičová, Z., Takáč, J. and Špaňo, M. (2016). Labile forms of carbon and soil aggregates. *Soil and Water Research* 11(4): 259-266.

Van Trump, J. I., Wrighton, K. C., Thrash, J. C., Weber, K. A., Andersen, G. L. and Coates, J. D. (2011). Humic acid-oxidizing, nitrate-reducing bacteria in agricultural soils. *Microbiology* 2: 1–9.

Williams, C. F., Agassi, M., Letey, J., Farmer, W. J., Nelson, S. D. and Ben-Hur, M. (2000). Facilitated transport of napropamide by dissolved organic matter through soil columns. *Soil Science Society of America Journal* 64(2): 590 - 594.

Yoder, R. E. (1936). A direct method of aggregate of analysis and a study of the physical nature of erosion losses. *Journal of the American Society of Agronomy* 28: 337-351.

Zhang, P., Wei, T., Jia, Z., Han, Q., Ren, X. and Li, Y. (2014). Effects of Straw Incorporation on Soil Organic Matter and Soil Water-Stable Aggregates Content in Semiarid Regions of Northwest China. *PLoS ONE* 9(3): e92839.

Zhang, Y., Wang, X., Wang, X. and Li, M. (2019). Effects of land use on characteristics of water-extracted organic matter in soils of arid and semi-arid regions. *Environmental Science and Pollution Research* 26(25): 26052-26059.

Zhao, M. X., Zhou, J. B. and Kalbitz, K. (2008). Carbon mineralization and properties of water-extractable organic carbon in soils of the south Loess Plateau in China. *European Journal of Soil Biology* 44: 158–165.

CHAPTER FIVE

5.0 IMPACT OF INORGANIC N AND BIOMASS ADDITION INTO SOIL ON SOIL NITROGEN, ORGANIC CARBON AND CROP YIELDS UNDER MAIZE –SOYBEAN INTERCROPPING

Abstract

The aim of the study was to determine effect of different rates of inorganic fertilizer (40 and 80 kg N ha^{-1}) combined with different maize and soybean residues (single dose of 2 Mg maize residue ha^{-1} and 0.5 Mg soybean residue ha^{-1} and double dose of 4 Mg maize residue ha^{-1} and 1.0 Mg soybean residue ha^{-1}) on soil nitrogen (N), soil organic carbon (SOC) and crop yields. The experiment was laid on Randomized Complete Block Design with three replications and six different treatments. The study was under maize and soybean intercropping in the first season, followed by maize monocropping in the second season and intercropping in the third season. Soils were sampled from 0 - 30 cm deep at every harvesting period in July. The study was conducted for three years in Magadu and two years in Suluti and Uyole. There were no significant ($p < 0.05$) differences in the soil N and SOC, between treatments in Magadu, Suluti and Uyole. In the first season in Magadu, the soil N ranged from 0.1% to 0.14% while in second season where maize alone was planted, soil N declined in a range of 0.103% to 0.096 % but soil N regained in the third season from 0.12% - 0.13%. Soil N values increased in both Suluti and Uyole sites in the second season in each treatment after amendments. There were no significant ($p < 0.05$) SOC differences between treatments in each season in Magadu Suluti and Uyole. Insignificant SOC values increment was realized in the treatments with double biomass doses in Magadu from 1.07% – 1.16% and 1.06 – 1.20% in the first and third seasons, respectively. The Suluti had maize grain yield ranged between 0.6 -1.35 Mg ha^{-1} in the first season and 0.75 - 1.18 Mg ha^{-1} in the second season while Uyole site had maize grain yield ranged between 1.01 - 1.9 Mg ha^{-1} and 0.97 - 1.79 Mg ha^{-1} in the first and second season, respectively. Magadu experienced a sharp decrease in grain yield in three season regardless of inorganic N and crop residue addition from 0.38 - 1.9 Mg ha^{-1}, 0.41 - 0.78 Mg $ha^{-1}$and 0.4 - 0.13 Mg ha^{-1} in the first, second and third seasons, respectively. However, at higher mineral N and crop residue dose the yield was enhanced than other treatments across all seasons in all three sites. The result from this study shows that, crop residue return under intercropping coupled with inorganic N may stabilize SOC and N with future prospect to add more SOC and N after a prolonged management. Crop yield were improved by addition of residue and 80 kg N ha^{-1} of inorganic N, nonetheless, subsequent increase in yield require improved soil properties under crop residue return over prolonged time.

Keywords: Soil organic carbon, Soil nitrogen, intercropping, crop residue, yield

5.1 Introduction

The largest terrestrial carbon (C) stock, which is estimated to reach 1,500 Pg of soil C (Batjes, 1996), is found in the 100 cm soil depth. The terrestrial pool may act as sink or source of C, depending on different land use and management strategies can offset or otherwise add CO_2 fluxes to atmospheric pool (Lal, 2007). Soil is continually undergoing different processes and acquires or loses materials, which may alter different physical and chemical properties and, consequently, soil quality. Soil organic carbon (SOC) is important for it influences soil chemical and physical properties such as pH (Hobbs, 2007), cation exchange capacity (CEC), nutrient and water holding capacity and formation of stable aggregates (Smith *et al.*, 2012; Varvel and Wilhelm, 2010).

Depletion of soil C in arable land is caused by removal of crop residues and low input agriculture (Lal, 2007). Therefore, crop residue retention is an important management strategy in maintaining and even increasing SOM levels which, in turn, increase soil C stock (Lal, 2007).

Use of fertilizer N has often been reported to enhance both grain and crop residue yields (Naab *et al.*, 2015; Amanullah *et al.*, 2009). Inorganic fertilizer N coupled with residues incorporation into soil, under conducive soil humidity and temperatures, will add significant amounts of SOM (Oertel *et al.*, 2016; Liao *et al.*, 2015; Naab *et al.*, 2015; Six *et al.*, 2002). In addition Liao *et al.* (2015) and Naab *et al.* (2015) reported that amount of residue returned is proportional to potential addition of SOM in the soil. For example, Wilhelm *et al.* (2007) proposed a range of 5.25 - 12.5 Mg of maize residues ha^{-1} as appropriate to maintain sufficient levels of SOC in American soils

The global estimate of agricultural crop residue is 3.7 Pg crop residues dry matter per annum (Bentsen *et al.*, 2014). However, smallholder agriculture in Africa cannot return enough residues to soil because it is challenged by residue burning, use as animal feed, firewood and others like bioethanol production (Jering *et al.*, 2013). Developing of soil management strategies in developing countries is crucial to increase grain yields and to ensure enough food supply and biomass yield for multiple demands of residues (Naab *et al.*, 2015).

The aim of this research was to study the impact of different levels of inorganic N and crop residues in a maize - soybean intercropping system on total N and SOC dynamics and grain and biomass yields.

5.2 Materials and Methods

5.2.1 Description of research areas

The research was conducted in Magadu, Suluti and Uyole. A detailed description of the research areas is presented in Chapter 3 (Section 3.3.1).

5.2.2 Treatment details and experimental design

This research was established in experimental plots which had been fallowed for between three to four years. Experimental plots in Magadu were established in March 2017 and the experimental plots were initiated at ARI-Uyole and Suluti in December 2017. The plots started as intercropping of maize and soybean and after residue (maize and soybean) application all plots were planted with maize alone in the second year, followed by maize-soybean intercropping in the third year.

The experiment was laid out in the Randomized Complete Block Design (RCBD), with three replications. Plot size was 9 square metres per plot (3x3 metres). Before planting, the field was ploughed using a hand hoe as practiced by smallholder farmers. Maize spacing was 75 cm x 30 cm, while the soybean was planted between maize rows (i.e 37.5 cm) from a maize row. Planting was carried out in March and harvested in July while in Mbeya (Uyole) and Ruvuma (Suluti) the planting was done in December and or early January while harvesting was done in July. During harvesting, maize plants were collected from an area of 3.6 m^2 (1.5 m x 2.4 m) while soybean in intercropped plots was harvested from area of 1.8 m^2 (0.75 m x 2.4 m).

Table 5.1: Treatments details and cropping schedule for three seasons in the research sites

Treatment details	**Season**		
	1	**2**	**3**
1. No Input(MZ Plant)- (No input P or N)	MZ	MZ	MZ
2. (MZ+SB)BiomP40N0-(1x Maize and Soybean residue P40, no N)	MZ + SB	MZ	MZ + SB
3. (MZ+SB)BiomP40N40-(1x Maize and Soybean residue P40 and N40)	MZ + SB	MZ	MZ + SB
4. (MZ+SB)BiomP40N80 (1x Maize and Soybean residue P40 and N80)	MZ + SB	MZ	MZ + SB
5. 2(MZ+SB)BiomP40N40-(2x Maize and Soybean residue P40 and N40)	MZ + SB	MZ	MZ + SB
6. 2(MZ+SB)BiomP40N80-(2x Maize and Soybean residue P40 and N80)	MZ + SB	MZ	MZ + SB

1. No Input(MZ Plant)=no input P fertilizer or N fertilizer,
2. (MZ+SB)BiomP40N0=(1x Maize and Soybean residue and P fertilizer at 40 kg P ha^{-1}, no N fertilizer),
3. (MZ+SB)BiomP40N40=(1x Maize and Soybean residue and P fertilizer at 40 kg P ha^{-1},N fertilizer 40 kg N ha^{-1})
4. (MZ+SB)BiomP40N80=(1x Maize and Soybean residue and P fertilizer at 40 kg P ha^{-1},N fertilizer 80 kg N ha^{-1})
5. 2(MZ+SB)BiomP40N40=(2x Maize and Soybean residue and P fertilizer at 40 kg P ha^{-1},N fertilizer 40 kg N ha^{-1})
6. 2(MZ+SB)BiomP40N80=(2x Maize and Soybean residue and P fertilizer at 40 kg P ha^{-1},N fertilizer 80 kg N ha^{-1})

NB: 1x= 2 Mg ha^{-1} of maize residue and 0.5 Mg ha^{-1} of soybean residue, 2x= 4 Mg ha^{-1} of maize residue and 1.0 Mg ha^{-1} of soybean residue. MZ= maize, SB= Soybean, MZ + SB= maize and soybean intercropping,

The grains were dried to adjust moisture content to 15.5 % for maize and 13 % for soybean (Al-Kaisi *et al.,* 2005) to determine yield. After harvesting the dried biomass was chopped into small pieces of 5-10 cm and incorporated back to soil using hand hoe.

5.2.3 Soil samples collection

Soil samples were collected after harvesting time; the soil samples were randomly collected diagonally in different spots in each plot from the 0 - 30 cm depth for chemical analysis. The soil surface was cleaned of plant and other residues before sampling. Samples were packed and carefully transported to ensure no disturbance of soil aggregates from field to laboratory. The soil samples were air-dried for three days and subsequently passed through a 2 mm sieve.

5.2.4 Soil samples data analysis

5.2.4.1 Soil organic carbon

Soil organic carbon was determined by the wet oxidation method of Walkley and Black (Nelson and Sommers, 1982). Disturbed soil samples were air dried for 2-3 days, mixed well and after gentle crushing they were passed through a 2 mm sieve. One gram of the soil was weighed and placed into 500 ml conical flask. Ten ml of 1 M $KCrO_3^{-2}$ was added, followed by addition of 20 ml of concentrated sulfuric acid in a fume hood. The mixture was left for 30 min and then 100 ml of distilled water were added followed by 10 ml of 85% phosphoric acid. The content were titrated against 0.5 M of ammonium ferrous sulfate (Mohr's salt) to quantify unreacted $KCrO_3^{-2}$.

5.2.4.2 Total nitrogen

Total nitrogen was determined by the micro-Kjeldahl digestion distillation method (Bremner and Yeomans, 1998).

5.2.5 Statistical data analysis

The data were subjected to analysis of variance (ANOVA) using GENSTAT 15th Edition Statistical Package. When significance at $p < 0.05$ was found, means were compared using New Duncan Multiple Range Test (DMRT) at $p < 0.05$.

5.3 Results and Discussion

5.3.1 Effects of inorganic fertilizer N and maize and soybean residues on soil N

The effects of fertilizer N and residue incorporation on soil N are presented in Table 5.2 for Magadu, Suluti and Uyole.

Table 5.2: Effects of crop residue incorporation and inorganic fertilization on soil N under maize – soybean intercropping in Magadu, Suluti and Uyole

Treatment	Magadu			Suluti		Uyole	
	Nitrogen (%)						
	Season1	**Season2**	**Season3**	**Season1**	**Season2**	**Season1**	**Season2**
No Input(MZ Plant)	0.135	0.100	0.128	0.049	0.088	0.119	0.153
(MZ+SB)BiomP40N0	0.103	0.103	0.121	0.044	0.065	0.11	0.148
(MZ+SB)BiomP40N40	0.124	0.100	0.126	0.049	0.082	0.112	0.145
(MZ+SB)BiomP40N80	0.119	0.096	0.126	0.049	0.083	0.126	0.151
2(MZ+SB)BiomP40N40	0.126	0.098	0.121	0.044	0.083	0.114	0.145
2(MZ+SB)BiomP40N80	0.114	0.098	0.119	0.051	0.089	0.098	0.146
	NS	NS	NS	NS	NS	NS	NS

NS= not significant different at p ≤ 0.05, **MZ**= maize, **SB**= Soybean, **MZ + SB**= maize and soybean intercropping

There were no significant ($p < 0.05$) differences in soil N between treatments in Magadu in all cropping seasons; the differences were slight and minor. However, the trends indicated a slight decline in soil N from first (0.135 - 0.103%) to second season (0.103-0.096%).

The decline in soil N in the second season may be explained as follows: Addition of crop residues (maize and/or soybean) to soil might have triggered greater need for N to be able to decompose large amount of crop residues. The phenomenon has been described by Janz *et al.* (2022), Mazilli *et al.* (2014), Li *et al.* (2013), Dyer *et al.* (2012) and Got and Ottow, (1988) which showed an increase in flux of N gases turnover soon after residue incorporation. In addition to that, it is possible that most of the N from decomposed soybean and maize residues from first season might have been used to supply N for maize growth in second season.

In the third season there were no significant ($p < 0.05$) differences observed between treatments regardless of the variable amount of N applied or biomass added. The trend of soil N content from all treatments showed a slight but non-significant regain of N in the third season (0.119% - 0.128%). This could be due to effect of cereal and legume intercropping advantage (Cong *et al.*, 2005) from maize and soybean and residue incorporation in season two. Mazilli *et al.* (2014) showed in their findings that below ground input of biomass increased N and C from maize and soybean crops in two successive seasons.

There were no significant ($p < 0.05$) differences between different treatments in both seasons at the Suluti and Uyole sites (Table 5.2). In Suluti, the range of soil N in first season (0.044% – 0.051%) was somewhat increased in the second season (0.065 % - 0.089%) while in Uyole the range (0.098% – 0.126%) in the first season was increased (0.145 - 0.153%) in the second season. The inorganic fertilizer N and soybean residues (narrow C:N ratio) might have reduced N demand by soil bacteria that lessened immobilization (Qiu *et al.*, 2016; Abiven and Recous, 2007).

5.3.2 Effects of inorganic fertilizer N and maize and soybean residues on soil organic carbon

The result in Table 5.3 is showing SOC values observed after three and two seasons in Magadu, and Uyole and Suluti research stations, respectively.

Table 5.3: Effects of crop residue incorporation and inorganic fertilization on SOC under maize – soybean intercropping in Magadu, Suluti and Uyole

Treatment	Magadu			Suluti		Uyole	
	Organic carbon (%)						
	Season1	Season2	Season3	Season1	Season2	Season1	Season2
No Input(MZ Plant)	1.31	1.16	1.13	0.80	0.78	2.12	1.76
(MZ+SB)BiomP40N0	1.42	1.20	1.17	0.79	0.71	1.83	1.72
(MZ+SB)BiomP40N40	1.15	1.14	1.16	0.83	0.76	1.86	1.72
(MZ+SB)BiomP40N80	1.16	1.15	1.10	0.83	0.74	1.91	1.75
2(MZ+SB)BiomP40N40	1.07	1.12	1.16	0.77	0.75	1.97	1.72
2(MZ+SB)BiomP40N80	1.06	1.13	1.20	0.80	0.76	1.88	1.72
	NS	NS	NS	NS	NS	NS	NS

NS= not significant different at $p \leq 0.05$, **MZ**= maize, **SB**= Soybean, **MZ + SB**= maize and soybean intercropping,
NB: 1X= 2 Mg maize residue ha^{-1} and 0.5 Mg soybean residue ha^{-1} and 2X= 4 Mg maize residue ha^{-1} and 1.0 Mg soybean residue ha^{-1}

Incorporation of residues and N in all sites did not result in statistical differences in SOC ($p > 0.05$) between the treatments in all seasons. Previous research by Chen *et al.* (2014) found that different soils types under residue and inorganic N fertilizer addition had significant quantities of CO_2 released in soil under long and short term studies. The results further indicated that addition of residues enhanced up to two fold of mineralized C as CO_2 which was lost to atmosphere. This might be the reason for insignificant SOC increments in the sites of present studies.

Li *et al.* (2013) reported that the combination of residues of maize and soybean results in narrowing of C:N ratio, compared to maize alone but slightly higher than the soybean C:N ratio. This results in relatively faster decomposition and hence more losses as $CO_{2,}$ leaving the soil C unchanged. Both Khan *et al.* (2007) and Mulvaney *et al.* (2009) reported that large applications of biomass residues and inorganic N even for a long time could not result in increased SOC. Similarly, Li *et al.* (2018) and Khan *et al.* (2007) reported that under high inorganic N application, there is acceleration of both residue and SOC decomposition, thereby losing SOC.

5.3.3 Effects of levels of inorganic N and biomass on maize and soybean grain yields in Magadu, Suluti and Uyole

5.3.3.1 Maize grain yields in Magadu

Maize grain yield in Magadu was observed to have significant ($p < 0.001$) differences between treatments in the first, second and third season (Table 5.4). Regardless of differences in biomass levels, plot 2(MZ+SB) BiomP40N80 and (MZ+SB) BiomP40N80 with 80 kg N ha^{-1} registered significant ($p < 0.05$) higher yield compared to the other treatments with 40 kg N ha^{-1} and 0 kg N ha^{-1}, due to readily available supply of N from fertilizer. These results agree with those of Sadeghi and Bahrani (2009) who reported significant higher yield under high N levels as result of supply of N to soil. There was an insignificant ($p < 0.05$) difference by the effect of N rate in N40's plots compared to untreated plots. For example (MZ+SB)BiomP40N40 and 2(MZ+SB)BiomP40N40 had slightly higher values than No Input(MZ Plant) by 0.41 and 0.47 Mg ha^{-1} and (MZ+SB)BiomP40N0 by 0.32 and 0.38 Mg ha^{-1}, respectively, in the first season.

Table 5.4: Maize and soybean grain yield in three different seasons under different rates of inorganic N and residue retention in Magadu, Morogoro

Treatments	Magadu				
	Maize	**Soybean**		**Maize**	**Soybean**
	Year 1 (2017)		**Year 2 (2018)**	**Year 3 (2019)**	
			Mg ha^{-1}		
No Input(MZ Plant)	0.38a			0.13a	
(MZ+SB)BiomP40N0	0.47a	0.31		0.14a	
(MZ+SB)BiomP40N40	0.79a	0.26		0.15a	
(MZ+SB)BiomP40N80	1.61b	0.29		0.33b	
2(MZ+SB)BiomP40N40	0.85a	0.32		0.20a	
2(MZ+SB)BiomP40N80	1.90b	0.30		0.46c	
p level	<0.001	NS		<0.001	
s.e	0.33			0.05	
cv%	32.7			19.9	

Means within a columns followed by the different letter(s) are significantly different at $p \leq 0.05$ according to New D.M.R.T, NS= not significant at $p \leq 0.05$, **MZ**= maize, **SB**= Soybean, **MZ + SB**= maize and soybean intercropping

The results observed that the N80 plots registered two fold maize grain yield compared to N40's plots in the first and third season regardless of the biomass doses because of readily available to plant of the N source as crop residues only applied after first season. A similar scenario was reported by Mupangwa *et al.* (2020) such that different N rates increased yield regardless of levels of biomass applied.

Addition of inorganic N in the soil is important for higher maize yields and quality (Biswas and Ma, 2016). However, effect of N rates in increasing grain yield was diminished in the second and third seasons, which may suggest the soil might have lost soil N through nitrate leaching (Hauggaard-Nielsen *et al.*, 2003), N_2O (Shen *at al.*, 2018) and due to effect of immobilization (Janz *et al.*, 2022; Mazilli *et al.*, 2014; Li *et al.*, 2013). A decline in maize grain yield was also observed by Naab *et al.* (2015) under 60 kg N ha^{-1} application in the second and third years while Agyare *et al.* (2006) observed a sharp decline in grain yields in the first four years of intercropping.

Fan *et al.* (2005) reported an increase in grain yield after 16 years additions of crop residues along with N and P as a result of improved SOC and water retention as compared to only N fertilizer and, control treatments without N addition. That as well could apply in Magadu site after long time of practice. The results of maize yield in Suluti in the first season showed significant ($p < 0.05$) difference between 2(MZ+SB) BiomP40N80 and the other different treatments. There were no statistical yield differences ($p < 0.05$) observed between (MZ+SB) BiomP40N80, N40, and N0 plots in Suluti (Table 5.5).

Table 5.5: Maize and soybean grain yield in two seasons under inorganic N and residue retention in Suluti and Uyole

Treatments	Suluti			Uyole		
	Season 1 (2018)		Season 2 (2019)	Season 1 (2018)		Season 2 (2019)
	Maize	Soybean	Maize	Maize	Soybean	Maize
	(Mg ha^{-1})					

No Input(MZ Plant)	0.70a		0.88	1.01a		1.29
(MZ+SB)BiomP40N0	0.63a	1.19	0.80	1.29ab	0.65	1.28
(MZ+SB)BiomP40N40	0.84a	1.24	0.75	1.40abc	0.59	1.39
MZ+SB)BiomP40N80	0.89a	1.23	1.02	1.77cd	0.72	1.53
2(MZ+SB)BiomP40N40	0.81a	1.20	0.71	1.57bcd	0.58	0.97
2(MZ+SB)BiomP40N80	1.35b	1.21	1.18	1.90d	0.68	1.79
p value	0.003	NS	NS	0.004	NS	NS
s.e	0.15			0.21		
cv%	17.1			13.9		

Means within a columns followed by the different letter(s) are significantly different at $p \leq 0.05$ according to New DMRT, NS= not significant at $p \leq 0.05$, **MZ**= maize, **SB**= Soybean, **MZ + SB**= maize and soybean intercropping.

The significantly ($p < 0.05$) higher maize yields in 2(MZ+SB)BiomP40N80 plot in both Suluti and Uyole is due to a positive effect of crop residues and inorganic N combination (Xu *et al.,* 2019; Wang *et al.,* 2018). The blend of maize and soybean crop residues could have narrowed the C:N ratio of crop residue mixture and lessen immobilization effect (Li *et al.*, 2013) which accumulated and supplied enough N to crops (Wang *et al.*, 2018; Xie *et al.*, 2014).

There were no significant ($p < 0.05$) differences in maize grain yields in the Suluti as well as in Uyole site in the second seasons. Both Suluti and Uyole had insignificantly ($p > 0.05$) higher yields probably due to high microbial N demand for residue decomposition and concomitant loss of soil N through leaching which consequently reduced yield performance of the maize crop (Shen *at al.,* 2018; Wang *et al.,* 2018; Kihara *et al.,* 2012; Hauggaard-Nielsen *et al.,* 2003).

5.3.3.2 Soybean grain yield in Magadu, Suluti and Uyole

Soybean grain yield in Magadu, Suluti and Uyole were not significantly ($p < 0.05$) different between intercropped plots in their first season. The range of soybean grain yield was 0.26 - 0.32 Mg ha^{-1}, 1.19 - 1.23 Mg ha^{-1} and 0.58 - 0.72 Mg ha^{-1} in Magadu, Suluti and Uyole, respectively. The results for soybean grain yield in this study matching other study by Tsujimoto *et al.* (2015) in Mozambique and Kihara *et al.* (2012) in Kenya.

It is hereby proposed that yield variations among sites (Magadu, Suluti and Uyole) could be due to differences in soil water potential and the dry spells that occurred in different growing stages of soybean under maize and soybean intercropping as previously observed by Tsujimoto *et al.* (2015).

Another reason for low yield in intercropped soybean is the 1:1 planting pattern which significantly affects most of the yield components such as pod and seed numbers (Wang *et al.*, 2020; Lv *et al.*, 2014). Planting space in this study was 37.5 cm between maize and soybean crops, more compacted as study by Wang *et al.* (2020) who reported more space of 60 and 80 cm. Therefore, it is also assumed that more reduced yield was occasioned from shading effect (Liu *et al.,* 2018; Yang *et al.,* 2017).

Other demonstrated reasons which might have likely affected yield in our sites include water and nutrient competition (Lv *et al.*, 2014; Kihara *et al.*, 2012; Ghosh *et al.*, 2009) from the dominant crop. According to Lv *et al.* (2014) under 1:1 (maize: soybean) planting pattern the nutrient competition is more important factors in determining yield components in which the soybean is suppressed than in monocropping in favor of maize crop.

Decline in soybean grain yield the third season in Magadu (Table 5.4) was marked in a range between 0.09 - 0.21 Mg ha^{-1} from 0.26 – 0.32 Mg ha^{-1} in the first year. Our result correspond to other study by Undie *et al.* (2012) who reported decrease in soybean grain yield in two subsequent years in the 1:1 maize and soybean cropping pattern by 51% and

86%, respectively, due nutrient competition and shading effect. Contradictory studies proposed higher soybean grain yields as level of residue retention increased. For example, in different studies by Lu (2020) and Wang *et al.* (2018) reported enhanced crop yields from crop residue retention caused by lowering soil bulk density and so increase in water filtration and, increased enzyme activities and significant high water use efficiency resulting higher yield per unit area.

5.3.4 Effect of levels of inorganic N and biomass incorporation on the maize and soybean biomass yield in Magadu, Suluti and Uyole

Results on crop residue yield are presented in Tables 5.6 and 5.7 for Magadu, Suluti and Uyole, respectively. The range of maize biomass yield was 5.83 - 11.21 Mg ha^{-1}, 0.74 - 1.57 Mg ha^{-1}, 10.74 - 12.78 Mg ha^{-1} in Magadu, Suluti and Uyole, respectively, in the first season with no significant ($p < 0.05$) differences between treatments under different crop residue levels and N rates. In the second season the maize residue yields decreased in Magadu (1.17-2.27 Mg ha^{-1}) and in Uyole (9.33 - 11.67 Mg ha^{-1}) but increased in Suluti (2.67- 4.78 Mg ha^{-1}).

Table 5.6: Maize and soybean yield in three different seasons under inorganic N and residue retention and rainfed at Magadu

	Magadu				
Treatments	**Maize Biomass**	**Soybean Biomass**	**Maize Biomass**	**Maize Biomass**	**Soybean Biomass**
	Year 1 (2017)		**Year 2 (2018)**	**Year 3 (2019)**	
	(Mg ha^{-1})				
No Input(MZ Plant)	5.83		1.17a	1.3	
(MZ+SB)BiomP40N0	6.67	0.55	1.33ab	1.96	0.26
(MZ+SB)BiomP40N40	8.33	0.65	1.27a	1.29	0.15
(MZ+SB)BiomP40N80	9.72	0.55	1.44bc	1.82	0.20
2(MZ+SB)BiomP40N40	9.44	0.86	1.56c	1.56	0.19
2(MZ+SB)BiomP40N80	11.21	0.55	2.27d	2.07	0.20
***p* level**	NS	NS	<0.001	NS	NS
s.e			0.09		
cv%			5.9		

Means within a columns followed by the different letter(s) are significantly different at p ≤ 0.05 according to New DMRT, NS= not significant at p ≤ 0.05, **MZ**= maize, **SB**= Soybean, **MZ + SB**= maize and soybean intercropping,

In the third season the maize biomass in Magadu (1.29 - 2.07 Mg ha^{-1}) was maintained as in second season. The decrease and inconsistency in yield and yield components in subsequent years was also observed by Undie *et al.* (2012) under intercropping. Significant ($p < 0.05$) maize biomass yield differences observed in the second season in the 2(MZ+SB)BiomP40N80, 2(MZ+SB)BiomP40N40 and (MZ+SB)BiomP40N80 over other treatments was presumed to be caused by supply to crop of N from both mineral N and residues (Shah *et al.,* 2003) which improved biomass yield. There were no significant ($p < 0.05$) differences in the soybean biomass yield between treatments in Magadu, Suluti and Uyole (Table 5.6 and 5.7) in all seasons.

Table 5.7: Maize and soybean yield in different seasons under inorganic N and residue retention in Suluti and Uyole

Treatments	**Suluti**			**Uyole**		
	Maize Biomass	**Soybean Biomass**	**Maize Biomass**	**Maize Biomass**	**Soybean Biomass**	**Maize Biomass**
	Year 1 (2018)		**Year 2 (2019)**	**Year 1 (2018)**		**Year 2 (2019)**
	(Mg ha^{-1})					
No Input(MZ Plant)	0.74		4.00	12.41		10.19
(MZ+SB)BiomP40N0	0.83	0.58	4.78	10.93	0.56	11.67
(MZ+SB)BiomP40N40	0.95	0.50	3.96	13.15	0.41	11.15
(MZ+SB)BiomP40N80	0.99	0.67	3.96	11.30	0.41	10.59
2(MZ+SB)BiomP40N40	1.22	0.60	2.67	12.78	0.48	9.33
2(MZ+SB)BiomP40N80	1.57	0.54	3.15	10.74	0.48	10.74
	NS	NS	NS	NS	NS	NS

NS= not significant at p≤0.05, **MZ**= maize, **SB**= Soybean, **MZ + SB**= maize and soybean intercropping, The range of soybean biomass yields in Suluti and Uyole were 0.50 - 0.67 Mg ha^{-1} and 0.41 - 0.56 Mg ha^{-1}, correspondingly, in the first season. Soybean biomass yield in Magadu was in the range of 0.55 - 0.86 Mg ha^{-1} and 0.15 - 0.26 Mg ha^{-1} in the first and third seasons, respectively. The range of soybean biomass yield from all sites were smaller compared to other study by Kihara *et al.* (2012) in a Kenyan soil who reported ≥ 1.0 Mg of soybean biomass ha^{-1}. Insignificant yields in three sites could be due to 1:1 planting pattern of the intercropping (Wang *et al.,* 2020; Undie *et al.*, 2012) which favour maize over soybean in nutrients uptake and shading effect to soybean (Liu *et al.,* 2018; Yang *et al.,* 2017) have usually lead the aboveground soybean biomass to be suppressed (Tsujimoto *et al.,* 2015).

5.4 Conclusions and Recommendations

5.4.1 Conclusions

Based on the result obtained, different levels of crop residue return under intercropping coupled with inorganic N have slightly reduced SOC in the second season, in all three sites, however, a slight increase in third season in Magadu may suggest future prospect of the intervention to add more SOC after a prolonged practice. Residue retention and inorganic fertilizer N was essential for the slight (not significant) increase in soil nitrogen observed in Uyole and Suluti; maintained soil N values in Magadu, then it is likely that overtime there could be significant increment in all three sites. Application of crop residue (maize and soybean) and 80 kg N ha^{-1} of inorganic N had relatively improved maize grain yield than other treatments.

5.4.2 Recommendations

1. Crop residue retention coupled with inorganic N fertilizer are recommended as farmers can reduce loss in soil organic matter and other soil properties and get substantial increase overtime.
2. It is recommended to include crop residue (4 Mg ha^{-1} of maize and 1 Mg ha^{-1} of soybean) coupled with inorganic N fertilizer at 80 kg N ha^{-1} to increase maize grain yields.
3. Further studies are recommended on use of inorganic N rates broadened above 80 kg N ha^{-1}, combined with residue retention, and different cropping patterns in the intercropping of maize and soybean (i.e 1:2, 2:2, 1:3).

References

Abiven, S. and Recous, S. (2007). Mineralisation of crop residues on the soil surface or incorporated in the soil under controlled conditions. *Biology and Fertility of Soils* 43: 849e852.

Agyare, W. A., Clottey, V. A., Mercer-Quarshie, H. and Kombiok, J. M. (2006). Maize yield response in a long-term rotation and intercropping systems in the Guinea Savannah zone of Northern Ghana. *Journal of Agronomy* 5: 232-238.

Al-Kaisi, M. M., Yin, X. and Licht, M. A. (2005). Soil carbon and nitrogen changes as affected by tillage system and crop biomass in a corn–soybean rotation. *Applied Soil Ecology* 30(3): 174-191.

Amanullah, M. K., Marwat, K. B., Shah, P., Maula, N. and Arifullah, S. (2009). Nitrogen levels and its time of application influence leaf area, height and biomass of maize planted at low and high density. *Pakistan Journal of Botany* 41(2): 761-768.

Batjes, N. H. (1996). Total carbon and nitrogen in the soils of the world. *Euopean Journal of Soil Science* 47: 151–163.

Bentsen, N. S., Felby, C. and Thorsen, B. J. (2014). Agricultural residue production and potentials for energy and materials services. *Progress in Energy and Combustion Science* 40: 59-73.

Biswas, D. K. and Ma, B. L. (2016). Effect of nitrogen rate and fertilizer nitrogen source on physiology yield, grain quality, and nitrogen use efficiency in corn. *Canadian Journal of Plant Science* 96: 392-403.

Bremner, J. R. and Yeomans, J. C. (1998). ‘’Laboratory techniques’’ In: J.R Wilson (Ed) *Advance in nitrogen cycling in agriculture ecosystem C.A.B Int*. Willing, England. [www.sciencepublishinggroup.com › journal › paperinfo › j.ijnrem.202106...] site visited on 15/08/2018.

Chen, X., Wang, X., Liebman, M., Cavigelli, M. and Wander, M. (2014). Influence of Residue and Nitrogen Fertilizer Additions on Carbon Mineralization in Soils with Different Texture and Cropping Histories. *PLoS ONE* 9(7): e103720.

Cong, W. F., Hoffland, E., Li, L., Janssen, B. H. and van der Werf, W. (2015). Intercropping affects the rate of decomposition of soil organic matter and root litter. *Plant and Soil* 391(1): 399-411.

Dyer, L., Oelbermann, M. and Echarte, L. (2012). Soil carbon dioxide and nitrous oxide emissions during the growing season from temperate maize-soybean intercrops. *Journal of Plant Nutrition and Soil Science* 175(3): 394-400.

Fan, T., Stewart, B., Yong, W., Junjie, L. and Guangye, Z. (2005). Long-term fertilization effects on grain yield, water-use efficiency and soil fertility in the dryland of Loess Plateau in China. *Agriculture, Ecosystems and Environment* 106: 313–329.

Ghosh, P. K. Tripathi, A. K., Bandyopadhyay, K. K. and Manna, M. C. (2009). Assessment of nutrient competition and nutrient requirement in soybean/sorghum intercropping system. *European Journal of Agronomy* 31: 43–50.

Gok, M. and Ottow, J. C. G. (1988). Effect of cellulose and straw incorporation in soil on total denitrification and nitrogen immobilization at initially aerobic and permanent anaerobic conditions. *Biology and Fertility of Soils* 5: 317-322.

Hauggaard-Nielsen, H., Ambus, P. and Jensen, E. S. (2003). The comparison of nitrogen use and leaching in sole cropped versus intercropped pea and barley. *Nutrient Cycling in Agroecosystems* 65: 269–300.

Hobbs, P. R. (2007). Conservation Agriculture: What Is It and Why Is It Important for Future Sustainable Food Production? *Journal of Agricultural Science* 145: 127–137.

Janz, B., Havermann, F., Lashermes, G., Zuazo, P., Engelsberger, F., Torabi, S. M. and Butterbach-Bahl, K. (2022). Effects of crop residue incorporation and properties on combined soil gaseous N2O, NO, and NH3 emissions—A laboratory-based measurement approach. *Science of the Total Environment* 807(2).

Jering, A., Klatt, A., Seven, J., Ehlers, K., Günther, J., Ostermeier, A. and Mönch, L. (2013). Sustainable use of global land and biomass resources. *Umweltbundesamt, Dessau-Roßlau*. 111pp.

Khan, S. A., Mulvaney, R. L., Ellsworth, T. R. and Boast, C. W. (2007). The myth of nitrogen fertilization for soil carbon sequestration. *Journal of Environmental Quality* 36(6): 1821-1832.

Kihara, J., Bationo, A., Waswa, B., Kimetu, J. M., Vanlauwe, B., Okeyo, J., Mukalama, J. and Martius, C. (2012). Effect of reduced tillage and mineral fertilizer application on maize and soybean productivity. *Experimental Agriculture* 48(2): 159-175.

Lal, R. (2007). Carbon management in agricultural soils. *Mitigation and Adaptation Strategies for Global Change* 12(2): 303-322.

Li, J. H., Li, F., Li, W. J., Chen, S., Abbott, L. K., Knops, J. M. H. (2018). Nitrogen additions promote decomposition of soil organic carbon in a Tibetan alpine meadow. *Soil Science Society of America Journal* 82(3): 614-622.

Li, L. J., Han, X. Z., You, M. Y., Yuan, Y. R., Ding, X. L. and Qiao, Y. F. (2013). Carbon and nitrogen mineralization patterns of two contrasting crop residues in a Mollisol: Effects of residue type and placement in soils. *European Journal of Soil Biology* 54: 1-6.

Liao, Y., Wu, W. L., Meng, F. Q., Smith, P. and Lal, R. (2015). Increase in soil organic carbon by agricultural intensification in northern China. *Biogeosciences* 12: 1403–1413.

Liu, X., Rahman, T., Song, C., Yang, F., Su, B., Cui, L., Bu, W. and Yang, W. (2018). Relationships among light distribution, radiation use efficiency and land equivalent ratio in maize-soybean strip intercropping. *Field Crops Research* 224: 91–101.

Lu, X. (2020). A meta-analysis of the effects of crop residue return on crop yields and water use efficiency. *PLoS ONE* 15(4): e0231740.

Lv, Y., Francis, C., Wu, P. T., Chen, X. L. and Zhao, X. N. (2014). Maize-soybean intercropping interactions above and below ground. *Crop Science* 54: 914-922.

Mazzilli, S. R., Armen, R. K., Oswaldo, R. E., Robert, B. J. and Gervasio, P. (2014) Priming of soil organic carbon decomposition induced by corn compared to soybean crops. *Soil Biology and Biochemistry* 75: 273 -281.

Mulvaney, R. L., Khan, S. A. and Ellsworth, T. R. (2009). Synthetic nitrogen fertilizers deplete soil nitrogen: a global dilemma for sustainable cereal production. *Journal of Environmental Quality* 38(6): 2295-2314.

Mupangwa, W., Thierfelder, C., Cheesman, S., Nyagumbo, I., Muoni, T., Mhlanga, B., Mwila, M., Sida, T. S. and Ngwira, A. (2020). Effects of maize residue and mineral nitrogen applications on maize yield in conservation agriculture-based cropping systems of Southern Africa. *Renewable Agriculture and Food Systems* 35(3): 322-335.

Naab, J. B., Mahama, G. Y., Koo, J., Jones, J. W. and Boote, K. J. (2015). Nitrogen and phosphorus fertilization with crop residue retention enhances crop productivity, soil organic carbon, and total soil nitrogen concentrations in sandy-loam soils in Ghana. *Nutrient Cycling in Agroecosystems* 102(1): 33-43.

Nelson, D. W. and Sommers, L. E. (1982). Total organic carbon. In: L. A. Page, R. H. Miller, and D. R. Keeney (Eds.) *Methods of soil analysis, Part 2* (2nd Ed.) Agronomy Monograph No. 9. American Society of Agronomy and Soil Science Society of America, Madison, WI. pp. 539-579.

Oertel, C., Matschullat, J., Zurba, K., Zimmermann, F. and Erasmi, S. (2016). Greenhouse gas emissions from soils—A review. *Geochemistry* 76(3): 327-352.

Qiu, Q., Wu, L., Ouyang, Z., Li, B., Xu, Y., Wu, S. and Gregorich, E. G. (2016). Priming effect of maize residue and urea N on soil organic matter changes with time. *Applied Soil Ecology* 100: 65-74.

Sadeghi, H. and Bahrani, M. J. (2009). Effects of crop residue and nitrogen rates on yield and yield components of two dryland wheat (*Triticum aestivum* L.) cultivars. *Plant Production Science* 12(4): 497-502.

Sakala, W. D., Cadisch, G. and Giller, K. E. (2000). Interactions between residues of maize and pigeonpea and mineral N fertilizers during decomposition and N mineralization. *Soil Biology and Biochemistry* 32: 679–688.

Shah, Z., Shah, S. H., Peoples, M. B., Schwenke, G. D. and Herriedge, D. F. (2003). Crop residue and fertilizer N effects on nitrogen fixation and yields of legume–cereal rotations and soil organic fertility. *Field Crops Research* 83: 1–11.

Shen, Y., Sui, P., Huang, J., Wang, D., Whalen, J. K. and Chen, Y. (2018). Greenhouse gas emissions from soil under maize–soybean intercrop in the North China Plain. *Nutrient Cycling in Agroecosystems* 110(3): 451- 465.

Six, J., Conant, R. T., Paul, E. A. and Paustian, K. (2002). Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant and Soil* 241: 155–176.

Smith, P., Davies, C. A., Ogle, S., Zanchi, G., Bellarby, J., Bird, N., Boddey, R. M., McNamara, N. P., Powlson, D., Cowie, A., van Noordwijk, M., Davis, S. C., Richter, D. d. B., Kryzanowski, L., van Wijk, M. T., Stuart, J., Kirton, A., Eggar, D., Newton-Cross, G., Adhya, T. K. and Braimoh, A. K. (2012). Towards an integrated global framework to assess the impacts of land use and management change on soil carbon: current capability and future vision. *Global Change Biology* 18: 2089–2101.

Tsujimoto, Y., Pedro, J. A., Boina, G., Murracama, M. V., Ito, O., Tobita, S., Oya, T., Cuambe, C. E. and Martinho, C. (2015). Performance of maize-soybean intercropping under various N application rates and soil moisture conditions in Northern Mozambique. *Plant Production Science* 18(3): 365-376.

Undie, U. L., Uwah, D. F. and Attoe, E. E. (2012). Effect of intercropping and crop arrangement on yield and productivity of late season maize/soybean mixtures in the humid environment of south southern Nigeria. *Journal of Agricultural Science* 4(4): 37-50.

Varvel, G. E. and Wilhelm, W. W. (2010). Long-term soil organic carbon as affected by tillage and cropping systems. *Soil Science Society of America Journal* 74(3): 915-921.

Wang, X., Jia, Z., Liang, L., Zhao, Y., Yang, B., Ding, R., Wang, J. and Nie, J. (2018). Changes in soil characteristics and maize yield under straw returning system in dryland farming. *Field Crops Research* 218: 11-17.

Wang, X., Wu, X., Ding, G., Yang, F., Yong, T., Wang, X. and Yang, W. (2020). Analysis of grain yield differences among soybean cultivars under maize–soybean intercropping. *Agronomy* 10(1): 110-127.

Wilhelm, W. W., Johnson, J. M., Karlen, D. L. and Lightle, D. T. (2007). Corn stover to sustain soil organic carbon further constrains biomass supply. *Agronomy Journal* 99: 1665-1667

Xie, J., Hou, Y., Yin, C., Kong, L., Qin, Y., Li, Q. and Wang, L. (2014). Effect of potassium application and straw returning on spring maize yield, nutrient absorption and soil potassium balance. *Journal of Plant Nutrition and Fertilizer* 20 (5): 1111–1119.

Xu, J., Han, H. F., Ning, T. Y., Li, Z. J. and Lal, R. (2019). Long-term effects of tillage and straw management on soil organic carbon, crop yield, and yield stability in a wheat-maize system. *Field Crop Research* 233: 33 – 40.

Yang, F., Liao, D., Wu, X., Gao, R., Fan, Y., Raza, M. A., Wang, X., Yong, T., Liu, W. and Liu, J. (2017). Effect of aboveground and belowground interactions on the intercrop yields in maize-soybean relay intercropping systems. *Field Crop Research* 203: 16–23.

CHAPTER SIX

6.0 INFLUENCE OF INORGANIC N AND RESIDUE RETENTION ON SOIL ORGANIC CARBON, NITROGEN AND AGGREGATE STABILITY IN A SOYBEAN - MAIZE ROTATION

Abstract

The objective of this study was to assess the improvement of soil organic carbon (SOC), total nitrogen (N), water extractable organic carbon (WEOC), and water stable aggregates (WSA) for three years (2017-2019). The study was done on ongoing research plots established in 2015 on the effect of management practices on grain yield properties through crop rotation and continuous monocropping under maize [*Zea mays* L.] and soybean [*Glycine max.* (L) Merr.] test crops. The experiment was laid based on a Randomized Complete Block Design (RCBD) with three replications comprising of three treatments in soybean monocropping; five treatments in rotation and two treatments in maize monocropping at different N and P fertilizer rates. Generally, there were no significant ($p < 0.05$) differences between cropping treatments on soil organic carbon (SOC), total soil nitrogen (N), water extractable organic carbon (WEOC) and water stable aggregates (WSA). There were no significant difference between treatments in soil N, however, there were increasing values of soil N in third than in first season in both Suluti and Uyole sites. The range of soil C in the Uyole site was from 1.22 % - 1.41 % in 2017 to 1.60 % – 1.94 % in 2019 indicating crop residue retention with inorganic fertilizer N was necessary to raise SOC level despite of insignificant differences between treatments. In Uyole, the CWEOC and HWEOC insignificantly increased over seasons with higher CWEOC and HWEOC values reached in the sole maize (120 kg N ha^{-1} and 20 kg P ha^{-1})

(197.16 mg C kg^{-1}) and in the inoculated soybean (295.7 mg C kg^{-1}). In the Suluti site, the CWEOC values were insignificantly higher in the third season and progressively decreasing the HWEOC values to third season. In Suluti site as well sole maize (120 kg N ha^{-1} and 20 kg P ha^{-1}) also registered higher CWEOC value of 321.3 mg kg^{-1} than all cropping systems. In both sites, Uyole and Suluti, mesoaggregates (2.00 mm - 0.5 mm) values were higher than macroaggregates (> 2.00 mm) and microaggregates (<0.250 mm). The trend showed that over time, there were decreases in distribution of macroaggregates and increase in microaggregates. Therefore, the result of this study show that maize and soybean rotation, crop residue retention and inorganic N fertilizer slowly enhances soil C and N and other soil properties and over extended time of management could intensify the results.

Keywords: Organic carbon, water-stable aggregates, water-extractable organic carbon, rotation, Uyole, Suluti

6.1 Introduction

Soil organic matter (SOM) provides an indicator of soil quality and predicts the ability of the soil to support sustainable agriculture (Janssen, 2011). The carbon (C) content in arable soils is heterogeneous, and depends on location, soil management, and soil type (Lal, 2010), among many other factors. Increasing yields and maintaining good soil attributes for sustainable production is a question of interest in the entire world (Kopittke *et al.,* 2019; Jannsen, 2011; Westrap *et al.,* 2004). After years of intensive cultivation, many soils have decreased their capacity to give high yields, and efforts for restoration of this less productive soil are continual (Kopittke *et al.,* 2019; Lal, 2010, Westrap *et al.,* 2004).

Increase in soil C sequestration through agriculture intensification and subsequent mitigation of greenhouse gases (GHG) is advocated (Di *et al.*, 2017; Lal, 2010) under conservation agriculture, no-till or minimum tillage (Chivenge *et al.*, 2006; West and Post, 2002), use of residue retention and cover crops (Wang *et al.*, 2019; Fujisaki *et al.*, 2018; Di *et al.*, 2017), crop diversification with leguminous plants (Borase *et al.*, 2020; Uzoh *et al.*, 2019) and appropriate use of inorganic fertilizer inputs (Puruwanto and Alam, 2020).

Crop rotation practices, which involve legumes increase soil C, microbial biomass C and N, and functional soil enzymes for nutrient transformation (Borase *et al.*, 2020). In addition, legumes have ability to fix nitrogen which has been found to increase soil N and crop yields of subsequent crops (Uzoh *et al.*, 2019). In terms of C sequestration potential, crop rotation can sequester up to 20 g C m^{-2} yr^{-1} (West and Post, 2002).

Residue retention increases SOC, maintains soil moisture (Iqbal *et al.*, 2013), increases soil infiltration, lowers bulk density of the soil (Chalise *et al.*, 2018), and has also been reported to increase microbial biomass (Salinas-Garcia *et al.*, 2001). For instance, the study by Wang *et al.* (2019) reported an annual C sequestration rate of 0.24 – 0.43 t C ha^{-1} yr^{-1} using wheat and rice residues, while Chalise *et al.* (2018) reported an increase of 22% of SOC and 15% of soil N in residue-amended than residue-removed soils.

However, the soil may require a balanced quality of the residues for better performance. For example, Wang *et al.* (2019) reported that wheat and rice residues increased methane and N_2O gas production, most prominent in the combined wheat and rice and wheat alone than in rice and control. Similarly, another study found an increase in CO_2-C efflux after incorporation of residues (Raiesi, 2006).

Soil stable aggregates confer structural stability of soil, reduce the vulnerability to erosion caused by rain or wind and enhance C storage (Šimanský *et al.,* 2017; Six *et al.,* 2004). Soil aggregates are formed as a function of many soil factors including soil organic matter (SOM) which is the centre for aggregation, and clay particles, carbonates, and complex ionic bridging which cement together small particles known as microaggregates (< 0.25µm) to form macroaggregates (> 250 µm) (Šimanský *et al.,* 2014; Six *et al.,* 2004; Six *et al.,* 2000). The macroaggregates are sensitive to small disturbances and may easily release attached C to re-form microaggregates (Six *et al.,* 2000; Cambadella and Elliot, 1993). Besides, macroaggregates are holding more C than microaggregates do (Šimanský and Bajcan, 2014; Šimanský *et al.,* 2017). However, different soil types have different capacities in storing the C in different aggregate sizes (Šimanský and Bajcan, 2014; Šimanský *et al.,* 2017), and soil types also determine the proportion of different aggregate sizes (Šimanský and Bajcan, 2014).

The SOM, on the other hand, is divided into C pools which are easily decomposed by microorganisms and other C pools which may be retained in the soil for some months, years, and, decades or even longer. The easily decomposed organic C pool is known as labile (biologically active) organic C fraction which is responsible for microbial biomass respiration and is an important soil management indicator (Hynes, 2005; Six *et al.,* 2002). The labile organic C fraction can be represented by water extractable organic carbon (WEOC), which is divided into that extracted by cold water (20 ^{o}C) and that by hot water (80 ^{o}C) for 16 hours (Ghani *et al.,* 2003). According Zsolnay (1996), the WEOC is the most labile and mobile organic pool, and therefore, might also mediate the transport of N and P (He and Wu, 2015). The labile organic carbon pool is primarily responsible for C stabilization of soil microaggregates within macroaggregates (Six *et al.,* 2000) in clay particles, thus it is crucial for C sequestration. In addition, Haynes *et al.* (1991) found that hot water extractable carbon is associated with the formation of macroaggregates.

Similarly, Šimanský and Bajcan (2014) pointed out that hot water extractable carbon is found mostly in higher aggregate sizes as a result of root C exudation and microbial bioproducts. Other studies have shown that this labile C is sensitive to land management practices such that changing forest and pasture to agriculture activities have reduced both CWEOC and HWEOC (Geraei *et al.*, 2016). The CWEOC was reduced from 108 to 44.4 mg kg^{-1} in conversion of forest and from 73 to 23 mg kg^{-1} from pasture to food crop agriculture, respectively (Geraei *et al.*, 2016). Meanwhile, the HWEOC was reduced from 933 to 276 mg kg^{-1} and from 497 to 244 mg kg^{-1} in the conversion of forest and pasture to agriculture activities, respectively (Geraei *et al.*, 2016).

The aim of this research was to study the contribution of plant biomass retention and inorganic N application in the soybean- maize rotation in enhancing soil organic C, N, WEOC and water stable aggregate size distribution. The research was done from a five years experiment designed to study long term changes in crop yields associated with soil management.

6.2 Materials and Methods

6.2.1 Description of study site

Mbeya is one of the regions of Tanzania, well known for agriculture activities and as the leading maize producer. Mbeya is located southwest of Tanzania and lies between longitude 32° 01' 00" E and 35° 01' 00" E, and latitude 6° 52' 00"S and 9° 41' 00" S. The region is bordered to the south by newly formed region of Songwe and the neighbouring country of Malawi, to the east by Iringa region; northwest and northeast by Tabora and

Singida regions respectively; it is also bordered by Lake Nyasa to south east. The region has a total land area of 35,954 square kilometres. It is comprised of 7 districts: Busokelo, Kyela, Mbarali, Rungwe, Mbeya City, Chunya, and Mbeya Rural.

The region is characterized by having a subtropical highland climate with humid summers and dry winters, and is dominated by high-mountains (Loleza and Rungwe Mountains) reaching the altitude sof 1,700 up to 2,960 m.a.s.l. The region is characterized by high average annual rainfall reaching 1,731.9 mm, a unimodal pattern of rain distribution starting late-November to April and sometimes to early May. The average annual minimum and maximum temperatures are 12.6 and 24.7 ^{o}C, respectively. Research plots at ARI – Uyole on the outskirts of Mbeya city, was located at latitude 08° 54′ 4″ S and 08° 56′ 7″ S and 033° 30′ 11″ E and 033° 32′ 28″ E, the altitude being 1779 m.a.s.l, with the soils at the research site classified as Inceptisols.

Ruvuma region is located between longitude 34° 34' 00" E and 38° 04' 00" E and between latitude 9°11'00" S and 11°45'00"S in the southwestern part of Tanzania it is bordered to the east by Mtwara Region, to the north by Morogoro, to the northeast by Lindi Region and Njombe to the northwest. The region is the fifth largest in Tanzania and has five districts known as Mbinga, Songea, Nyasa, Namtumbo and Tunduru, having a total land area of 63,669 square kilometres. Rainfall is of a unimodal pattern starting from December to April, with an average annual rainfall of 1,039.0 mm. The average annual minimum and maximum temperatures are 14.9 and 27.2 ^{o}C, respectively.

The-Suluti site located at latitude 10^{o} 34′ 32″ S and 10^{o} 35′ 2″ and longitude 036° 7′ 36″ E and 036° 8′ 3″ E in Ruvuma region, within Namtumbo district. The site has an average annual rainfall of 1039 mm in a unimodal pattern between December and April.

6.2.2 Treatment details and experimental design

This research was undertaken in Uyole (Mbeya) and Suluti (Ruvuma) in 2017 in the ongoing research plots established in 2015 (N2ARFICA Project) located in Uyole (Mbeya) and Suluti (Ruvuma) to study yield changes following different soil/crop management practices.

The present study was designed to follow the trends of C, N, WEOC, and WSA of the soil resulting from maize and soybean rotation under residues retention and different rates of inorganic N. The research commenced in 2017 and involved ten (10) treatments, comprised of three treatments of continuous soybean with no N fertilizer amendments, two treatments of continuous maize, and five soybean- maize rotations under different N and P levels. All crop residues after harvesting were left on their original plots until the next season. The quantity of residue remaining was set as new treatment for the next season. Before planting for the next season, the plot area was ploughed and harrowed by tractor.

The experiment was laid out in the randomized complete block design (RCBD), with three replications. Plot sizes were 25 square metres (5 m x 5 m). The details of the ten treatments are shown in Table 6.1. The data for three years were collected from 2017-2019, regarding the 2017 season as season one, 2018 as season two and 2019 as season three.

6.2.3 Soil sample collection

Soil samples were collected after crop harvesting time; the soil samples were randomly collected diagonally at 5 different spots in each plot from the 0 - 30 cm depth for soil aggregate (physical) and chemical analysis.

Table 6.1: Treatment details and cropping sequence from 2015-2019

Treatments	Treatments details	Crop sequence 2015	2016	2017 Season 1	2018 Season 2	2019 Season 3
SB-SL	Sole soybean- No input	Soybean	Soybean	Soybean	Soybean	Soybean
SB – (INC)	Sole soybean : only rhizobial inoculant	Soybean	Soybean	Soybean	Soybean	Soybean
SB – (INC+ P)	Sole soybean : inoculants and P fertilizer	Soybean	Soybean	Soybean	Soybean	Soybean
(**MZ / SB - P+INC)**	Maize and soybean rotation : P on soybean and inoculant; no input	Soybean	Maize	Soybean	Maize	Soybean
(MZ (½N&P) / SB (P+INC)	Maize and soybean rotation : P on soybean and inoculant; half dose of N and P	Soybean	Maize	Soybean	Maize	Soybean
(MZ(P+ ½ N) / SB (P+INC)	Maize and soybean rotation : P on soybean and inoculant; full dose of P and half N	Soybean	Maize	Soybean	Maize	Soybean
(**MZ(P+N) / SB (P+INC)**	Maize and soybean rotation : P on soybean and inoculant; full dose of P and N	Soybean	Maize	Soybean	Maize	Soybean
(MZ(Rec. Inpt) / SB (INC)	Maize and soybean rotation : recommended input on maize; only inoculant in soyabean	Maize	Soybean	Maize	Soybean	Maize
(MZ-SL - no Inpt)	Sole maize : no input	Maize	Maize	Maize	Maize	Maize
(MZ-SL – Rec. Inpt)	Sole maize : recommended input maize	Maize	Maize	Maize	Maize	Maize

NB: The full dose and recommended input was 120 kg N ha^{-1} and 20 kg P ha^{-1}, while the half dose was 60 kg N ha^{-1} and 10 kg P ha^{-1}, respectively.The surface soil was first cleaned of plant debris and other residues and the sampling was done. Samples were packed and carefully transported to ensure no disturbances of soil aggregates from field to laboratory. The soil samples were air-dried for aggregate stability tests. For soil chemical analysis, the moist soil samples were air-dried for three days and subsequently passed through a 2 mm sieve

6.2.4 Soil sample analysis

6.2.4.1 Soil organic carbon and nitrogen

The method for soil organic carbon and nitrogen was explained in detail section 3.2.4.1 and 3.2.4.2.

6.2.4.2 Water extractable organic carbon and water stable aggregates

The methods for water extractable organic carbon and water stable aggregates were explained in detail section 4.2.3.2 and 4.2.3.3.

6.2.5 Statistical data analysis

Treatment data were subjected to analysis of variance (ANOVA) using GENSTAT 15th Edition Statistical Packages. When significance at $p < 0.05$ was found, means were compared using Duncan Multiple Range Test (DMRT) at $p < 0.05$.

6.3 Results and Discussion

6.3.1 Effects of inorganic N and residue retention on total soil nitrogen

The results for total soil nitrogen in Uyole and Suluti sites are presented in Table 6.2.

6.3.1.1 Soil N in soybean monocropping

The soybean monocropping system in Uyole site showed no significant ($p < 0.05$) differences in N between different treatments (Table 6.2).

Table 6.2: Influence of inorganic fertilizer and biomass residue retention on soil N at Uyole and Suluti

		Nitrogen (%)					
Cropping system	**Treatment**	**Uyole**			**Suluti**		
		Season1	**Season2**	**Season3**	**Season1**	**Season2**	**Season3**
Soybean monocropping	SB-SL	0.124	0.117	0.149	0.054	0.082	0.081
	SB (INC)	0.133	0.128	0.142	0.058	0.079	0.093
	SB (INC+ P)	0.149	0.124	0.138	0.061	0.082	0.090
Maize and Soybean rotation	MZ/SB(P+INC)	0.138	0.124	0.149	0.061	0.084	0.086
	MZ (½ N&P)/SB (P+INC)	0.131	0.121	0.149	0.054	0.086	0.089
	MZ(P+ ½N)/SB (P+INC)	0.131	0.128	0.145	0.056	0.091	0.083
	MZ(P+N)/SB (P+INC)	0.147	0.124	0.145	0.056	0.089	0.088
	MZ(Recc Inpt)/SB (INC)	0.133	0.124	0.149	0.058	0.082	0.081
Maize monocropping	MZ-SL (No inpt)	0.128	0.126	0.145	0.056	0.074	0.090
	MZ-SL (Recc Inpt)	0.133	0.124	0.145	0.058	0.090	0.092
		NS	NS	NS	NS	NS	NS

NS= not significant at $p \leq 0.05$

Only numerical differences were observed in which N was slightly higher in SB (INC+ P) > SB (INC) > SB-SL in season 1 while this trend was reversed in the third season. The range of soil N was 0.124 % - 0.149 %, 0.117 % - 0.128 %, 0.138 - 0.149 % in the first, second, and third seasons, respectively.

In the Suluti site (Table 6.2) there were no significant ($p < 0.05$) differences in soil N between the soybean monocropping treatments in all three seasons, as in Uyole. The range of soil N in the first, second and third seasons were 0.054 % - 0.061 % < 0.079 % - 0.082 % < 0.081 % - 0.093 %, respectively, indicating some soil N increment over the seasons.

Soybean residue has a narrow C:N ratio (Casado-Murillo and Abrill, 2013; Li *et al.,* 2013) whereby the residues immediately decompose to mineralize N (Parton *et al.,* 2007). Therefore, it is probable that the soybean residues decomposed to release available N (Li *et al.,* 2013; Raesi, 2006), thereby, the residues improving soil N content and soil fertility status (Li *et al.,* 2013; Raesi, 2006) over the seasons.

6.3.1.2 Soil N in monocropping of maize

There were no significant ($p < 0.05$) differences between MZ-SL (Recc. Inpt) and MZ-SL (No Inpt) within three seasons in Uyole. The plot with fertilizer N could not have hastened decomposition of maize residue to enhance significant addition of soil N than plot with crop residue without fertilizer N. It appears that when soil was amended with crop residues of wide C:N ratio like those of maize, the soil microbes decomposed more of the soil N to meet their N demands (Hall *et al.,* 2019; Parton *et al.,* 2007) which consume soil nitrogen.

Addition of inorganic N fertilizer in MZ-SL (Recc Inpt) was expected to suppress mineralization of soil N by providing a ready source of N (Mahal *et al.*, 2019). According to Mulvaney *et al.* (2009), inorganic N leads to a decline soil N in the surface and the subsurface soils. The applied fertilizer could also have been used mainly for maize development due to its high demand (Cassman *et al.,* 2002) with very little, if any residual N supporting decomposition of the maize residue. Hence, total N could not be significantly increased in the plot that received maize residues and inorganic N as seen in Table 6.2.

6.3.1.3 Soil N in the rotation of maize and soybean crops

The soil N in the maize and soybean rotation in Uyole site (Table 6.2) did not have significant ($p < 0.05$) differences between treatments. The range of soil N was 0.131% - 0.147% in the first season decreasing to 0.121% - 0.128% in the second season. The reasons for decline in soil N in season 2 could be due to decomposition of soybean residues at a faster rate in the rotation (Hall *et al.*, 2019; Casado - Murillo and Abrill, 2013) coupled with a high maize crop demand for N (Cassman *et al.*, 2002).

The Suluti site recorded no significant ($p < 0.05$) differences between rotation treatments in each season (Table 6.2). Yet, there seems to be prospects of soil N increase over time as soil N tended to increase from first to third seasons (in the range of 0.131% - 0.147% to 0.145% - 0.149% in Uyole and 0.054% - 0.061% and 0.081% - 0.089%) in Suluti, respectively.

6.3.2 Effects of inorganic N and residue retention on soil organic carbon

The results for total soil organic carbon in Uyole and Suluti sites are presented in Table 6.3.

6.3.2.1 SOC in soybean monocropping

The Uyole soybean monocropping in un-inoculated with rhizobia (SB-SL), the inoculated (SB (INC)) and the inoculated plus phosphorus (P) fertilizer (SB (INC+P)) showed no statistical significant ($p < 0.05$) differences in SOC (Table 6.3) in the three seasons. In Uyole the range of SOC was 1.22 % to 1.40 % in the first season and appreciably higher in the second season (1.83 % - 1.96 %) and reduced in third season (1.64 % – 1.60 %).

Table 6.3: Effects of maize and soybean rotation and inorganic N fertilization, and crop residue retention on SOC in Uyole and Suluti

Cropping system	Treatments	Organic C (%)					
		Uyole			Suluti		
		Season1	Season2	Season3	Season1	Season2	Season3
Soybean monocropping	SB-SL	1.36	1.83	1.64	0.80	1.01	0.75
	SB (INC)	1.22	1.96	1.60	0.71	0.88	0.79
	SB (INC+ P)	1.40	1.84	1.63	0.76	0.98	0.80
Maize and	MZ/SB(P+INC)	1.27	1.91	1.67	0.78	0.83	0.82

Soybean rotation	MZ (½ N&P)/SB (P+INC)	1.39	1.81	1.86	0.81	0.92	0.80
	MZ(P+ ½N)/SB (P+INC)	1.41	1.99	1.94	0.73	0.82	0.72
	MZ(P+N)/SB (P+INC)	1.30	1.86	1.58	0.80	1.01	0.79
	MZ(Recc Inpt)/SB (INC)	1.27	1.85	1.60	0.74	0.87	0.76
Maize monocropping	MZ-SL (No inpt)	1.29	1.90	1.65	0.85	0.86	0.80
	MZ-SL (Recc Inpt)	1.38	1.91	1.61	0.78	0.87	0.74
		NS	NS	NS	NS	NS	NS

NS= not significant at $p \leq 0.05$

Suluti site showed similar trend as in Uyole, with no significant ($p < 0.05$) differences between soybean monocropping treatments in each season. In both sites the SOC increased somewhat in the second season and declined in the third season. Decline in SOC in the soybean in continuous monocropping was also observed by Dou *et al*. (2007). According to Cong *et al.* (2015b) the observed decline could be caused by SOM decomposition due to lower recalcitrance of SOM from the additional biomass residue into the soil, in which the rejuvenated SOM and young labile C were quickly consumed by soil microbes. In addition, the smallest amount of soybean residue input as compared to maize crop residue from continuous soybean could be reason for low SOC in the soybean monocropping system (Dou *et al.*, 2007).

6.3.2.2 SOC in maize monocropping

The results for maize monocropping in Uyole showed no significant ($p < 0.05$) differences in SOC between the two treatments. There were only insignificant differences observed in all seasons between monocropped maize (Table 6.3). Meanwhile, the SOC trends show more SOC in the second season which was 1.9 % in both treatments from 1.3 % of the first season (Table 6.3). Li *et al.* (2020) also reported an increase in SOC by straw return alone, reaching 0.13 Mg C ha^{-1} yr^{-1} but 0.51 Mg C ha^{-1} yr^{-1}, due to the effect of inorganic fertilizer N in plots which had more than 8 years and higher fertilization rate.

The SOC showed a decreased trend from 1.9% in the second season to 1.6 % in third season. The observed decrease in SOC can be due to the addition of maize biomass which results to soil C decomposition (Soil C priming) (Qiu *et al.,* 2016). Hall *et al.* (2019) and Kaleeem *et al.* (2015) observed a loss up to 140% and 67 %, respectively, of soil C under maize residue addition. Another study by Poffenbarger *et al.* (2017) reported decline in SOC in the continuous corn system without N fertilizer application.

No significant ($p < 0.05$) difference was observed between maize monocropped treatments in the Suluti as well. Very negligible differences were measured in the MZ-SL (No Inpt) between three years, while MZ-SL (Rec Inpt) registered SOC loss by 14.81% in third season from second season's SOC.

6.3.2.3 SOC in the rotation of maize and soybean

The maize and soybean rotation plots in the Uyole and Suluti sites with different N rates in showed no significant ($p < 0.05$) SOC differences (Table 6.3). Although all treatments showed insignificant differences in SOC, these treatments in the maize soybean rotation showed a trend of slight SOC increase in the second and decreased in the third season. For example, in the Uyole site (Table 6.3) the MZ(P + ½N)/SB (P+INC) and MZ (½ N&P)/SB (P+INC treatments (half dose of N) the SOC values were increased in the second season and maintained/increased in third season compared to MZ(P+N)/SB (P+INC) and MZ(Recc Inpt)/SB (INC) which declined their SOC values in the third season.

Poffenbarger *et al.* (2017) observed significant SOC in the 0-15 cm; despite using recommended nitrogen rate in the MZ(P+N)/SB (P+INC) and /or MZ(Recc Inpt)/SB (INC) treatments the significant SOC increments was not established in the corn-soybean rotation. Nonetheless, the moderate N rate was important to raise the SOC values in Uyole which was also observed by Mahal *et al.* (2019).

Liu *et al.* (2014) reported in their meta-analysis study that saturation of SOC may occur after 12 years of continuous straw amendment. Hence, in the current case, more time will be needed to achieve the substantial amount of SOC in Uyole and Suluti sites through maize and soybean rotation.

6.3.3 Water extractable organic carbon

The results for water extractable organic carbon (WEOC) in Uyole and Suluti are presented in Table 6.4. The WEOC is a small fraction of the total OC but it is an important source of energy for soil microbes which drives soil biogeochemical cycle (Fiedler *et al.*, 2015).

6.3.3.1 Cold and Hot water extractable organic carbon in monocropping of soybean

Generally, there were no significant ($p < 0.05$) differences in CWEOC and HWEOC within soybean monocropping, within maize and soybean rotation, or within maize monocropping. Insignificant ($p < 0.05$) differences in CWEOC between soybean monocropping treatments were observed in the season1 (65.5 - 68.61 mg C kg^{-1}) followed by season two by 76.98 – 89.91 mg C kg^{-1}, and higher (98.58 - 135.55 mg C kg^{-1}) in the third season, showing progressively increasing trend in CWEOC over the years in Uyole. Therefore, the soil in the Uyole site quickly responded positively (Hynes, 2005) from the impact of residue incorporation. Decomposition of residue from soil microbes or SOC added labile (WEOC) carbon in soil (Zhao *et al.*, 2008).

The HWEOC in the Uyole site showed a somewhat increasing trend with seasons in all three treatments and more pronounced in the SB (INC) reaching maximum of 295.7 mg C kg^{-1}, two times and 1.85 higher than SB-SL and SB (INC+ P) treatments, respectively. The value was higher than in maize monocropping and the rotation system. In the Suluti site, the CWEOC trend was appreciably higher in the third season and maximum in SB (INC) with 167.3 mg C kg^{-1}. The HWEOC were 143.87 – 110.28 mg C kg^{-1}, 140.88- 76.85 mg C kg^{-1}, and 102.46 - 51.23 mg C kg^{-1}, respectively, in first, second and third seasons. Unlike in Uyole, the Suluti site showed progressively decreasing HWEOC values with time/ seasons.

Table 6.4: Cold water extractable organic carbon (CWEOC) and hot water extractable organic carbon (HWEOC) in maize and soybean rotation

Cropping system	Treatment	UYOLE						SULUTI					
		CWEOC			HWEOC			CWEOC			HWEOC		
		mg C kg^{-1}						mg C kg^{-1}					
		Season1	Season2	Season3	Season1	Season2	Season3	Season1	Season2	Season3	Season1	Season2	Season3
Soybean monocropping	SB-SL	68.61	89.91	98.58	76.10	103.0	147.9	127.2	89.7	128.7	110.28	102.46	102.46
	SB (INC)	65.5	89.78	135.55	46.30	77.2	295.7	93	76.8	167.3	143.87	76.85	64.04
	SB (INC+ P)	66.24	76.98	98.58	103.30	115.8	160.2	75.2	76.8	115.8	124.95	140.88	51.23
Maize and soybean rotation	MZ/SB(P+INC)	83.75	76.98	123.22	105.80	90.1	221.8	149.4	51.2	154.5	129.38	115.27	64.04
	MZ (½ N&P)/SB (P+INC)	48.52	89.72	123.22	81.70	128.7	110.9	74.7	115.3	193.1	103.62	115.27	38.42
	MZ(P+ ½N)/SB (P+INC)	49.37	64.10	123.22	73.40	103.0	123.2	104.7	89.7	167.3	114.26	140.89	38.42
	MZ(P+N)/SB (P+INC)	128.57	102.72	160.19	108.0	115.8	160.2	113.9	76.8	141.6	74.54	89.66	76.85
	MZ(Recc Inpt)/SB (INC)	92.19	115.46	110.90	98.0	128.7	123.2	135.6	89.7	128.7	84.06	102.46	76.85
Maize monocropping	MZ-SL (No inpt)	76.55	128.27	135.55	57.2	90.1	135.5	161.7	89.7	128.7	140.75	102.46	76.85
	MZ-SL (Recc Inpt)	67.13	89.91	197.16	63.3	64.4	147.9	116.5	89.7	321.3	101.61	115.27	38.42
		NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

NS= not significant at $p \leq 0.05$

The variation in WEOC from both sites could be due to the fact that WEOC from under residue usually degraded quite fast in the soil (Chantigny, 2003). Similar to that, other studies reported that in less than 24 hours soil microbes can assimilate the dissolved organic carbon soon after they are released from organic substrates in soils (Eilers *et al.*, 2010; Gregorich *et al.*, 2003).

Another reason for WEOC variations in Suluti and Uyole under soybean monocropping (Table 6.4) could be due to different biodegradability of soybean residue C. Kaboneka *et al.* (1997) reported that one half and one third of soybean residue were decomposed in different soils in three days. Referred to as rapid decomposition, this was a result of quick microbial consumption of water soluble C among other readily available C compounds.

6.3.3.2 Cold and Hot water extractable organic carbon in maize monocropping

The Uyole site showed progressive increased trends of both CWEOC and HWEOC from first to third seasons. The MZ-SL (No Input) had insignificantly ($p < 0.05$) higher CWEOC values in the first and second seasons, however, the MZ-SL (Recc Input) had 61.61 mg C kg^{-1} slightly higher CWEOC than the MZ-SL (No Input), and slightly higher CWEOC value (197.16 mg C kg^{-1}) than all cropping systems in the third season. The HWEOC in third season was higher in the MZ-SL (Recc Input) in the Uyole (147.9 mg C kg^{-1}) than MZ-SL (No Input).

In Suluti site as well the MZ-SL (Recc Inpt) also registered slightly higher but insignificant ($p < 0.05$) CWEOC value of 321.3 mg kg^{-1} than all cropping systems. Other studies also reported increase in WEOC by amending soils with inorganic N fertilizer (Gong *et al.*, 2009). The inorganic fertilizer reduced C: N ratio of the residue input and induced quick residue decomposition (Li *et al.*, 2018) to release and increase soil WEOC.

Contradicting results on negative effect of inorganic N fertilizer on WEOC concentration were reported in other studies by Li *et al.* (2020), Xu *et al.* (2013) and Coulter *et al.* (2009). Their study correspond to the results for HWEOC decline as in Suluti (Table 6.4), higher in the MZ-SL (Recc Input) (115.27 mg C kg^{-1} to 38.42 mg C kg^{-1}) as compared to a slight decline in the MZ-SL (No Input) (102.46 mg C kg^{-1} to 76.85 mg C kg^{-1}) in the third season. Besides, continuous maize appeared to lessen the WEOC (Grebliunas *et al.*, 2016), which, according to Gregorich *et al.* (2002), the maize cropped land contains readily decomposable fractions due to its high hydrophilic labile N rich compounds.

Grebliunas *et al.* (2016) and Qualls and Haines (1992) reported that source of variations of WEOC observed in different soils are also caused by their leaching to lower soil horizon and soil underground water soon after they are released from organic sources. This implies that acquiring significant WEOC - C between treatments in both soils of Uyole and Suluti sites will take longer time as it need simultaneous SOM addition. The stabilization of SOC as proposed in the study by Zhao *et al.* (2008) is reflected by low consumption of WEOC.

6.3.3.3 Cold and Hot water extractable organic carbon in the rotation of maize and soybean

All rotation plots in Uyole insignificantly ($p < 0.05$) increased their CWEOC values in third season (Table 6.4). The maize- soybean treatments under half N dose in Uyole progressively increased their CWEOC contents in all season while treatments under full dose of fertilizer (MZ(P+N)/SB (P+INC) attained highest CWEOC value in the first (128.57 mg C kg^{-1}) and third (160.19 mg C kg^{-1}) seasons. In Suluti site except in one treatment, other treatments increased their CWEOC values in third season as well. Results are in agreement with Yan *et al.* (2016) and Embacher *at al.* (2008) who elaborated that residue and fertilizer have positive impact on amount and on the quality of the WEOC.

Decrease in CWEOC value in some treatments in the second season could be due to loss of WEOC which are caused by microbial activities as microbes rapidly immobilize labile C as they are produced (Grebliunas *et al.,* 2016; Fang *et al.*, 2014; Yuste *et al.,* 2007) if they are not infiltrate to lower horizons or stabilized in the soil aggregates.

The variations which were observed among treatments could have been further intensified by biodegradability of WEOC (Gregorich *at al.,* 2003) and differences in recalcitrance from a less humified and younger CWEOC-C resulting from amendment of N fertilizer and residues (Yan *et al*., 2016), which were quickly consumed by microbes and/ adsorbed on mineral surfaces (Kaiser and Zech, 1998).

The HWEOC in Uyole accounted for no significant ($p < 0.05$) difference between rotation treatments. The range for HWEOC in Uyole was 73.4 - 108 mg C kg^{-1} in first season, 90.1 - 128.7 mg C kg^{-1} in second season and 110 - 221.8 mg C kg^{-1} in third season, increasing over season simultaneously. Nevertheless, in Suluti site, HWEOC sharply decreased in the third season in all treatments and mostly in the MZ (P+ ½N)/SB (P+INC), losing 102.47 mg C kg^{-1}in the second season to only retain 38.42 mg C kg^{-1}. The loss in HWEOC can be ascribed to its higher biodegradability (Gregorich *et al.,* 2003) in which addition of N source increased the chance for WEOC microbial consumption (Li *et al.,* 2018; Mazzarino *et al.,* 1993).

6.3.4 Effect of residue incorporation and different N levels on water stable aggregate size distribution

Generally it was shown in the Suluti and Uyole sites that the proportion of mesoaggregates (2.00 mm – 0.5 mm) was slightly higher than the macroaggregates (>2.00 mm) and microaggregates (<0.250 mm) in all three seasons in the soybean monocropping (Tables 6.5; Tables 6.6; Tables 6.7).

Table 6.5: Effect of cropping system on distribution of aggregate sizes under N and biomass addition in three years in Suluti

Season	Aggregate types	Treatments									
		Soybean Monocropping			Maize and soybean rotation					Maize monocropping	
		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
			%				%			%	
Season 1	Macroaggregates	34.61	28.63	30.61	28.42 a	33.64	24.27 a	20.73	32.59	26.80	19.67
	Mesoaggregates	45.08	48.87	47.79	46.98 b	42.87	53.12 b	56.21	36.68	47.34	55.99
	Microaggregates	20.31	22.51	21.60	24.60 a	23.48	22.61 a	23.06	30.73	25.86	24.34
	s.e.m	NS	NS	NS	4.41	NS	2.9	NS	NS	NS	NS
	cv%				22.9		15				
Season 2	Macroaggregates	17.52 a	16.17 a	26.74	32.10	24.81	8.84 a	24.96	30.30	18.14 a	9.80 a
	Mesoaggregates	58.51 b	55.14 b	45.63	38.46	50.72	53.13 b	39.03	35.85	47.96 b	41.68 b
	Microaggregates	23.97 a	28.69 a	27.63	29.45	24.47	38.02 b	36.01	33.84	33.90 ab	48.53 b
	s.e.m	4.18	6.05	NS	NS	NS	5.85	NS	NS	6.2	5.88
	cv%	21.7	31.4				30.4			24.6	30.5
Season 3	Macroaggregates	11.72 a	25.86	21.12	20.47	15.42 a	13.85 a	16.63 a	29.12	27.63	29.27
	Mesoaggregates	61.98 b	47.61	58.71	44.55	53.81 b	52.10 b	51.45 b	34.83	40.33	41.68
	Microaggregates	26.30 a	26.52	20.17	34.98	30.77 a	34.04 ab	31.92 a	36.05	32.05	29.06
	s.e.m	4	NS	NS	NS	5.31	7.03	3.9	NS	NS	NS
	cv%	20.7				27.6	36.5	20.6			

Means within a column in each treatment followed by the different letter(s) are significantly different at $p \leq 0.05$ according to New DMRT
NS= not significant at $p \leq 0.05$

T1=SB-SL, T2=SB (INC), T3= MZ/SB(P+INC), T4=MZ (½ N&P)/SB (P+INC), T5= MZ(P+ ½N)/SB (P+INC), T6=MZ(P+N)/SB (P+INC), T7=MZ(Recc Inpt)/SB (INC), T8=MZ(Recc Inpt)/SB (INC), T9=MZ-SL (No inpt), T10=MZ-SL (Recc Inpt)

Table 6.6: Aggregate size distribution under N and biomass addition for three seasons in Suluti and Uyole

Season	**Treatments**	**Suluti**			**Uyole**		
		Aggregate sizes (%)			**Aggregate sizes (%)**		
		Macroaggregates	Mesoaggregates	Microaggregates	Macroaggregates	Mesoaggregates	Microaggregates
Season1	SB-SL	34.61	45.08	20.31	27.39	51.48	21.14
	SB (INC)	28.63	48.87	22.51	31.09	46.07	22.84
	SB (INC+ P)	30.61	47.79	21.60	32.53	44.7	22.77
	MZ/SB(P+INC)	28.42	46.98	24.60	32.74	48.79	18.47
	MZ (½ N&P)/SB (P+INC)	33.64	42.87	23.48	31.36	45.83	22.81
	MZ(P+ ½N)/SB (P+INC)	24.27	53.12	22.61	38.82	42.74	18.45
	MZ(P+N)/SB (P+INC)	20.73	56.21	23.06	34.31	45.23	20.46
	MZ(Recc Inpt)/SB (INC)	32.59	36.68	30.73	29.62	50	20.37
	MZ-SL (No inpt)	26.8	47.34	25.86	31.9	45.66	22.44
	MZ-SL (Recc Inpt)	19.67	55.99	24.34	23.41	51.06	25.53
		NS	NS	NS	NS	NS	NS
Season2	SB-SL	17.52	58.51	23.97	20.05	47.8	32.15
	SB (INC)	16.17	55.14	28.69	26.67	36.93	36.4
	SB (INC+ P)	26.74	45.63	27.63	20.45	40.07	39.49
	MZ/SB(P+INC)	32.10	38.46	29.45	32.4	36.08	31.52
	MZ (½ N&P)/SB (P+INC)	24.81	50.72	24.47	32.54	38.31	29.15
	MZ(P+ ½N)/SB (P+INC)	8.84	53.13	38.02	38.71	33.04	28.24
	MZ(P+N)/SB (P+INC)	24.96	39.03	36.01	25.09	43.3	31.6
	MZ(Recc Inpt)/SB (INC)	9.80	41.68	48.53	20.02	48.98	30.99
	MZ-SL (No inpt)	30.30	35.85	33.84	39.26	34.77	25.97
	MZ-SL (Recc Inpt)	18.14	47.96	33.90	28.66	36.38	34.96
		NS	NS	NS	NS	NS	NS
Season3	SB-SL	11.72	61.98	26.30	23.1	44.84	32.06
	SB (INC)	25.86	47.61	26.52	18.64	51.66	29.7
	SB (INC+ P)	21.12	58.71	20.17	19.35	51.04	29.62
	MZ/SB(P+INC)	20.47	44.55	34.98	29.99	48.45	26.02

MZ (½ N&P)/SB (P+INC)	15.42	53.81	30.77	23.59	56.24	20.17
MZ(P+ ½N)/SB (P+INC)	13.85	52.10	34.04	16.82	53.06	30.11
MZ(P+N)/SB (P+INC)	16.63	51.45	31.92	18.48	53.46	28.06
MZ(Recc Inpt)/SB (INC)	29.27	41.68	29.06	25.85	47.9	26.25
MZ-SL (No inpt)	34.83	29.20	36.85	15.91	51.69	29.65
MZ-SL (Recc Inpt)	27.63	40.33	32.05	21.64	47.98	30.38
	NS	NS	NS	NS	NS	NS

NS= not significant at p≤0.05

Table 6.7: Effect of cropping system on distribution of aggregate sizes under N and biomass addition in three years in Uyole

Season	Aggregate sizes	Treatments									
		Soybean Monocropping			Maize and soybean rotation					Maize monocropping	
		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
			%				%				%
	Macroaggregates	27.39 a	31.09 a	32.53 ab	32.74	31.36	38.82	34.31	31.90	23.41 a	29.62 b
Season 1	Mesoaggregates	51.48 b	46.07 b	44.70 b	48.79	45.83	42.74	45.23	45.66	51.06 b	50.00 c
	Microaggregates	21.14 a	22.84 a	22.77 a	18.47	22.81	18.45	20.46	22.44	25.53 a	20.37 a
	s.e.m	7.79	4.88	4.67	NS	NS	NS	NS	NS	5.8	2.05
	cv%	28.6	17.9	17.2						19.4	7.5
	Macroaggregates	20.05 a	26.67	20.45	32.40	32.54	38.71	25.09	39.26	28.66	20.02 a
Season 2	Mesoaggregates	47.80 b	36.93	40.07	36.08	38.31	33.04	43.30	34.77	36.38	48.98 c
	Microaggregates	32.15 a	36.40	39.49	31.52	29.15	28.24	31.60	25.97	34.96	30.99 b
	s.e.m	18.3	NS	NS	NS	NS	NS	NS	NS	NS	2.53
	cv%	4.98									9.3
Season 3	Macroaggregates	23.10	18.64	19.35 a	29.99 a	23.59 a	16.82	18.48 a	15.91 a	21.64 a	25.85

Mesoaggregates	44.84	51.66	51.04 b	48.45 b	56.24 b	53.06	53.46 b	51.69 c	47.98 b	47.90
Microaggregates	32.06	29.70	29.62 a	26.02 a	20.17 a	30.11	28.06 a	29.65 b	30.38 ab	26.25
s.e.m	NS	NS	5.63	5	4.36	NS	6.47	3.1	6.73	NS
cv%			20.7	17.6	16		23.8	11.7	24.7	

Means within a column in each treatment followed by the different letter(s) are significantly different at $p \leq 0.05$ according to New DMRT

NS= not significant at p≤0.05, T1=SB-SL, T2=SB (INC), T3= MZ/SB(P+INC), T4=MZ (½ N&P)/SB (P+INC), T5= MZ(P+ ½N)/SB (P+INC), T6=MZ(P+N)/SB (P+INC), T7=MZ(Recc Inpt)/SB (INC), T8=MZ(Recc Inpt)/SB (INC), T9=MZ-SL (No inpt), T10=MZ-SL (Recc Inpt)

The macroaggregates proportion generally decreased from season to season, the breakdown resulted in higher values of microaggregates as also reported by Six *et al.* (2000). Under continuous soybean, soil decreases aggregate stabilization due to loss in other soil attributes like SOC and SON (Nouwakpo *et al.,* 2018; Zuber *et al.,* 2015; Bathke and Blake, 1984).

The decrease in macroaggregates was as well caused by soil disturbances (Al-Kaisi *et al.,* 2014; Six *et al.,* 2000; Cambadella and Elliot, 1993) during land preparation, or enhanced microbial decomposition of young labile C of soybean residues occluded in the large aggregates sizes. The fast decomposition of soybean residue increases easily decomposable components (Stewart *et al.,* 2015), eventually cause fast consumption of SOM which is an important soil aggregates binding agent (Al-Kaisi *et al.,* 2014). In the maize rotation, same as in soybean monocropping the trend was such that the macroaggregates decreased over time/season and thus increased values of mesoaggregates and microaggregates (Table 6.6).

The immediate breakdown of soil aggregates due to soybean residues amendment which have narrow C:N and low lignin levels, is due to low recalcitrance and hence hastens soybean C decomposition by soil microorganisms. In this way little residue remain over time (Stewart *et al.,* 2015; Abril *et al.,* 2013). More on to recalcitrance, the inorganic N fertilizer may also act as a dispersing agent to soil clay (Haynes and Naidu, 1998), and together with soybean residues facilitate quick decomposition of soybean residues resulting to lower SOC and less aggregate stability (Zuber *et al.,* 2015; Coulter *et al.,* 2009).

The macroaggregates decreased in the second season but slightly increased in the third season in the maize monocropping in Suluti consequently resulted in decline of microaggregates from 48.53% in season 2 to 29.02% in season 3 in the MZ-SL (Recc Inpt). In the Uyole site the macroaggregates increased in the MZ-SL (Recc Inpt) in seasons 2 to 3 from 20.02% to 25.85% reducing the microaggregates proportion as indication of aggregate stabilization, and storage of SOC in soil aggregate fractions (Al-Kaisi *et al.,* 2014). Similar study by Nouwakpo *et al.* (2018) showed that addition of maize residues increased macroaggregation percentage by increasing cohesion between smaller size aggregates coupled with the recalcitrant chemical nature of the maize residue (Stewart *et al.,* 2015). Therefore, soil aggregate stabilization from inclusion of maize residues in maize monocropping are appropriate management in the future for both Uyole and Suluti sites.

6.4 Conclusions and Recommendations

6.4.1 Conclusions

Based on the results, it can be concluded that in both sites, even though there were no significant differences between treatments, it may inferred that crop management started to slightly increase the values of soil N in third as compared to the first season. Also, both sites provided an insight that residue retention was necessary to slightly raise SOC content in other seasons as compared to the first season. This implies that over long term there are possibilities of increasing soil N significantly, hence gradual soil N increase over time may also enhance SOC levels to reach significant quantities.

The proportion of macroaggregates whose quantity declined season to season in most of the treatments was accompanied with simultaneous increases in proportion of mesoaggregates and microaggregates. The decrease in macroaggregates might have resulted in C loss over time.

6.4.2 Recommendations

1. The combination of maize or soybean residues retention and inorganic N is recommended for increasing soil N and SOC in both Suluti and Uyole.

References

Abril, A., Casado-Murillo, N., Vázquez, C. and Olivera, P. (2013). Labile and recalcitrant carbon in crop residue and soil under no-till practices in central region of Argentina. *The Open Agriculture Journal* 7(1): 32 – 39.

Al-Kaisi, M. M., Douelle, A. and Kwaw-Mensah, D. (2014). Soil microaggregate and macroaggregate decay over time and soil carbon change as influenced by different tillage systems. *Journal of Soil and Water Conservation* 69(6): 574-580.

Amador, J A., Alexander, M. and Zika, R. G. (1989). Sequential photochemical and microbial degradation of organic molecules bound to humic acid. *Applied and Environmental Microbiology* 55: 2843–2849.

Bathke, G. R. and Blake, G. R. (1984). Effects of soybeans on soil properties related to soil erodibility. *Soil Science Society of America Journal* 48: 1398-1401.

Borase, D. N., Nath, C. P., Hazra, K. K., Senthilkumar, M., Singh, S. S., Praharaj, C. S., Singh, U. and Kumar, N. (2020). Long-term impact of diversified crop rotations and nutrient management practices on soil microbial functions and soil enzymes activity. *Ecological Indicators* 114: 106322.

Cambardella, C. A. and Elliott, E. T. (1993). Carbon and nitrogen distribution in aggregates from cultivated and native grassland soils. *Soil Science Society of America Journal* 57: 1071–1076.

Casado-Murillo, N. and Abril, A. (2013). Decomposition and carbon dynamics of crop residue mixtures in a semiarid long term no-till system: effects on soil organic carbon. *The Open Agriculture Journal* 7(1): 11 – 21.

Chalise, K. S., Singh, S., Wegner, B. R., Kumar, S., Pérez-Gutiérrez, J. D., Osborne, S. L., Nleya, T., Guzman, J. and Rohila, J. S. (2019). Cover crops and returning residue impact on soil organic carbon, bulk density, penetration resistance, water retention, infiltration, and soybean yield. *Agronomy Journal* 111(1): 99-108.

Cassman, K. G., Dobermann, A. and Walters, D. T. (2002). Agroecosystems, nitrogen-use efficiency, and nitrogen management. *AMBIO: Journal of the Human Environment* 31(2): 132-140.

Chantigny, M. H. (2003). Dissolved and water-extractable organic matter in soils: a review on the influence of land use and management practices. *Geoderma* 113: 357–380.

Cong, W. F., Hoffland, E., Li, L., Six, J., Sun, J. H. Bao, X. G., Zhang, F. S. and van Der Werf, W. (2015a). Intercropping enhances soil carbon and nitrogen. *Global Change Biology* 21(4): 1715-1726.

Cong, W. F., Hoffland, E., Li, L., Janssen, B. H. and van der Werf, W. (2015b). Intercropping affects the rate of decomposition of soil organic matter and root litter. *Plant and Soil* 391(1-2): 399-411.

Coulter, J. A., Nafziger, E. D. and Wander, M. M. (2009). Soil organic matter response to cropping system and nitrogen fertilization. *Agronomy Journal* 101: 592–599.

Di, J., Feng, W., Zhang, W., Cai, A. and Xu, M. (2017). Soil organic carbon saturation deficit under primary agricultural managements across major croplands in China. *Ecosystem Health and Sustainability* 3(7): 1364047.

Dou, F., Wright, A. L. and Hons, F. M. (2007). Depth distribution of soil organic C and N after long-term soybean cropping in Texas. *Soil and Tillage Research* 94(2): 530-536.

Eilers, K. G., Lauber, C. I., Knight, R. and Fierer, N. (2010). Shifts in bacterial community structure associated with inputs of low molecular weight carbon compounds to soil. *Soil Biology and Biochemistry* 42: 896 – 903.

Embacher, A., Zsolnay, A., Gattinger, A. and Munch. J. C. (2008). The Dynamics of Water Extractable Organic Matter (WEOM) in Common Arable Topsoils: II. Influence of Mineral and Combined Mineral and Manure Fertilization in a Haplic Chernozem. *Geoderma* 148: 63 - 69.

Fang, H., Cheng, S., Wang, Y., Yu, G., Xu, M., Dang, X., Li, L. and Wang, L. (2014). Changes in soil heterotrophic respiration, carbon availability, and microbial function in seven forests along a climate gradient. *Ecological Research* 29(6): 1077-1086.

Fiedler, S. R., Buczko, U., Jurasinski, G. and Glatzel, S. (2015). Soil respiration after tillage under different fertilizer treatments–implications for modelling and balancing. *Soil and Tillage Research* 150: 30-42.

Fujisaki, K., Chevallier, T., Chapuis-Lardy, L., Albrecht, A., Razafimbelo, T., Masse, D., Ndour, Y. B. and Chotte, J. L. (2018). Soil carbon stock changes in tropical croplands are mainly driven by carbon inputs: A synthesis. *Agriculture, Ecosystems and Environment* 259: 147-158.

Ghani, A., Dexter, M., Perrott, K. W. (2003). Hot-water extractable carbon in soils; a sensitive measurement for determining impacts of fertilization, grazing and cultivation. *Soil Biology and Biochemistry* 35(9): 1231–1243.

Gong, W., Yan, X. Y., Wang, J. Y., Hu, T. X. and Gong, Y. B. (2009). Long-term manuring and fertilization effects on soil organic carbon pools under a wheat–maize cropping system in North China Plain. *Plant and Soil* 314(1): 67-76.

Green, C. J. and Blackmer, A. M. (1995). Residue decomposition effects on nitrogen availability to corn following corn or soybean. *Soil Science Society of America Journal* 59: 1065-1070.

Gregorich, E. G., Beare, M. H., Stoklas, U. and St-Georges, P. (2003). Biodegradability of soluble organic matter in maize-cropped soils. *Geoderma* 113: 237–252.

Hall, S. J., Russell, A. E. and A'lece, R. M. (2019). Do corn-soybean rotations enhance decomposition of soil organic matter?. *Plant and Soil* 444(1): 27-442.

Haynes, R. J. and Francis G. S. (1993). Changes in microbial biomass C, soil carbohydrate composition and aggregate stability induced by growth of selected crop and forage species under field conditions. *Journal of Soil Science* 44: 665-675.

Haynes, R. J. (2005). Labile organic matter fractions as central components of the quality of agricultural soils. *Advances in Agronomy* 85: 221–268.

Haynes, R. J., Naidu, R. (1998). Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. *Nutrient Cycling in Agroecosystems* 51: 123–137.

He, Z. and Wu, F. (2015). Labile organic matter: chemical compositions, function, and significance in soil and the environment.' (SSSA: Madison, WI, USA).

Iqbal, A., Beaugrand, J., Garnier, P. and Recous, S. (2013). Tissue density determines the water storage characteristics of crop residues. *Plant and Soil* 367(1): 285–299.

Janssen, B. H. (2011). Simple models and concepts as tools for the study of sustained soil productivity in long-term experiments. I. New soil organic matter and residual effect of P from fertilizers and farmyard manure in Kabete, Kenya. *Plant and Soil* 339: 3–16.

Kaiser, K. and Zech, W. (1998). Rates of dissolved organic matter release and sorption in forest soils. *Soil Science* 163: 714–725.

Kaleeem, A, M., Mahmood, T. M., Sabir, N. and Khurshid, M. (2015). Impact of the addition of different plant residues on nitrogen mineralization–immobilization turnover and carbon content of a soil incubated under laboratory conditions. *Solid Earth* 6(1): 197-205.

Kemper, W. D. and Chepil, W. S. (1965). Size distribution of aggregates. *Methods of Soil Analysis: Part 1 Physical and Mineralogical Properties, Including Statistics of Measurement and Sampling* 9: 499-510.

Kemper, W. D. and Rosenau, R. C. (1986). Aggregate stability and size distribution. *Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods* 5: 425-442.

Kogel-Knabner, I. (2002). The macromolecular organic composition of plant and micro-bial residues as inputs to soil organic matter. *Soil Biology and Biochemistry* 34: 139–162.

Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A. and Lombi, E. (2019). Soil and the intensification of agriculture for global food security. *Environment International* 132: 105078.

Lal, R. (2010). Managing soils and ecosystems for mitigating anthropogenic carbon emissions and advancing global food security. *BioScience* 60(9): 708-721.

Li, J. H., Li, F., Li, W. J., Chen, S., Abbott, L. K., Knops, J. M. H. (2018). Nitrogen additions promote decomposition of soil organic carbon in a Tibetan alpine meadow. *Soil Science Society of America Journal* 82(3): 614-621.

Li, L. J., Han, X. Z., You, M. Y., Yuan, Y. R., Ding, X. L. and Qiao, Y. F. (2013). Carbon and nitrogen mineralization patterns of two contrasting crop residues in a Mollisol: Effects of residue type and placement in soils. *European Journal of Soil Biology* 54: 1- 6.

Li, T., Zhang, Y., Bei, S., Li, X., Reinsch, S., Zhang, H. and Zhang. J. (2020). Contrasting impacts of manure and inorganic fertilizer applications for nine years on soil organic carbon and its labile fractions in bulk soil and soil aggregates. *Catena* 194:104739.

Liu, C., Lu, M., Cui, J., Li, B., Fang, C. (2014). Effects of straw carbon input on carbon dynamics in agricultural soils: a meta-analysis. *Global Change Biology* 20: 1366–1381.

Mahal, N. K., Osterholz, W. R., Miguez, F. E., Poffenbarger, H. J., Sawyer, J. E., Olk, D. C., Archontoulis, S. V. and Castellano, M. J. (2019). Nitrogen fertilizer suppresses mineralization of soil organic matter in maize agroecosystems. *Frontiers in Ecology and Evolution* 7(59): 1-12.

Márquez, C. O., Garcia, V. J., Cambardella, C. A., Schultz, R. C. and Isenhart, T. M. (2004). Aggregate size stability distribution and soil stability. *Soil Science Society of America Journal* 68(3): 725-735.

Mazzarino, M. J., Szott, L. and Jimenez, M. (1993). Dynamics of total C and N, microbial biomass, and water soluble C in tropical agro-ecosystems. *Soil Biology and Biochemistry* 25: 205–214.

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., Chaplot, V., Chen, Z., Cheng, K., Das, B. S., Field, D. J., Gimona, A., Hedley, C. B., Hong, S. Y., Mandal, B., Marchant, B. P., Martin, M., McConkey, B. G., Mulder, V. L., O'Rourke, S., Richer-de-Forges, A. C., Odeh, I., Padarian, J., Paustian, K., Pan, G., van Wesemael, B., Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma* 292: 59–86.

Mulvaney, B. J. and Page, A. L. (1982). Nitrogen-total. *Methods of soil analysis: Part*, *2*, pp. 595-624.

Mulvaney, R. L., Khan, S. A. and Ellsworth, T. R. (2009). Synthetic nitrogen fertilizers deplete soil nitrogen: a global dilemma for sustainable cereal production. *Journal of Environmental Quality* 38(6): 2295-2314.

Nath, C. P., Hazra, K. K., Kumar, N., Praharaj, C. S., Singh, S. S., Singh, U. and Singh, N. P. (2019). Including grain legume in rice–wheat cropping system improves soil organic carbon pools over time. *Ecological Engineering* 129: 144-153.

Nelson, D. W. and Sommers, L. E., (1996). Total carbon, organic carbon, and organic matter. *Methods of Soil Analysis: Part 3 Chemical Methods* 5: 961-1010.

Nouwakpo, S. K., Song, J. and Gonzalez, J. M. (2018). Soil structural stability assessment with the fluidized bed, aggregate stability, and rainfall simulation on long-term tillage and crop rotation systems. *Soil and Tillage Research* 178: 65-71.

Partey, S. T., Preziosi, R. F. and Robson, G. D. (2014). Improving maize residue use in soil fertility restoration by mixing with residues of low C-to-N ratio: effects on C and N mineralization and soil microbial biomass. *Journal of Soil Science and Plant Nutrition* 14(3): 518-531.

Parton, W., Silver, W. L., Burke, I. C., Grassens, L., Harmon, M. E., Currie, W. S., King, J. Y., Adair, E. C., Brandt, L. A., Hart, S. C. and Fasth, B. (2007). Global-scale similarities in nitrogen release patterns during long-term decomposition. *Science* 315(5810): 361-364

Poffenbarger, H. J., Barker, D. W., Helmers, M. J., Miguez, F. E., Olk, D. C., Sawyer, J. E., Six, J. and Castellano, M. J. (2017). Maximum soil organic carbon storage in Midwest US cropping systems when crops are optimally nitrogen-fertilized. *PLoS One* 12(3): e0172293.

Purwanto, B. H. and Alam, S. (2020). Impact of intensive agricultural management on carbon and nitrogen dynamics in the humid tropics. *Soil Science and Plant Nutrition* 66(1): 50-59.

Qiu, Q., Wu, L., Ouyang, Z., Li, B., Xu, Y., Wu, S. and Gregorich, E. G. (2016). Priming effect of maize residue and urea N on soil organic matter changes with time. *Applied Soil Ecology* 100: 65-74.

Qualls, R. G. and Haines, B. L. (1992). Biodegradability of dissolved organic matter in forest throughfall, soil solution, and stream water. *Soil Science Society of America Journal* 56: 578–586.

Raiesi, F. (2006). Carbon and N mineralization as affected by soil cultivation and crop residue in a calcareous wetland ecosystem in Central Iran. *Agriculture, Ecosystems and Environment* 112 (1): 13–20.

Salinas-Garcia, J. R., Baez-Gonzalez, A. D., Tiscareno-Lopez, M. and Rosales- Robles, E. (2001). Residue removal and tillage interaction effects on soil properties under rain-fed corn production in Central Mexico. *Soil and Tillage Research* 59: 67–79.

Šimanský, V. and Bajčan, D. (2014). The stability of soil aggregates and their ability of carbon sequestration. *Soil Water Research* 9: 111-118.

Šimanský, V., Kravka, M. and Jonczak, J. (2017). Stability of soil aggregates in loamy soils of Slovakia. *Journal of Elementology* 22(2): 581-592.

Šimanský, V. Kolenčík, M. and Puškelová, Ľ. (2014). Effects of carbonates and bivalent cations and their relationships with soil organic matter from the view point of aggregate formation. *Agriculture (Poľnohospodárstvo)* 60(3): 77–86.

Six, J., Bossuyt, H., Degryze, S. and Denef, K. (2004). A history of research on the link between (micro) aggregates, soil biota, and soil organic matter dynamics. *Soil and Tillage Research* 79: 7–31.

Six, J., Elliott, E. T. and Paustian, K. (2000). Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry* 32: 2099–2103.

Stewart, C. E., Moturi, P., Follett, R. F. and Halvorson, A. D. (2015). Lignin biochemistry and soil N determine crop residue decomposition and soil priming. *Biogeochemistry* 124(1): 335-351.

Uzoh, I. M., Igwe, C. A., Okebalama, C. B. and Babalola, O. O. (2019). Legume-maize rotation effect on maize productivity and soil fertility parameters under selected agronomic practices in a sandy loam soil. *Scientific Reports* 9(1): 1-9.

Wang, H., Shen, M., Hui, D., Chen, J., Sun, G., Wang, X., Lu, C., Sheng, J., Chen, L., Luo, Y. and Zheng, J. (2019). Straw incorporation influences soil organic carbon sequestration, greenhouse gas emission, and crop yields in a Chinese rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system. *Soil and Tillage Research* 195: 104377.

West, T. O. and Post, W. M. (2002). Soil organic carbon sequestration rates by tillage and crop rotation. *Soil Science Society of America Journal* 66: 1930–1946.

Westarp, S. V., Sandra Brown, H. S. and Shah, P. B. (2004). Agricultural intensification and the impacts on soil fertility in the Middle Mountains of Nepal. *Canadian Journal of Soil Science* 84(3): 323-332.

Xu, N., Wilson, H. F., Saiers, J. E. and Entz, M. (2013). Effects of Crop Rotation and Management System on Water-Extractable Organic Matter Concentration, Structure, and Bioavailability in a Chernozemic Agricultural Soil. *Journal of Environmental Quality* 42: 179–190.

Yan, L., Zhang, J., Zhao, X., Li, M., Gao, Q. and Zhao, L. (2016). Effect of long-term application of corn stalks and inorganic fertilizers on fluorescence characteristics of water extractable organic matter in a meadow black soil of northeast China. *Toxicological and Environmental Chemistry* 98(5-6): 541-550.

Yuste, J. C., Baldocchi, D. D., Gershenson, A., Goldstein, A., Misson, L. and Wong, S. (2007). Microbial soil respiration and its dependency on carbon inputs, soil temperature and moisture. *Global Change Biol*ogy 13: 1–18.

Zhang, S. L., Wang, R. J., Yang, X. Y., Sun, B. H. and Li, Q. H. (2016). Soil aggregation and aggregating agents as affected by long term contrasting management of an Anthrosol. *Scientific Reports* 6: 39107.

Zhao, M., Zhou, J. and Kalbitz, K. (2008). Carbon mineralization and properties of water-extractable organic carbon in soils of the south Loess Plateau in China. *European Journal of Soil Biology* 44(2): 158-165.

Zsolnay, A. (1996). Dissolved humus in soil waters. In: *Humic Substances in Terrestrial Ecosystems*. A. Piccolo (ed.). Elsevier, Amsterdam, The Netherlands. pp.171Y223.

Zuber, S. M., Behnke, G. D., Nafziger, E. D. and Villamil, M. B. (2015). Crop rotation and tillage effects on soil physical and chemical properties in Illinois. *Agronomy Journal* 107: 971–978.

CHAPTER SEVEN

7.0 GENERAL CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The soils of Magadu and Uyole have different morphological and chemical properties. According to USDA Soil Taxonomy, the soil of Magadu (SUA) and Uyole pedon (UYOLE-P1) were classified as *Typic Kandiustults* and *Andic Dystrudepts*, respectively. The soil of Magadu has been rated as low in organic matter, total nitrogen, and available phosphorus. Generally the soils have poor fertility and need soil management to sustain agriculture and other land uses. The soil of Uyole has medium rated OM and N (low), P (medium), and K (very high), together with medium to high CEC and BS, the soil is likely to offer moderately favorable soil conditions for crop production.

The soil organic carbon (SOC), soil nitrogen (N), and the crop yield were not significantly enhanced after three years in Magadu and two years each in Suluti and Uyole under intercropping, rotation or monocropping, and that significant increment may require long periods of time to accumulate. On other hand, inorganic N fertilizer combined with residue incorporation insignificantly elevated grain and total biomass yield.

In addition, these cropping systems in three and two years could not improve water extractable organic carbon (WEOC) and aggregate stability significantly; yet, continuous maize under residue retention can retain most of larger aggregates than other cropping systems. Crop residue return under intercropping coupled with inorganic N appears insignificantly to enhance stabilized SOC and N.

Combination of inorganic N fertilizer and different levels of crop residue returned in soils under intercropping have slightly (not significantly) increased SOC in the third season in Magadu site, and an increase in soil nitrogen in Uyole and Suluti. This cropping management may add more SOC and N after a prolonged practice. Moreover, use of crop residue (maize and soybean) and 80 kg N ha^{-1} of inorganic N had relatively improved maize grain yield.

In the five years of maize and soybean rotation under maize and soybean residue retention and inorganic N amendment, it is inferred that crop management started to slightly increase values of soil C and N and, thus, over the long term there are possibilities of significantly increasing these two soil properties. The loss of larger aggregates whose quantity declined due to soil disturbance in the soil preparation could have resulted in C loss over time in both sites and reduced effective SOC sequestration.

7.2 Recommendations

Based on the results of this study, the following recommendations are put forward:

i. Due to low fertility in the study sites, soil reconstitution is mandatory through land and crop management which include, but not limited to, no-tilling or conservation tillage, manuring and proper fertilizer application; residue retention, liming for potential buffering of soil pH especially at SUARAT-P1 and crop rotation and intercropping with leguminous crops.

ii. In order to maximize crop yields, and to increase SOC and N sequestration, the interventions (cropping system and residue retention) should be undertaken on a long term basis as other studies have also indicated. Use of inorganic N fertilizer is encouraged since it could enhance SOC, soil N, in addition to increasing grain and biomass yields.

iii. Crop residue retention coupled with inorganic N fertilizer under intercropping are recommended in Magadu, Suluti and Uyole as farmers can reduce loss in soil organic matter and other soil properties and get substantial increase over seasons. Moreover, including crop residue (4 Mg ha^{-1} of maize and 1 Mg ha^{-1} of soybean) coupled with inorganic N fertilizer at 80 kg N ha^{-1} will enhance maize grain yields.

iv. The combination of maize or soybean residues retention and inorganic N in maize – soybean rotation is recommended for increasing soil N and SOC in both Suluti and Uyole. However, in order to maximize and maintain SOM, it is suggested to shift to conservation/ or minimum tillage practice to stop or reduce soil aggregate disturbances for effective C sequestration.