RELATIONSHIPS BETWEEN SOIL PROPERTIES AND TREE SPECIES DIVERSITY IN SELECTED MIOMBO WOODLAND ECOSYSTEMS, TANZANIA

BULENGA, GEORGE BUNYATA

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ECOSYSTEMS SCIENCE AND MANAGEMENT OF SOKOINE UNIVERSITY OF AGRICULTURE. MOROGORO, TANZANIA.

2016

ABSTRACT

This study aimed to assess relationships between selected edaphic properties with tree species diversity and amount of soil organic carbon at Kitulang'halo (Morogoro district) and Kibutuka (Liwale district) Miombo woodland ecosystems in Tanzania. Ten and eleven clusters were studied in Kitulang'halo and Kibutuka, respectively. Some of these clusters were those established by National Forest Resource Monitoring and Assessment (NAFORMA) while others were imbedded in order to increase reliability of data. Each cluster had ten circular plots of 15 m radius set at 250 m intervals. Three plots (4, 7 and 10) from each cluster were chosen systematically for soil and tree data collection making a total of 63 plots. All tree species with DBH $\geq$ 5 cm were measured and identified by their botanical names. Soil sampling was done by digging a soil mini-pit to 30 cm depth (NAFORMA approach) at intervals of 10 cm and augering to 100 cm depth (World Agroforestry Centre (ICRAF) approach) at 20 cm depth interval. Tree species diversity was determined using Shannon-Wiener diversity index (H'). Soil chemical properties (soil organic carbon (SOC), total nitrogen, exchangeable bases, cation exchange capacity, available phosphorus and soil pH) from samples collected by NAFORMA approach were analyzed by standard methods. SOC from soil samples collected by ICRAF approach was analyzed by Mid Infrared Radiation (MIR) method. Kitulang'halo had 123 different tree species (H'= 4.26) while Kibutuka had 102 different tree species (H'= 4.06). SOC, total N, Ca^{2+}, K^{+}, Na^{+} and CEC were higher at Kibutuka than at Kitulang'halo, while Mg^{2+}, available P and pH were higher at Kitulang'halo. Tree species richness was positively related to SOC. Though this relationship was weak, it was significant at $P<0.05$, suggesting that SOC was high at higher tree species diversity. Tree species richness was not related to other soil chemical properties. The amount of SOC at 0-30 cm depth was about 42% of the total contained at 100 cm depth with about 58% of SOC in layer 30-100 cm depth in both sites. There was a consistent decrease in SOC storage with increasing soil depth in Kitulang'halo while at Kibutuka the maximum of SOC was found at 20-40 cm (40 t/ha), and then decreased with depth to 100 cm. The amount of SOC estimated by MIR method (ICRAF approach) and Walkley-Black method (NAFORMA approach) differed significantly (*$P<0.05$*), whereby the NAFORMA approach estimated more SOC than ICRAF approach. Kitulang'halo and Kibutuka Miombo woodland ecosystems require promoting conservation activities to increase a wide range of ecosystem processes and functions.

DECLARATION

I, Bulenga, George Bunyata do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is the result of my own original work done within the registration period and that it has neither been submitted nor being concurrently submitted in any other institution.

24/11/2016

Bulenga, George Bunyata
(MSc. Candidate)

Date

The declaration above is confirmed by:

24/11/2016

Prof. Maliondo, S. M. S. (SUA-Tanzania)
(Supervisor)

Date

15/12/2016

Dr. Gert Nyberg (LUT-Sweden)
(Supervisor)

Date

COPYRIGHT

ACKNOWLEDGEMENTS

I wish to extend my sincere gratitude to Biodiversity Project and Climate Change Impacts, Adaptation and Mitigation (CCIAM) Programme through Sokoine University of Agriculture. Collage of Forestry, Wildlife and Tourism in the Department of Forest Resources Assessment and Management for their financial assistance (sponsorship), which made execution of this study possible. I am grateful to my supervisors, Prof. S. M. S Maliondo of the Collage of Forestry, Wildlife and Tourism, Sokoine University of Agriculture in Tanzania and Dr. Gert Nyberg of Lulea University of Technology in Sweeden for their tireless efforts, valuable guidance and constructive criticism which have made the completion of this study possible. Particular thanks also go to Dr. Josiah Katani, Mr. Daniel Charles, Mr. Hamidu Seki, Mr. Amon Mwaijengo and Mr. Charles Kilawe for their assistance during data collection and analysis.

Special thanks go to Liwale District Natural Resources Officer, Mr. D. Damas for his consultation of the village leaders in Kibutuka ward and paving the way during data collection. I am deeply indebted to my beloved parents Nashon Bulenga Ndaro and Sherebia Joseph Masogo, my sisters Jane, Neema, Nyamkubi and Nyabweke, my young brothers George and Masogo for their patience, inspiration and heartfelt encouragement during the whole process of this study.

DEDICATION

This work is dedicated to my beloved parents Nashon Bulenga Ndaro and Sherebia Joseph Masogo who laid down the foundation of my education, and to my wife Emiliana Magesa and my children Evans George Bulenga and Everlyne George Bulenga for their material and moral support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS AND ACRONYMS

AAS	Atomic Absorption Spectrophotometer
BD	Bulk Density
CEC	Cation Exchange Capacity
DBH	Diameter at Breast Height
EB	Exchangeable Bases
FAO	Food and Agriculture Organization of the United Nations
FES	Flame Emission Spectrophotometer
GHGs	Greenhouse gases
ICRAF	International Centre for Research in Agroforestry
IR	Diffuse reflectance infrared spectroscopy
MIR	Mid infrared
NAFORMA	National Forest Resource Monitoring and Assessment
NGOs	Non Governmental Organizations
OC	Organic Carbon
REDD	Reducing Emissions from Deforestation and Forest Degradation
SOC	Soil Organic Carbon
SUA	Sokoine University of Agriculture
UNESCO	United Nations Educational, Scientific and Cultural
URT	United Republic of Tanzania

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

The variations in soil properties influence the survival and distribution patterns of flora in a given environment (Engler and Guisan, 2009). This variation can also cause differences in environmental conditions worldwide. Studies by Li *et al.* (2009) revealed that soil properties of different locations exhibited significant differences with distinct tree species diversity. Tree diversity has been reported to be affected by SOC, total nitrogen (N), available phosphorus (P), soil pH, exchangeable bases (EB) (Calcium Ca^{2+}, Magnesium Mg^{2+}, Potassium K^{+}, and Sodium Na^{+}), cation exchange capacity (CEC), and total acidity (TA) (Folster *et al.*, 2001).

There has been a growing interest in knowing and understanding the dynamics of soil organic carbon (SOC) stocks of various ecosystems worldwide. This is because, the earth is facing the greatest challenge of carbon dioxide (CO_2) released into the atmosphere which is becoming a global problem (Stephens, 2006). Small changes in soil conditions can upset the original balance of soil carbon cycle, increase carbon (C) loss from soil, and hence release more greenhouse gases (GHGs) into the atmosphere. Inventory and monitoring of existing C pools in Miombo ecosystems is very important for climate change mitigation strategies such as reducing emissions from deforestation and forest degradation, conservation of forest carbon stocks, sustainable management of forests and enhancement of forest carbon stocks (REDD^{+}) (UNFCCC, 2011) as well as understanding the global C budget (Munishi *et al.*, 2010).

The implementation for sustainable management of forest ecosystems, requires an understanding of how soil chemical properties relate with tree species diversity. Also, to estimate the amount of SOC as it is a key attribute to soil physical, chemical as well as biological properties.

Currently, sampling and analytical approaches for estimation of soil chemical properties are varied and produce potentially conflicting results. Different approaches have been used when sampling and analyzing SOC stock, resulting in a confusing array of choices when selecting a method to be used (Périé and Ouimet, 2008). Thus, it is necessary to make comparisons between SOC content determined using different approaches.

1.2 Problem Statement

Understanding which soil properties are responsible for the maintenance of tree species diversity in tropical forests especially the Miombo woodlands is still an open debate and one of the numerous central questions in plant ecology (John *et al.*, 2007; Andersen *et al.*, 2009; Laclau *et al.*, 2010; Cleveland *et al.*, 2011). In Tanzania, and particularly for the Kitulang'halo and Kibutuka Miombo woodland ecosystems, such studies are lacking. There is also a lack of data about relationships between tree species diversity and soil properties in tropical forest ecosystems in Africa (Fine *et al.*, 2005; Nadeau and Sullivan, 2015).

On the other hand, the amount and vertical distribution patterns of SOC are less described (Jobbágy and Jackson, 2000; Meersmans *et al.*, 2009; Harrison *et al.*, 2011), although they can exert strong influence on the ecological community of plants and ecosystem processes and functions (Maestre and Reynolds, 2006).

Therefore, this study aimed to investigate the relationship between tree species diversity and selected soil chemical properties and determine the amount of SOC at Kitulang'halo and Kibutuka Miombo woodland ecosystems in Tanzania.

1.3 Justification of the Problem

Knowing the relationship between soil chemical properties and tree diversity together with amount of SOC has important contribution to filling existing ecological gaps as well as making contribution to the future national REDD^{+} strategy. The findings from this study will provide inputs for appropriate ecosystem management at many scales. Therefore, policy and decision makers, natural resource managers, investors, Non Governmental Organizations (NGOs), academicians and other stakeholders will be informed on available SOC, other soil chemical properties and their potential contribution to tree species diversity for appropriate actions.

1.4 Objectives

1.4.1 General objective

To assess the relationships between soil chemical properties and tree species diversity at Kitulang'halo and Kibutuka Miombo woodland ecosystems in Tanzania.

1.4.2 Specific objectives

The specific objectives of this study were to:

(i) Assess tree species diversity in the study areas;

(ii) Determine soil chemical properties in the two study areas;

(iii) Assess the relationship between tree species richness and soil chemical properties;

(iv) Determine vertical distribution patterns of SOC in soil profiles of the two study areas;

(v) Compare the amount of SOC determined by the two methods of SOC analysis.

1.4.3 Hypotheses

Ho: Tree species diversity of two study sites is not different.

Ho: Soil chemical properties of the two study areas are not different.

Ho: Soil chemical properties have no relationship with tree species richness.

Ho: Soil organic carbon does not vary consistently with soil depth.

Ho: There is no significance difference between the amounts of SOC analyzed by two methods.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Tree Species Diversity in Miombo Woodland Ecosystems

Species diversity refers to the number of different species in a particular area and their distribution together with relative frequencies while species richness is the actual number of different species in a community rather than the number of individuals contained therein (Harrison *et al*., 2007). Miombo woodlands display local variation in structure and floristic composition mainly influenced by past and present land use, edaphic properties and climatic conditions (Desanker *et al.*, 1997; Givnish, 1999).

Tropical forest ecosystems are known for having the highest plant biodiversity on the planet. Miombo woodlands are extremely rich in tree species in spite of their apparent uniformity in structure and composition over large areas. The number of higher plant species in the Miombo ecoregion is estimated to be 8,500 species, out of which. 334 are trees (Frost, 1996). According to Harrison and Grace (2007), tree species richness in Miombo woodlands of Tanzania ranges from 79 to 95 and occasionally reaches 102 species. That is why this study needed to investigate the reality of these findings at Kitulang'halo and Kibutuka Miombo woodland ecosystems.

2.2 Tree Species Richness and its Relationship with Soil Chemical Properties

Soils are highly heterogeneous in both space and time, and this heterogeneity has strong consequences on plant distribution (Huber-Sannwald and Jackson, 2001). Botanists have long recognized that the distribution, habit, and composition of tree species are greatly influenced by the edaphic properties (Brady *et al.*, 2005). Differences in the distribution and abundance of tree species in any environment are an indication of the variation in soil chemical properties (Engler and Guisan, 2009).

Several studies have, however, emphasized the influence of varying soil properties on the distribution and abundance of flora species in different locations (John *et al.*, 2007; Udoh *et al.*, 2007; Medinski, 2007; Cannone *et al.*, 2008; Zare *et al.*, 2011). Species richness and distribution is related to soil pH, total acidity, exchangeable bases, CEC, available P, total N, and SOC (Dubbin *et al.*, 2006; Marini *et al.*, 2007; Silva and Batalha, 2008). Therefore, this study aimed to add knowledge to the above findings in Miombo woodland ecosystems of Kitulang'halo and Kibutuka.

2.3 Amount and Vertical Distribution Patterns of Soil Organic Carbon in Soil Profiles

According to Batjes (1996), analyses of various soil profiles suggest that the subsoil layer (30-100 cm) contains significant quantities of SOC than topsoil layer. The 30-100 cm depth layer is estimated to contain as much SOC as the 0-30 cm layer (FAO, 2001; Jobbágy and Jackson, 2000; Batjes 1996). Yang *et al.* (2010) suggested that the vertical distribution of SOC in forest ecosystems generally showed that SOC at 20cm interval decreased as soil depth increased; this is in agreement with the findings of other researchers (Jobbágy and Jackson, 2000). There are distinct differences in the distribution of SOC between the topsoil and the subsoil sections, depending on land use (Lal, 2005). Transition from forest to agricultural land use leads to a significant decrease of SOC in the topsoil (Riezebos and Loerts, 1998). Similar decrease in SOC in the topsoil was reported when forest land was converted to cultivated land (Celic, 2005). This study was intended to determine vertical patterns of SOC with depth at both Kitulang'halo and Kibutuka Miombo woodland ecosystem.

2.4 Sampling and Analytical Approaches on the Amount of Soil Organic Carbon

In the context of carbon sequestration and GHGs emission studies, carbon stock in the soil need to be quantified precisely (Périé and Ouimet, 2008). There are several approaches reported and followed for SOC estimations but each method has its own advantages and disadvantages. In soil sample collection approaches, some use the soil auger and cylinders while others excavate soil pits. The current analytical approaches to determine SOC depend on two categories of approaches often described as "intensive" and "non-intensive" (McCarty *et al.*, 2002). The intensive approaches include dry combustion for total carbon, calcimeter method for inorganic carbon and wet oxidation for SOC (Walkley and Black, 1934). These methods are conventional and standard procedures but are time-consuming, laborious and expensive. In recent years, several radiation based methods are used as an alternatives, because of their multiple advantages. These methods include diffuse reflectance infrared spectroscopy (IR) like mid-infrared (MIR) (Cécillon *et al.*, 2009). These methods are rapid, simple, reproducible, and some times more accurate than conventional analytical methods (Cécillon *et al.*, 2009). Therefore, this study was conducted to compare the amount of SOC analyzed by two methods of SOC analysis for Miombo woodland ecosystems.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of Study Sites

3.1.1 Geographical location

The study was conducted at Kibutuka Miombo woodland in Liwale District and Kitulang'halo Miombo woodland in Morogoro district, Tanzania. Liwale district lies between 36° 50' and 38° 48' E, 8° and 10° 50' S while Kitulang'halo is situated at 37° 57'E and 06° 41'S. Liwale is found in Lindi region, while Kitulang'halo is in Morogoro region about 50 km east of Morogoro municipality towards Dar es Salaam. The predominant feature in this area is the Kitulang'halo hill which is about 800 m above sea level.

3.1.2 Climate

The climate of Liwale District is influenced by the south east (SE) winds in midyear and the north east (NE) winds during the turn of the year. The temperature ranges from 20°C to 30°C and the average temperature is 25°C per annum. The rainfall pattern is bi-modal with a dry season from July to October. The short rain period starts from late November to January, whereas long rains continue from March to May. According to Mtwara weather station, the annual rainfall for Liwale ranges from 600 mm to 900 mm. The climate of Kitulang'halo varies from tropical to sub-humid depending on the aspect. The area is within the 700 mm to 1000 mm rainfall belt with wet season from October to May and dry season from June to October. The mean annual temperature is 24.3°C while the annual minimum and maximum temperature are 18°C and 30°C, respectively. January is the hottest month, while June is the coldest.

3.1.3 Vegetation

Vegetation is characterized by Miombo woodland and the predominant genera are *Brachystegia*, *Julbernardia*, and *Isobelinia* reaching a height of 15-20 m, while most of trees are in an under storey at 5-10 m height include *Diplorhynchus candylocarpon*, *Combretum zeyheri*, *Combretum apiculatum* to mention a few.

3.1.4 Soils

The soils of the Miombo woodland are generally leached, sandy and poor in nutrients (Campbell *et al.* 1996; Frost 1996 and Backéus *et al.*, 2006). These soils include those classified as Hypoluvic Arenesol besides Profondic and Arenic Luvisols. However, Msanya *et al.* (1995) classified soils of Kitulang'halo Miombo woodland as Cambisol, Phaeozem and Lixisol according to FAO-UNESCO classification. Liwale area is mainly occupied by a sandy clay soil that is deep, while Kitulang'halo soils are shallow due to hard pan and mostly sandy loam (Msanya *et al.*, 1995).

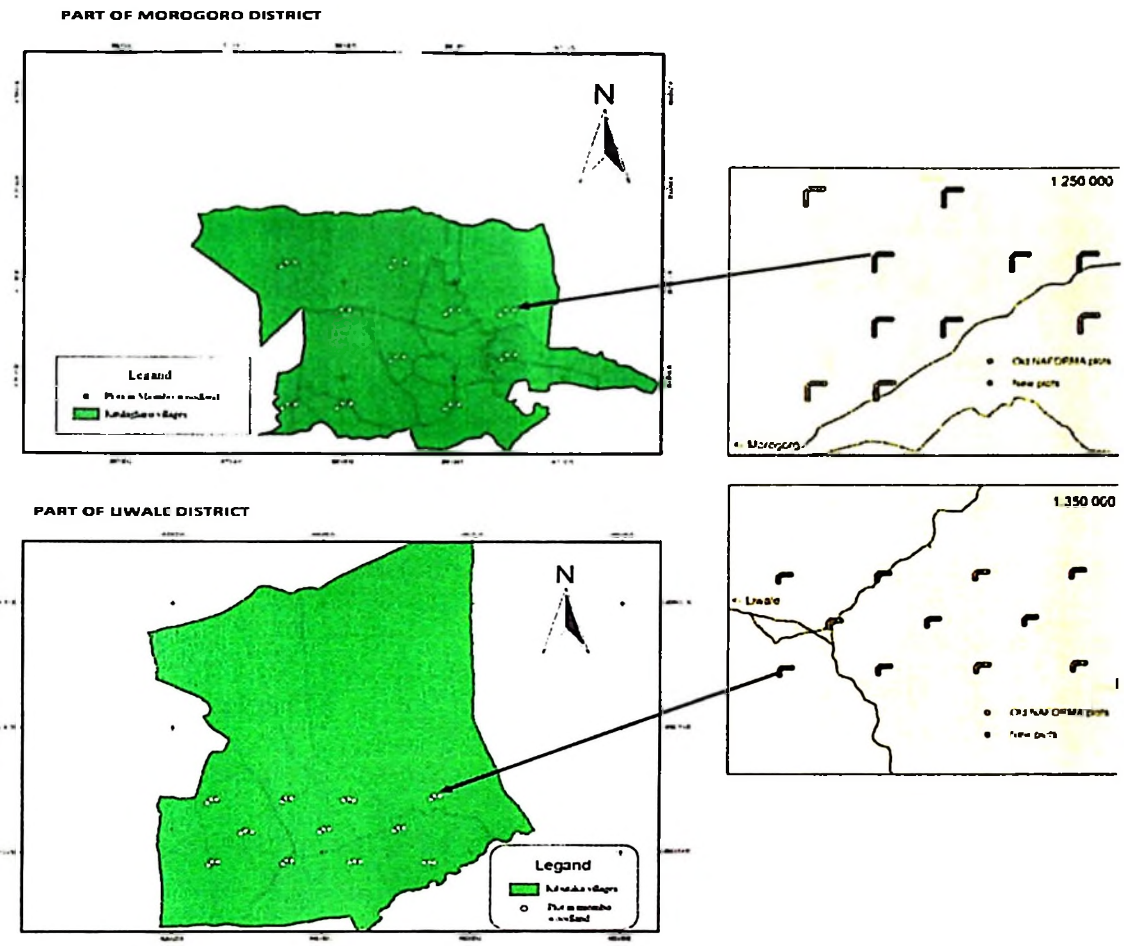

Figure 1: Maps showing the location of clusters in Miombo woodlands at Kitulang'halo in Morogoro District and Kibutuka in Liwale District.

3.1.5 Population

According to the 2012 National Population Census, Liwale district has a population of 91,380 people while Morogoro district has a population of 286, 248 people (URT, 2013).

3.2 Sampling Design and Vegetation Sampling

The National Forest Resource Monitoring and Assessment (NAFORMA) forest inventory exercise conducted between 2009 and 2013 established a number of sampling clusters in Kitulang'halo and Kibutuka Miombo woodlands. In this study only eight NAFORMA clusters were used for soil samples collection where thirteen clusters in the two study areas were added in order to improve the reliability of the estimates. Therefore, a total of twenty one clusters were sampled, ten in Kitulang'halo and eleven in Kibutuka (Fig. 1). Each cluster had ten circular plots of 15 m radius spaced at intervals of 250 m. Five plots were laid towards north while the other five were laid towards east. Three plots in each cluster were chosen systematically for data collection making a total of sixty three (63) plots. In each plot, three sub plots were demarcated at an interval 5 m from the plot center. Slope correction of plot radius was considered during plot layout. In each sub-plot, all plant species with diameter at breast height (DBH) $\geq$ 5 cm were measured, counted and identified by their botanical names.

3.3 Soil Samples Collection

Soil samples from each sampling plot were collected and stored in paper bags before being analyzed in the laboratory for selected properties.

3.3.1 Soil samples collection through soil mini-pit (NAFORMA approach)

At each soil sampling plot, four points located systematically at main compass direction (east, south, west and north) were identified. At each point, a soil mini-pit was excavated to 30 cm depth, with at least one vertical surface that was used for soil sampling. Where the soil was too hard to dig a 30 cm deep pit, sampling was limited to the upper 10cm or 20cm layers, and this was noted in the field forms. On the vertical face of the soil mini-pit, three layers were marked at each 10 cm depth interval: 0-10 cm, 10-20 cm and 20-30 cm, where the volumetric soil samples were taken. Soil core or soil sampling cylinders with inner diameter of 7 cm and height of 4.8 cm was used to collect soil samples. From each sampling plot, soil samples collected at the same sampling depth was placed into a clearly labelled paper bag to form a composite soil sample of the plot at the particular depth. Therefore, there were three composite soil samples from each sampling plot.

3.3.2 Soil samples collection through soil auger (ICRAF approach)

A soil auger was used to collect soil samples from the center of the plot about 3 m towards east. The rationale was to avoid the compaction of soil which was done at the center during plot layout. At this point, three randomly selected sites were chosen for soil sample collection at different depth interval: 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm. Maximum sampling depth was noted together with the reason, whether it was due to hardpan, stones, ground water or large surface roots. Soil samples at each depth from three sites were mixed to form composite sample. The total weight of the composite soil sample was measured by using digital weighing scale to the nearest gram. Then, this sample was subdivided to get a sub-sample which was also further subdivided to get approximately 500 g for each depth.

3.4 Data Analysis

3.4.1 Analysis of tree species diversity

Tree species diversity was determined using Shannon-Wiener diversity index (H'). This is the most widely used index of diversity, which combines species richness and evenness and is not affected by sample size (Kent, 2012). The larger value of H' indicates the greater species diversity and vice versa. H' considers both species richness (number of different species present in a community) and species evenness or dominance (species relative abundance and their distribution). It was calculated by:

$$H' = -\sum_{i=1}^{s} (pi)(lnpi)$$

Where Pi = ni / N (ni = the number of individuals in a single species i, N = the total number of individuals in the community for all species), H' = the Shannon-Wiener Index.

3.4.2 Analysis of soil chemical properties

In the laboratory, all air dried soil samples were ground and passed through a 2 mm sieve to remove stones and gravel. Fine and coarse roots were also removed. SOC, total N, available P, pH, CEC, EB and total acidity were analyzed.

3.4.2.1 Soil organic carbon

SOC from the soil samples collected using NAFORMA approach were determined by the Walkley-Black dichromate wet oxidation method, whereby the oxidizable matter in the soil is oxidized by 1N $K_2Cr_2O_7$ solution (Walkley-Black, 1934). SOC from soil samples collected using ICRAF approach at 0-20 cm was determined by MIR spectroscopy. The amount of SOC in tones per hectare was obtained by the following model:

BD (g/cm^3) × OC (%) × depth (cm) × 10 000 m^2/100.

Where; BD =Bulk Density (g/cm^3), OC = Organic Carbon in %.

3.4.2.2 Total nitrogen

Total N content was determined using Micro-Kjeldahl method (Jackobson, 1992).

3.4.2.3 Available phosphorus

Available P was determined using Bray P-1 method (Jackson, 1962).

3.4.2.4 Exchangeable bases

The dominant exchangeable bases in the soil are Ca^{2+}, Mg^{2+}, K^+ and Na^+. Ca^{2+} and Mg^{2+} were analyzed and determined by AAS (Atomic Absorption Spectrophotometer), while Na^+ and K^+ were analyzed and determined by FES (Flame Emission Spectrophotometer).

3.4.2.5 Cation exchange capacity

After extraction of exchangeable bases, the residual soil was washed with ethanol and then the remaining ammonium (NH_4^+) was extracted with 10% Sodium chloride (NaCl) for determination of CEC by titration.

3.4.2.6 Soil pH in water

Soil pH based on water was measured using Beckman's glass electrode pH meter (Meclean, 1965) after 10 g of the soil sample was suspended in 25 mL distilled water (1:2.5 ratio of soil to water).

Most analyses were done at the Laboratory of Forest Biology and Laboratory of Soil Science at Sokoine University of Agriculture (SUA). Analysis of SOC by MIR spectroscopy was done in Nairobi Kenya at ICRAF soil Laboratory.

3.4.3 Statistical data analysis

To examine relationships between soil chemical properties and tree species richness, simple linear regression analyses in SAS software were done for Kibutuka data at $P \leq 0.005$.

A comparison of SOC at 0-20 cm depth which were analyzed by two different approaches was based on student *t*-test to compare their means at $P<0.05$ to test if there was statistically significant difference in the amount of SOC.

CHAPTER FOUR

4.0 RESULTS

4.1 Tree Species Diversity at Kibutuka and Kitulang'halo Miombo Woodlands

Table 1 shows that Kitulang'halo Miombo woodland had 123 different tree species (Shannon-Wiener diversity index 4.26), while Kibutuka had 102 different tree species (Shannon-Wiener diversity index 4.06) showing that Kitulang'halo had 17 % more tree species than Kibutuka.

Dominant tree species at Kitulang'halo Miombo woodland were *Combretum molle* 68, *Julbernadiardia globiflora* 60, *Diplorhynchus condylocarpon* 52, *Scorodophleus fischeri* 39, *Commiphora africana* 36, *Brachystegia boehmii* 36 and *Acacia nigrensis* 35, while Kibutuka Miombo woodland was dominated by *Combretum molle* 61, *Combretum sp* 41, *Milletia stuhlmanii* 41, *Combretum zeyheri* 35, *Acacia nigrensis* 32, *Acacia robusta* 32 and *Combretum collinum* 30 (Appendix 2).

Table 1: Shannon-Wiener diversity indices at Kitulang'halo and Kibutuka

Site	Number of species	Shannon-Wiener diversity indices
Kibutuka	102	4.06
Kitulang'halo	123	4.26

4.2 Soil Chemical Properties at 0-30 cm Depth

The soil properties from the two study sites are shown in Table 2. The mean SOC were 1.58±0.04% at Kibutuka and 1.23±0.04% at Kitulang'halo while the mean total nitrogen (TN) were 0.07±0.003% at Kibutuka and 0.06±0.003% at Kitulang'halo. The mean values of CEC in the soil were 20.11±1.37 $cmolkg^{-1}$ at Kibutuka and 17.48±1.40 $cmolkg^{-1}$ at Kitulang'halo. The levels of available P were 9.56±1.44 $mgkg^{-1}$ at Kibutuka and 13.88±2.88 $mgkg^{-1}$ at Kitulang'halo, while the mean values of pH were 5.90±0.07 at Kibutuka and 6.61±0.04 at Kitulang'halo. The levels of K^+ and Na^+ were 0.72±0.07 cmol (+) kg^{-1} and 0.18±0.05 cmol (+) kg^{-1} at Kibutuka and 0.62±0.07 cmol (+) kg^{-1} and 0.15±0.01 cmol (+) kg^{-1} at Kitulang'halo, respectively. The levels of Ca^{2+} and Mg^{2+} were 12.49±1.18 cmol (+) $kg^{-1}$and 3.70±0.39 cmol (+) kg^{-1}at Kibutuka and 10.76±1.42 cmol (+) $kg^{-1}$and 6.06±0.91 cmol (+) kg^{-1} at Kitulang'halo, respectively.

Table 2: Soil properties in Kitulang'halo and Kibutuka Miombo woodlands at 30 cm depth

Soil properties	Mean values ± SE	
	Kibutuka	Kitulang'halo
BD (gcm^{-3})	1.4±0.01	1.57±0.02
pH in H_2O	5.90±0.07	6.61±0.04
SOC (%)	1.58±0.04	1.23±0.04
Total N (%)	0.07±0.003	0.06±0.003
Available P (mg kg^{-1})	13.88±2.88	9.56±1.44
Ca^{2+} ($cmolkg^{-1}$)	12.49±1.18	10.76±1.42
Mg^{2+} ($cmolkg^{-1}$)	3.70±0.39	6.06±0.91
K^+ ($cmolkg^{-1}$)	0.72±0.07	0.62±0.07
Na^+ ($cmolkg^{-1}$)	0.18±0.05	0.15±0.01
CEC ($cmolkg^{-1}$)	20.11±1.37	17.48±1.40

4.3 Relationship between Tree Species Richness and Soil Chemical Properties at Kibutuka Miombo Woodland Ecosystem in Liwale District

Tree species richness was positively related to SOC, the relationship was significant at $P< 0.05$ though it was very weak r = 0.07 (Table 3). The other soil chemical variables were not significantly related with tree species richness.

Table 3: Correlation between tree species richness and soil chemical properties at Kibutuka Miombo woodland ecosystem

Soil chemical properties	Statistical parameters	
	P value	**r**
SOC (t h^{-1})	0.007	0.07
Total N (%)	0.72	0.05
Available P (mg kg^{-1})	0.40	-0.11
Ca^{2+} ($cmolkg^{-1}$)	0.36	0.12
Mg^{2+} ($cmolkg^{-1}$)	0.86	0.02
K^{+} ($cmolkg^{-1}$)	0.87	0.02
Na^{+} ($cmolkg^{-1}$)	0.56	0.08
CEC ($cmolkg^{-1}$)	0.53	0.08
pH in H_2O	0.67	-0.03
Total acidity	0.47	-0.09

4.4 Amount of Soil Organic Carbon in 0-30 cm (NAFORMA approach) and 30-100 cm (ICRAF approach) Soil Depths

The mean amount of SOC at 30 cm depth was about 42% of the total contained to 100 cm depth in both sites (Table 4), with about 58% of SOC contained within 30-100 cm depth. Overall, Kibutuka contained more SOC than Kitulang'halo in each of the two depths.

Table 4: Amount of SOC obtained by using different sampling approaches at Kitulang'halo and Kibutuka Miombo woodlands at 0-30 cm and 0-100 cm

Site	Soil Organic Carbon (t ha^{-1})				
	Top soil (0-30 cm)	Sub soil (30-100 cm)	0-100 cm	% in top 30 cm	Subsoil/ Topsoil
Kibutuka	64.80	88.02	152.82	42.40	1.40
Kitulang'halo	48.28	69.09	117.30	41.13	1.43

4.5 Vertical Distribution of Soil Organic Carbon in Soil Profiles at Kitulang'halo and Kibutuka Miombo Woodlands

There was a consistent decrease in SOC storage with increasing soil depth at Kitulang'halo while at Kibutuka the maximum amount of SOC was at 20-40 cm (40 t/ha) then decreased with depth to 100 cm (Fig. 2). In total, SOC at Kibutuka was 31% higher than that at Kitulang'halo Miombo woodland.

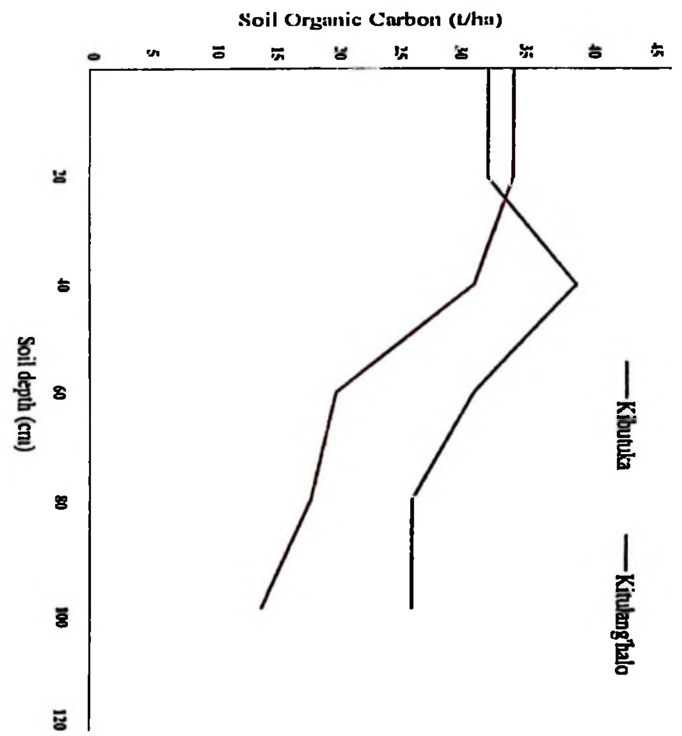

Figure 2: Vertical distribution of SOC in Miombo woodlands of Kibutuka in Liwale District and Kitulang'halo in Morogoro District, Tanzania

4.6 Soil Organic Carbon determined using MIR (ICRAF approach) and Walkley-Black (NAFORMA approach)

The mean proportions of SOC determined using MIR and Walkley-Black methods at Kibutuka Miombo woodland were 0.74 ± 0.62% and 0.98 ± 0.62%, respectively (Table 5).

Table 5: Percentage Soil Organic Carbon at Kibutuka Miombo Woodland Ecosystem

Approach	Mean values ± SE of SOC (%)
MIR	0.74 ± 0.62
Black and Walkley	0.98 ± 0.62

The mean SOC determined using Walkley-Black was found to be significantly higher (*P<0.05*) than that determined using MIR method (Table 6).

Table 6: Mean values of SOC (t ha^{-1}) obtained using two methods of SOC analysis at Kibutuka Miombo Woodland Ecosystem

Approach	Mean ± SE (t ha^{-1})	*t*-Ratio	*P*-value
MIR	33.35 ± 3.2		
Walkley-Black	41.89 ± 3.2	2.59	0.01

CHAPTER FIVE

5.0 DISCUSSION

5.1 Tree Species Diversity in Miombo Woodlands of Kitulang'halo and Kibutuka

Species richness in Miombo woodlands of Tanzania ranges from 79 to 95 and occasionally reaches 102 species (Harrison, 2007). Backéus (2006) found 86 species around Ihombwa village in Tanzania. In this study Kitulang'halo and Kibutuka Miombo woodland ecosystems had 123 and 102 tree species, respectively. This compares well with the study by Giliba *et al.* (2011) who found 110 tree species in Bereku Miombo woodland forest reserve in Tanzania. The high species richness in the study areas may be attributed to the presence of the riverine forests that contributes to the growth of many species. Kibutuka woodland in Liwale district is currently being degraded due to sesame cultivation with no management activities while degradation in Kitulang'halo forest is lower due to some management enforcement. Hence, Kitulang'halo forest had more tree species than Kibutuka forests. This study suggests that anthropogenic activities could be among the factors associated with the difference in species richness at Kitulang'halo and Kibutuka Miombo woodlands.

This study revealed Shannon-Weaver diversity indices of 4.26 and 4.06 at Kitulang'halo and Kibutuka Miombo woodlands, respectively (Table 1). These values agree with those of Giliba *et al.* (2011) who reported Shannon-Wiener Index of diversity (H') of 4.27 for the Miombo Woodland of Bereku forest reserve, Tanzania. Comparative studies elsewhere in Miombo woodlands by a number of scholars have reported smaller values. For instance, Nduwamungu (1997) and Zahabu (2001) reported H' values of 3.79 and 3.13, respectively in Miombo Woodlands of Kitulang'halo forest reserve in Tanzania. These indices are composed of species richness (number of species) and evenness (species distribution)

(Magurran, 1988); the larger the value of H' the greater the species diversity and vice versa. An ecosystem with H' value greater than 2 is regarded as of medium to highly species diversity (Barbour *et al.*, 1999). Thus, Miombo Woodlands of Kitulang'halo and Kibutuka have high species diversity.

5.2 Soil Chemical Properties in Kitulang'halo and Kibutuka Miombo Woodland at 0-30 cm Depth

Leskiw (1998) reported that forest soils should be slightly acidic for nutrient supply to be balanced. A fertile soil generally has a pH range between 5.5 and 7.2, which makes the essential elements and nutrients available to the flora. Kibutuka and Kitulang'halo Miombo woodlands had soils with pH of 5.90 and 6.61, respectively which are within the specified range. According to Euro Consult (1989), Foth (2006), Landon (1991) and Baize (1993), the majority of soils in tropics and sub-tropics rated as acidic soils had mean pH value of 5.9 (medium acidic), are favorable for the growth of plants in forest areas. The values of pH in this study are similar to the pH values of 5.68 recorded by Dondeyne *et al.* (2004) at Angai forest in Liwale district and pH values of 6.40 recorded by Msanya *et al.* (1995) at Kitulang'halo forest in Morogoro district, Tanzania. Therefore, pH of soils in Kibutuka and Kitulang'halo Miombo woodlands is increasing overtime, this might lead into soil alkalinity.

In addition, the high proportion of available P in Kibutuka plots suggest the effects of application of fertilizers to improve the soil nutrient by farmers for sesame cultivation. This could be true because, some plots in Kibutuka forest were located in cultivated areas as a result of forest degradation. Chidumayo and Kwibisa (2003) reported similar results as they observed higher available P in cultivated plots than in mature woodland and fallow plots, and attributed the increase to the application of P fertilizers to crops by farmers.

The mean exchangeable bases, particularly exchangeable Ca^{2+}, Na^{+} and K^{+} were also higher at Kibutuka Miombo woodland than at Kitulang'halo. These basic cations according to Foth (2006) may become insufficient in the soil for plant uptake as a result of continuous leaching caused by increased precipitation. The CEC usually gives an idea of the potential fertility of the soil. Landon (1991) reported ranges between 15 cmol (+)/kg and 25 cmol (+)/kg as satisfactory for growth of most plants. The results from this study indicated 20.11cmol (+) kg^{-1} at Kibutuka and 17.48 cmol (+) kg^{-1} at Kitulang'halo which are within the range. This means that Kibutuka soils are more fertile compared to Kitulang'halo soils. Angai soils which is part of Kibutuka forest are clayey and more fertile; this is reflected by their higher organic carbon (Dondeyne *et al.*, 2004).

The high contents of SOC and TN in soil at Kibutuka Miombo woodland may be attributed to the rate of nutrients returned to the soil through the leaf fall and subsequent decay of litter. This could be true because, many plots in Kibutuka forest were intact. Kibutuka soils in Miombo woodlands are clayey and more fertile; this is reflected by their higher organic carbon, TN and exchangeable Ca content (Dondeyne *et al.*, 2004). It suggests that these soils were originally formed on an old land surface which was rejuvenated later (Dondeyne *et al.*, 2004).

5.3 Relationships between Tree Species Richness and Soil Chemical Properties at Kibutuka Miombo Woodland Ecosystem in Liwale District

In this study, tree species richness was weakly correlated with SOC. Although weakly correlated, these results agree with the findings of Fornara and Tilman (2008), which showed that more soil C is related to higher tree species diversity. Dondeyne *et al.* (2004) working in Angai forest, Liwale, Tanzania concluded that variations in vegetation composition were strongly related to variations in SOC. Since vast forest areas are managed and harvesting of tree species is selective, both C storage and tree diversity can actively be promoted together (Per-Marten *et al.*, 2014). Certainly, it would be a desirable win-win strategy in forestry if increases in, or at least the maintenance of, the tree species diversity would be accompanied by enhanced C storage (or at least the preservation of the existing stocks) (Kessler *et al.*, 2012).

In this study, tree species richness was not related to total N, available P, EB (Ca^{2+}, Mg^{2+}, K^+, Na^+), CEC, total acidity and pH. These results agree with the findings of Fu *et al.* (2004) who found no relationship between tree species richness and total N while working in a heterogeneous deciduous broad-leaved forest near Beijing, China. On the other hand, Nirmal Kumar *et al.* (2010) found some relationships between species richness and soil chemical fertility factors (concentration of exchangeable K, Ca and Mg; Olsen P, and Al; CEC, pH, and total N) in a dry deciduous forest with low annual rainfall in western India. This study had looked at both plant species richness in relation to soil chemical fertility in a tropical forest, but these results do not agree with results of this study. This divergence may be generated by a difference in rainfall between the two ecosystems. Janssens *et al.* (1998) worked in temperate grassland ecosystems and found a positive relationship between plant species richness and the concentration of available P and K in soil. Their results did not agree with the findings of this research and the divergence may be attribute to ecosystem processes like carbon cycle which occurs between different ecosystems.

5.4 Soil Organic Carbon in 0-30 cm and 30-100 cm Soil Depths

Whereas, it is widely accepted that SOC is largely concentrated in the top 30 cm of the soil, there is growing evidence that deeper soil horizons have the capacity to sequester high amounts of SOC despite the lower concentrations in the subsoil (Swift, 2001). Results support this view as the amount of SOC at 30-100 cm depth relative to that at 0-30 cm was higher by a mean factor of 1.4 at both Kibutuka and Kitulang'halo Miombo woodlands (Table 4). Brahim *et al.* (2014) reported that the soils of Tunisia stored 0.405 Pg C in the top soil layer (0-30 cm) and 1.006 Pg C at lower depth in (0-100 cm); implying that the sub soil horizon stored about 1.48 times higher SOC than the top 0-30 cm which is consistent with this study. Other scholars argued that, the 30-100 cm depth layer is estimated to contain as much SOC as the topsoil layer (Jobbágy and Jackson, 2000; FAO, 2001). Rumpel and Kögel-Knabner (2011) identified three main processes involved in SOC incorporation into deep soil layers that were probably responsible for heterogeneous SOC distributions: (1) preferential flow of dissolved organic C down the soil profile; (2) plant rooting behavior such as root exudations and root overprint; and (3) SOC transport by bioturbation. However, deeper soil layers may impede the translocation of organic C since their porosity is often lower due to higher bulk densities resulting from compaction by overlying layers and possibly increased clay contents due to eluviations (Wu *et al.*, 2011). It was also suggested that the amount of SOC variation could also be affected by water, soil and air availability in the soil (Gao *et al.*, 2014; Zhang *et al.*, 2015).

5.5 Site Difference in Amount of Soil Organic Carbon

Soil organic carbon present at any location is influenced by a series of complex interactions between plant growth, climate, soil type or parent material, topography and site management. In this study, Kibutuka Miombo woodland contained more SOC than Kitulang'halo Miombo woodland ecosystem. It is reported that, SOC content increases with precipitation and temperature, driving decomposition and incorporation of soil organic matter (SOM) (Sierra *et al.*, 2015). Studies by Marin-Spiotta and Sharma (2013) reported that, in tropical soils, climate (rainfall and temperature) plays a major role in C storage than other factors. However, these explanations are not sufficient to explain the difference between the two Miombo woodland sites found in this study where annual rainfall for these sites ranges from 700 mm to 1000 mm and 600 mm to 900 mm, respectively with average annual temperatures of 25^0C for Kibutuka and 24.3^0C for Kitulang'halo. The two sites have more less similar climatic conditions and their difference in SOC could be due to other factors such as topography. The terrain at Kitulang'halo forest is predominantly hilly compared to the low-lying Kibutuka site. This might have caused to different soil formation pathways and hence the difference in the amounts of SOC. Sheikh *et al.* (2009) reported decreasing SOC stocks in sub-tropical forest of Garhwal Himalayas with elevation due to increased in sustainable management strategies at lower elevation. Contrary to this results, Tang *et al.* (2012) and Hoffmann *et al.* (2014) reported an increase SOC stocks with elevation due to relatively higher moisture levels and lower temperatures. According to Sierra *et al.* (2015), the major factors affecting organic matter in soils are elevation, climate and biotic condition. Other factors include clay, depth and development of the profile.

Physical characteristics and the underlying geologic formation determine both nutrient content and the water nutrient retention capacity of a given soil (Bell, 1982). Availability of nutrients is influenced by underlying geology, rate of weathering and transport of materials into and out of an area by water (Bell, 1982). Angai forest soils in Liwale district are least affected by erosion, deep being sandy clays (Dondeyne *et al.*, 2004), while Kitulang'halo soils are shallow due to a hard pan being sandy loams making them to contain less SOC (Msanya *et al.*, 1995). The SOC contents generally increases with clay and fine silt contents due to the ability of clay to protect SOC from decomposition by various physicochemical mechanisms (Heitkamp *et al.*, 2012).

5.6 Vertical Distribution of Soil Organic Carbon at Kitulang'halo and Kibutuka Miombo Woodland Ecosystems

Soil organic carbon content declined consistently with increasing soil depth in non-disturbed natural forest and this was shown in Kitulang'halo forest (Fig. 2). Yang *et al.* (2010) suggested that the vertical distribution of SOC in forest ecosystems at 20 cm intervals decrease as soil depth increases. This agrees with findings of other researchers (Jobbágy and Jackson, 2000). Some researchers suggested that the decrease of decomposition rates with soil depth affects vertical distribution of SOC (Gill *et al.*, 1999). Kalbitz (2008), on the other hand, found that the vertical distribution of soil organic carbon was affected by cultivation practices within the forest. Similar results were found in this study (Figure 2) where SOC contents in Kibutuka plots increased from 0-20 cm to 20-40 cm depths followed by decreasing pattern below. There are distinct differences in the distribution of SOC in the topsoil and the subsoil depending on land use (Lal, 2003). The clearing of forests for sesame crop production at Kibutuka in Liwale district invariably resulted in loss of SOC in the topsoil. This may be due to removal of biomass (including slash burning) during land clearing, and a reduction in the quantity and quality of organic inputs added to the soil. Soil mixing in tillage systems can completely translocate surface SOC to lower depths (Riezebos and Loerts, 1998). Similarly a decrease in SOC was reported when forest land was converted to cultivated land in the tropical forest (Celik, 2005). In addition, Guo and Gifford (2002) reported that soils lost 42% of their SOC stock upon conversion from forest to crop land.

However, different forest management regimes are observed between the two sites in this study. Kitulang'halo is a reserved forest under Sokoine University of Agriculture (SUA) and central government, and is subjected to lower encroachment pressure compared to Kibutuka Miombo woodland. A large part of the forest at Kibutuka is managed by the village government making it easily encroached. Therefore. land use planning will be the best option to reverse this situation in Liwale district to enhance forest conservation to increase SOC stock through REDD^{+} initiatives.

5.7 Soil Organic Carbon Determined by two Methods of Soil Organic Carbon Analysis

Results showed that Walkley-Black method (NAFORMA approach) estimated SOC higher than the Mid Infrared method (ICRAF approach) (Table 5). The results are similar to those reported by Stevens *et al.* (2006) whereby the Walkley-Black laboratory values were higher than those determined by radiation method. Wang *et al.* (2012) also reported that the Walkley-Black method provided an accurate estimate of SOC with 100% recovery for most soil samples. Lettens *et al.* (2007) also demonstrated that compared with the automated CNS technique, the Walkley-Black method yielded almost 100% recoveries for SOC in the calcareous soils. Owing to its low cost and minimal requirements in laboratory equipment, the Walkley-Black procedure is still used widely to measure SOC content (Chatterjee *et al.*, 2009). This could be due to its reliable estimation of SOC when compared with other analytical approaches. But if the sources of laboratory error can be identified, the infrared method may in fact be a better tool for interpretation than the wet chemical analysis (Janik *et al.*, 1998).

Soil sample collection using ICRAF approach was challenged by presence of a hardpan at Kitulang'halo plots. but not at Kibutuka plots. There were no difficulties in both plots of Kitulang'halo and Kibutuka when sampling soil using NAFORMA approach. Our assumptions is that sampling approaches for determining SOC at any location is influenced by soil type or parent material, topography and site management. And therefore, traditional methods should not be ignored particularly when determining SOC in different ecosystems.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Miombo woodland of Kitulang'halo had higher tree species richness than Kibutuka. Tree species richness had very weak and positive relationship with SOC but there was no relationship between tree species richness and the other soil chemical variables at Kibutuka plots. Miombo woodland of Kibutuka had higher values of most of the soil chemical properties. There was higher amount of SOC in deeper soil layers (30-100 cm) than in the top layers (0-30 cm) in both Kitulang'halo and Kibutuka Miombo woodlands. In this study, results suggest that vertical distribution of SOC would be affected by tillage activities. However, Kibutuka plots showed greater amount of SOC than Kitulang'halo. Analytical method of determining SOC using Walkley-Black method (NAFORMA approach) estimated higher SOC than MIR method (ICRAF approach) but further studies are needed.

6.2 Recommendations

Promoting conservation activities to increase tree species diversity and SOC stock through REDD$^+$ initiatives in Kitulang'halo and Kibutuka Miombo woodland ecosystems is crucial. The patterns and controls of soil chemical properties, and importantly SOC storage are critical for understanding of the ecosystem processes and the feedback of this pool to atmospheric composition and climate change.

There is also a need for greater understanding of the appropriate sampling and analytical methods to estimate SOC stock in different ecosystems. Proper forest management is essential for ecosystem processes and functions leading into producing a wide range of ecosystem services. Finally, further research is required in other forest/woodland ecosystems in Tanzania to investigate the relationships between tree species diversity and soil properties.

REFERENCES

Andersen, K. M., Benjamin, L., Turner, B. L. and Dalling, J. W. (2009). Soil-based habitat partitioning in understorey palms in lower montane tropical forests. *Journal of Biogeography* 37: 278-289.

Backéus, I., Pettersson, B., Strömquist, L. C. and Ruffo, C. (2006). Tree communities and structural dynamics in Miombo (*Brachystegia–Julbernardia*) woodland, Tanzania. *Forest Ecology and Management* 230(1-3):171-178.

Baize, D. (1993). *Soil Science Analysis:* A Guide to Correct Use, John Wiley and Sons Ltd., West Sussex. 192pp.

Barbour, M., Burk, J. H., Pitts, W. D., Gillians, F. S. and Schwartz, M. W. (1999). *Terrestrial Ecology*. Chicago, Illinois: Addson Wesley Longman, Inc.

Batjes, N. H. (1996). Total carbon and nitrogen in the soils of the world. *European Journal of Soil Science* 47(2): 151-163.

Bell, R. H. V. (1982). The effect of soil nutrient availability on community structure in African ecosystems. In: Huntley, B. J. and Walker, B. H. (eds) *Ecology of Tropical Savannas*. Springer, Berlin, Heidelberg New York. pp193–216.

Brady, K. U., Kruckeberg, A. R. and Bradshaw, H. D, Jr. (2005). Evolutionary ecology of plant adaptation to serpentine soils. *Annual Review of Ecology, Evolution and Systematics* 36: 243-266.

Brahim, N., Ibrahim, H. and Hatira, A. (2014). Tunisian Soil Organic Carbon Stock– Spatial and Vertical Variation. *Procedia Engineering* 69:1549-1555.

Campbell, B., Frost, P. and Byron, N. (1996). Miombo woodlands and their use: Overview and key issues. Center for International Forest Research (CIFOR), Bogor, Indonesia.

Cannone, N., Wagner, D., Hubberten, H. W., Guglielmin, M. (2008). Biotic and abiotic factors influencing soil properties across a latitudinal gradient in Victoria Land, Antarctica. *Geoderma* 144: 50-65.

Cécillon, L., Barthès, B. G., Gomez, C., Ertlen, D., Genot, V., Hedde, M., Stevens, A. and Brun, J. J. (2009). Assessment and monitoring of soil quality using near-infrared reflectance spectroscopy (NIRS). *European Journal of Soil Science* 60(5): 770-784.

Celik, I. (2005). Land-use effects on organic matter and physical properties of soil in a southern Mediterranean highland of Turkey. *Soil and Tillage Research* 83: 270–277.

Chatterjee, A., Lal, R., Wielopolski, L., Martin, M. Z. and Ebinger, M. H. (2009). Evaluation of different soil carbon determination methods. *Critical Reviews in Plant Science* 28(3): 164-178.

Chidumayo, E. N. and Kwibisa, L. (2003). Effects of deforestation on grass biomass and soil nutrient status in Miombo Woodland, Zambia. *Agric. Ecosyst. Environ.* 96: 97-105.

Cleveland, C. C., Townsend, A. R. and Taylor, P. (2011). Relationships among net primary productivity, nutrients and climate in tropical rain forest: a pan-tropical analysis. *Ecol. Lett.* 14: 939-947.

Desanker, P. V., Frost, P. G. H., Justice, C.O. and Scholes, R. J. (1997). The Miombo network frameworks for a terrestrial transect study of land-use and land-cover change in the Miombo ecosystems of Central Africa. *The International Geosphere-Biosphere Programme* (IGBP) Report 41, Stockholm, Sweden.

Dondeyne, S., Wijffels, A., Emmanuel, L. B., Deckers, J. and Hermy, M. (2004). Soils and vegetation of Angai forest: Ecological insights from a participatory survey in South Eastern Tanzania. *Crit. Rev. Plant Sci.* 22(2): 151-184.

Dubbin, W. E., Penn, M. G. and Hodson, M. E. (2006). Edaphic influences on plant community adaptation in the Chiquibul forest of Belize. *Geoderma* 131:76-88.

Engler, R. and Guisan, A. (2009). Predicting plant distribution and dispersal in a changing climate. *Diversity and Distribution* 15(4): 590-601.

Euro Consult, (1989). Agriculture Compendium for Rural Development in the Tropics and Sub Tropics, 3rd ed., Elsevier, Amsterdam, Oxford, New York, Tokyo. 740pp.

FAO (2001). Global Forest Resources Assessment 2000. Main report. *FAO Forestry Paper* 140: 479.

Fine, P. V. A., Douglas, C. D., Muñoz, G. V., Mesones, I. and Cameroun, K. M. (2005). The contribution of edaphic heterogeneity to the evolution and diversity of Burseraceae trees in the Western Amazon. *Evolution* 59(7): 1464-1478.

Folster, H., Dezzeo, N. and Priess, J. A. (2001). Soil-vegetation relationship in base-deficient premontane moist forest-savanna mosaics of the Venezuelan Guyana. *Geoderma* 104: 95-113.

Fornara, D. A. and Tilman, D. (2008). Plant functional composition influences rates of soil carbon and nitrogen accumulation. *Journal of Ecology* 96: 314–322.

Foth, H. D. (2006). *Fundamentals of Soil Science.* 8th Edition. New York: John Wiley and Sons.

Frost, P. (1996). The ecology of Miombo Woodlands. In: B Campbell (Ed.): *The Miombo in Transition: Woodlands and Welfare in Africa.* Bogor, Indonesia: Center for International Forestry Research (CIFOR). pp11-57.

Fu, B. J. Liu, S. L. Ma, K. M. and Zhu, Y.G. (2004). Relationships between soil characteristics, topography and plant diversity in a heterogeneous deciduous broad-leaved forest near Beijing, China. *Plant and Soil* 261(1-2): 47–54.

Gao, J., Lei, G., Zhang, X. and Wang, G. (2014). Can δ 13 C abundance, water-soluble carbon, and light fraction carbon be potential indicators of soil organic carbon dynamics in Zoigê wetland? *Catena* 119: 21-27.

Giliba, R. A., Boon, E. K., Kayombo, C. J., Musamba, E. B., Kashindye, A. M. and Shayo, P. F. (2011). Species Composition, Richness and Diversity in Miombo Woodland of Bereku Forest Reserve, *Tanzania Journal of Biodiversity* 2(1): 1-7.

Gill, R., Burke, I. C., Milchunas, D. G. and Lauenroth, W. K. (1999). Relationship between root biomass and soil organic matter pools in the shortgrass steppe of eastern Colorado. *Ecosystems 2*(3): 226-236.

Givnish, T. J. (1999). On the causes of gradients in tropical tree Diversity. *Journal of Ecology* 87 (2): 193–210.

Guo, L. B. and Gifford, R. M. (2002). Soil carbon stocks and land use change: a Meta analysis. *Global Change Biology* 8(4): 345-360.

Harrison, R. B., Footen, P. W. and Strahm, B. D. (2011). Deep soil horizons: contribution and importance to Soil Carbon pools and in assessing Whole-Ecosystem Response to Management and Global Change. *Forest Science* 57: 67-76.

Harrison, S. and Cornell, H. (2008). Toward a better understanding of the regional causes of local community richness. *Ecology Letters* 11: 969–979.

Harrison, S. and Grace, J. B. (2007). Biogeographic affinity helps explain productivity-richness relationships at regional and local scales. *American Naturalist* 170: 5-15.

Harrison, S., Davies, K. F., Grace, J. B., Safford, H. D. and Viers, J. H. (2006). Exotic invasion in a diversity hotspot: disentangling the direct and indirect relationships of exotic cover to native richness in the Californian serpentine flora. *Ecology* 87: 695-703.

Harrison, S., Safford, H. D., Grace, J. B., Viers, J. H. and Davies, K. F. (2006). Regional and local species richness in an insular environment: serpentine plants in California. *Ecological Monographs* 76: 41–56.

Heitkamp, F., Jacobs, A., Jungkunst, H. F., Heinze, S., Wendland, M. and Kuzyakov, Y. (2012). Processes of soil carbon dynamics and ecosystem carbon cycling in a changing world. In R. Lal *et al.* (eds.), *Recarbonization of the Biosphere* (395-428). Springer Netherlands.

Hoffmann, U., Hoffmann, T., Johnson, E. A. and Kuhn, N. J. (2014). Assessment of variability and uncertainty of soil organic carbon in a mountainous boreal forest (Canadian Rocky Mountains, Alberta). *Catena* 113: 107 – 112.

Huber-Sannwald, E. and Jackson, R. B. (2001). Heterogeneous soil-resource distribution and plant responses – from individual-plant growth to ecosystem functioning. *Progress in Botany* 62: 451-476.

Jackobson, S. T. (1992). Chemical reactions and air change during decomposition of organic matter. *Resource Conserve and Recycle* 6: 259-266.

Janik, L. J., Merry, R. H. and Skjemstad, J. O. (1998). Can Mid Infrared Diffuse Reflectance analysis replace soil extractions? *Animal Production Science* *38*(7): 681-696.

Janssens, F., Peeters, A. and Tallowin, J. R. B. (1998). Relationship between soil chemical factors and grassland diversity. *Plant and Soil* 202(1): 69–78.

Jobbágy, E. G. and Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *EcologicalApplications* 10: 423- 436.

John, R., Dalling, J. W., Harms, K. E., Yavitt, J. B., Stallard, R. F., Mirabello, M., Hubbell, S. P., Valencia, R., Navarrete, H., Vallejo, M. and Foster, R. B. (2007). Soil nutrients influence spatial distributions of tropical tree species. *PNAS* 104: 864-869.

Kalbitz, K. and Kaiser, K. (2008). Contribution of dissolved organic matter to carbon storage in forest mineral soils. *Journal of Plant Nutrition and Soil Science* 171(1): 52-60.

Kent, M. (2012). *Vegatation Description and Data Analysis: A Practical Aproach*. USA. (Second Ed.). pp1- 414.

Kessler, M., Hertel, D., Jungkunst, H. F., Kluge, J., Abrahamczyk, S. and Bos, M. (2012) Can Joint Carbon and Biodiversity Management in Tropical Agroforestry Landscapes Be Optimized? *PLoS ONE* 7(10): e47192. doi:10.1371/journal.pone.0047192.

Laclau, J. P., Ranger, J. and Goncalves, J. L. M. (2010). Biogeochemical cycles of nutrients in tropical Eucalyptus plantations main features shown by intensive monitoring in Congo and Brazil. *Forest Ecology and Management* 259: 1771-1785.

Lal, R. (2003). Cropping systems and soil quality. *Journal of Crop Production* 8(1/2): 33-52.

Lal, R. (2005). Soil erosion and carbon dynamics. *Soil and Tillage Research* 81(2): 137-142.

Landon, J. R. (1991). *Booker Tropical Soil Manual,* A handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Longman Scientific and Technical Publishers, Essex. 474pp.

Leskiw, L. A. (1998). Land capability classification for forest ecosystems in the oil sands region. Alberta Environmental Protection. *Edmonton* 30(18): 23-56.

Lettens, S., De Vos, B., Quataert, P., Van Wesemael, B., Muys, B. and Van Orshoven, J. (2007). Variable carbon recovery of Walkley-Black analysis and implications for national soil organic carbon accounting. *European Journal of Soil Science* 58(6): 1244-1253.

Li, Q., Ding, Z., Wang, Y., Zhang, X. and Hang, Y. (2009). Soil nutrients levels and annual dynamic changes of Laoshan Tea Gardens. *Chinese Agricultural Science Bulletin* 13: 108-122.

Liu, F., WU, X., Bai, E., Boutton, T. W. and Archer, S. R. (2011). Quantifying soil organic carbon in complex landscapes: an example of grassland undergoing encroachment of woody plants. *Global Change Biology* 17(2): 1119-1129.

Maestre, F. T. and Reynolds. J. F. (2006). Small-scale spatial heterogeneity in the vertical distribution of soil nutrients has limited effects on the growth and development of *Prosopis glandulosa* seedlings. *Plant Ecology* 183: 65-78.

Magurran, A. E. (1988). Why diversity? In *Ecological Diversity and Its Measurement* (1-5). Springer Netherlands.

Marini, L., Scotton, M., Klimek, S., Isselstein. J. and Pecile, A. (2007). Effects of local factors on plant species richness and composition of Alpine meadows. *Agriculture, Ecosystems and Environment* 119: 281-288.

Marín-Spiotta, E. and Sharma, S. (2013). Carbon storage in successional and plantation forest soils: a tropical analysis. *Global Ecology and Biogeography* 22(1): 105-117.

McCarty, G. W., Reeves. J. B., Reeves V. B., Follett. R. F. and Kimble. J. M. (2002). Mid-Infrared and Near-Infrared Diffuse Reflectance Spectroscopy for Soil Carbon Measurement. *Soil Science Society of America Journal* 66: 640–646.

Medinski, T. (2007). Soil Physical and Chemical Properties and their Influence on the Plant Species Richness of Arid, South-Western Africa. Thesis Presented for the Degree of Master of Science in Conservation Ecology, University of Stellenbosch.

Meersmans, J., van Wesemael, B., De Ridder, F., Fallas Dotti, M., De Baets, S. and Van Molle, M. (2009). Changes in organic carbon distribution with depth in agricultural soils in Northern Belgium. *Global Change Biology* 15: 2739-2750.

Msanya, B. M., Kimaro, D. N. and Shayo-Ngowi, A. J. (1995). Soils of Kitulang'halo forest reserve area, Morogoro district, Tanzania.

Munishi, P. K. T., Mringi, S., Shirima, D. D. and Linda, S. K. (2010). The role of the Miombo woodlands of the Southern highlands of Tanzania as carbon sinks, *Journal of Ecology and the Natural Environment* 2(12): 261-269.

Nadeau, M. B. and Sullivan, T. P. (2015). Relationships between plant biodiversity and soil fertility in a mature tropical forest, Costa Rica, *International Journal of Forestry Research* 2015: 1-13.

Nduwamungu, J. (1997). *Tree and Shrub Diversity in Miombo Woodlands. A Case Study at SUA Kitulang'halo Forest Reserve, Morogoro, Tanzania.* M.Sc. Thesis, Unpublished. Morogoro: Sokoine University of Agriculture. 143pp

Nirmal Kumar, J. I., Kumar, R. N., Bhoi, R. K. and Sajish, P. R. (2010). Tree species diversity and soil nutrient status in three sites of tropical dry deciduous forest of western India. *Tropical Ecology* 51(2): 273–279.

Périé, C. and Ouimet, R. (2008). Organic carbon, organic matter and bulk density relationships in boreal forest soils. *Canadian Journal of Soil Science* 88: 315–325.

Per-Marten, S., Felix, H., Christoph, L., Ann-Catrin, F. and Hermann, F. J. (2014). Higher subsoil carbon storage in species-rich than species-poor temperate forests. *Environmental Research Letters* 9: 1-3.

Riezebos, H. T. and Loerts, A. C. (1998). Influence of land use change and tillage practice on soil organic matter in southern Brazil and eastern Paraguay. *Soil and Tillage Research* 49 (3): 271-275.

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.

Sheikh, M. A., Kumar, S. and Kumar, M. (2012). Above and below ground organic carbon stocks in a sub-tropical Pinus roxburghii Sargent forest of the Garhwal Himalayas. *Forestry Studies in China* 14(3): 205-209.

Sierra, C. A., Trumbore, S. E., Davidson, E. A., Vicca, S. and Janssens, I. (2015). Sensitivity of decomposition rates of soil organic matter with respect to simultaneous changes in temperature and moisture. *Journal of Advances in Modeling Earth Systems* 7(1): 335-356.

Silva, D. M. and Batalha, M. A. (2008). Soil-vegetation relationships in cerrados under different fire frequencies. *Plant and Soil* 311: 87-96.

Stephens, J. (2006). Growing interest in carbon capture and storage (CCS) for climate change mitigation. *Sustainability: Science, Practice, and Policy* 2(2): 4-13.

Stevens, A., Van Wesemael, B., Vandenschrick, G., Touré, S. and Tychon, B. (2006). Detection of carbon stock change in agricultural soils using spectroscopic techniques. *Soil Science Society of America Journal* 70(3): 844-850.

Swift, R. S. (2001). Sequestration of carbon by soil. *Soil Science* 166(11): 858-871.

Tang, J. W., Yin, J. X., Qi, J. F., Jepsen, M. R. and Lü, T. T. (2012). Ecosystem carbon storage of tropical forests over limestone in Xishuangbanna, southwest China. *Journal of Tropical Forest Science* 24(3): 399 – 407.

Udoh, B. T., Ogunkunle, A. O. and Ndaeyo, N. U. (2007). Influence of soil series and physico-chemical properties on weed flora distribution at Moor Plantation Ibadan, South-western Nigeria. *Journal of Agricultural Society Science* 3(2): 55-58.

UNFCCC (2011). Policy approaches and positive incentives on issues relating to reducing emissions from deforestation and forest degradation in developing countries; and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries. Part C and appendix II. *Report of the Conference of the Parties on its 16th Session. 1/CP.16 FCCC/CP/2010/7/Add.1.*

URT (2013). The 2012 population and housing census population distribution by administrative areas. Tanzania Census General Report. 58, 83.

Walkley, A. and Black, I. A. (1934). An examination of the Degljareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* 37: 29-38.

Wang, X., Wang, J. and Zhang, J. (2012). Comparisons of three methods for organic and inorganic carbon in calcareous soils of northwestern China. *PlOS one* 7(8): e44334.

Wu, H., Guo, Z. and Peng, C. (2003). Distribution and storage of soil organic carbon in China. *Global Biogeochemical Cycles* 17: 1048.doi: 10.1029/2001GB001844.

Yang, Y. H., Fang, J. Y., Guo, D. L., Ji, C. J. and Ma, W. H. (2010). Vertical patterns of soil carbon, nitrogen and carbon: nitrogen stoichiometry in Tibetan grasslands, *Bio-geosciences Discuss* 7: 1-24.

Zahabu, E. (2001). Impact of Charcoal Extraction to the Miombo Woodlands: The Case of Kitulangalo area, Tanzania. MSc. Thesis, Unpublished. Morogoro: Sokoine University of Agriculture. 121pp.

Zare, S., Jafari, M., Tavili, A., Abbasi, H. and Rostampour, M. (2011). Relationship between environmental factors and plant distribution in arid and semi-arid area (Case Study: Shahriyar Rangelands, Iran). *American-Eurasian Journal of Agriculture and Environmental Science* 10(1): 97-105.

Zhang, K., Dang, H., Zhang, Q. and Cheng, X. (2015). Soil carbon dynamics following land-use change varied with temperature and precipitation gradients: evidence from stable isotopes. *Global Change Biology* 21(7): 2762-2772.

APPENDICES

Appendix 1: Amount of soil organic carbon per depth at Kitulang'halo and Kibutuka Miombo woodland ecosystems, Tanzania

Soil depth (cm)	Kibutuka SOC (t ha^{-1})	Kitulang'halo SOC (t ha^{-1})
0-20	32.25±3.09	34.32±4.08
20-40	39.41±4.12	31.26±3.09
40-60	31.34±3.07	20.42±3.05
60-80	26.37±3.06	18.12±3.04
80-100	26.08±3.06	14.35±2.81
Total	155.45	118.47

Appendix 2: Tree species at Kitulang'halo and Kibutuka Miombo woodlands ecosystems

S/N	Tree species at Kitulang'halo	Abundance	Tree species at Kibutuka	Abundance
1	*Albizia anthelmintica*	17	*Acacia abbreviata*	2
2	*Acacia gummifera*	1	*Acacia aesidentalis*	2
3	*Acacia hockii*	2	*Acacia mellifera*	1
4	*Acacia mellifera*	14	*Acacia nigrenscens*	32
5	*Acacia nigrescens*	35	*Acacia nitotica*	2
6	*Acacia pennata*	12	*Acacia robusta*	32
7	*Acacia pentagona*	9	*Acacia sp*	2
8	*Acacia nilotica*	12	*Acacia tortilis*	1
9	*Acacia robusta*	15	*Acacia xanthophloea*	13
10	*Acacia polyacantha*	3	*Adansonia digitata*	2
11	*Acacia sieberiana*	2	*Albizia harveyi*	19
12	*Acacia sp.*	12	*Allophylus sp.*	3
13	*Acacia tortilis*	6	*Afzelia quanzensis*	4
14	*Afzelia quanzensis*	2	*Annona sp.*	6
15	*Albizia chinensis*	1	*Bauhonia Peterseana*	6
16	*Albizia harveyi*	18	*Berchemia discolor*	1
17	*Albizia versicolor*	1	*Boscia salicitoria*	4
18	*Albizia petersiana*	9	*Brachystegia boehmii*	2
19	*Beilschmiedia kweo*	8	*Brachystegia speciformis*	16
20	*Berchemia discolor*	1	*Bridelia cathartica*	4
21	*Bombax rhodognaphalon*	1	*Cassia abbreviata*	7
22	*Boscia salicifolia*	2	*Cassia sp.*	4
23	*Brachystegia boehmii*	36	*Cambretum binderianum*	19
24	*Brachystegia microphylla*	6	*Combretum collinum*	30
25	*Brachystegia spiciformis*	20	*Combretum molle*	61
26	*Bridelia cathartica*	3	*Combretum zeyheri*	35
27	*Carpodiptera africana*	4	*Commiphora africana*	4
28	*Casaeria battiscombei*	15	*Commiphora mossambicensis*	5

29	*Cassia abbreviata*	23	*Combretum sp.*	41
30	*Cassia fistula*	1	*Cordia africana*	5
31	*Catunaregam spinosa*	1	*Cordia sp.*	5
32	*Combretum binderanum*	10	*Crossopteryx febrifuga*	8
33	*Combretum collinum*	20	*Dalbergia boehmii*	23
34	*Combretum fragrans*	6	*Dalbergia nitidula*	2
35	*Combretum molle*	68	*Dalbergia melaxylon*	8
36	*Combretum gueinzii*	1	*Diospyros sp.*	4
37	*Combretum schumannii*	12	*Diospyros fischeri*	2
38	*Combretum zeyheri*	17	*Diplorhynchus condylocarpon*	27
39	*Commiphora africana*	36	*Dombeya rotundifolia*	5
40	*Crossopteryx febrifuga*	1	*Dombeya shupangae*	3
41	*Croton scheffleri*	13	*Erythrophleum africanum*	2
42	*Crotton sylvaticus*	13	*Euclea natalensis*	2
43	*Cussonia arborea*	6	*Ficus altissima*	1
44	*Cussonia spicata*	5	*Ficus thonningii*	1
45	*Cussonia zimmermannii*	5	*Flacourtia indica*	3
46	*Dalbergia boehmii*	5	*Flueggea virosa*	1
47	*Dalbergia melanoxylon*	24	*Friesodielsia oborata*	2
48	*Dalbergia nitidula*	2	*Grewia holstii*	1
49	*Dalbergia obovata*	9	*Grewia sp.*	3
50	*Deinbolia borbonica*	1	*Grewia bicolar*	4
51	*Dibera laranthfolia*	1	*Holarrhena pubescens*	1
52	*Dichrostachys cinerea*	30	*Hymenocardia ulmoides*	6
53	*Diplorhynchus condylocarpon*	52	*Julbernardia globiflora*	8
54	*Diospyros consolatae*	1	*Kigelia africana*	1
55	*Diospyros fischeri*	5	*Lannea schimperi*	3
56	*Diospyros sp.*	1	*Lannea schweifurthii*	14
57	*Dombeya cincinata*	1	*Lannea sp.*	3
58	*Dombeya rotundifolia*	28	*Lecaniodiscu traxinifolius*	6
59	*Dracaena deremensis*	6	*Lonchocarpus bussei*	5
60	*Drypetes gerrardii*	2	*Lonchocarpus capasa*	14

61	*Drypetes reticulata*	2	*Manilkara mochisia*	1
62	*Ehretia amoena*	1	*Markhamia lutea*	18
63	*Erythrococca kirkii*	2	*Markhamia platycalyx*	17
64	*Erythroxylum emarginatum*	1	*Markhamia sp.*	3
65	*Erythroxylum sp.*	2	*Markhamia obtusifolia*	11
66	*Euphorbia nyikae*	7	*Markhamia zanzibarica*	13
67	*Flueggea virosa*	25	*Markhamia obtusifolia*	19
68	*Gardenia ternifolia*	1	*Milletia stuhlmannii*	41
69	*Grewia bicolor*	10	*Milletia sp.*	4
70	*Grewia ectasicarpa*	2	*Monodora junodii*	1
71	*Grewia similis*	3	*Ochna sp.*	1
72	*Grewia sp.*	25	*Pseudolachnostylis maprouneifolia*	12
73	*Grewia goetziana*	15	*Pterocarpus Angolensis*	10
74	*Haplocoelum inoploeum*	1	*Stereospermum kunthianum*	3
75	*Holarrhena pubescens*	2	*Strychnos potatus*	1
76	*Julbernardia globiflora*	60	*Strychnus angolensis*	11
77	*Lannea schweinfurthii*	7	*Pteleopsis myrtifolia*	10
78	*Kigelia africana*	2	*Pterocarpus sp.*	7
79	*Lannea schimperi*	4	*Pterocarpus tinctorius*	17
80	*Lannea sp.*	5	*Strychnus spinosa*	5
81	*Lecaniodiscus fraxinifolius*	1	*Strychnos potatorum*	6
82	*Lonchocarpus bussei*	6	*Strychnos innocua*	3
83	*Lonchocarpus capassa*	2	*Schlerocarya birrea*	1
84	*Manihot asculenta*	2	*Sclerocary birrea*	11
85	*Manilkara sulcata*	3	*Scorodophloeus sp.*	2
86	*Markhamia obtusifolia*	7	*Steculia africana*	1
87	*Markhamia sp.*	7	*Sterculia appendiculata*	2
88	*Markhamia zanzibarica*	4	*Stereospermum kunthianum*	10
89	*Millettia usaramensis*	24	*Tamarindus indica*	1
90	*Ochna schweinfurthiana*	2	*Terminalia*	2

			brownii	
91	*Ozoroa insignis*	1	*Terminalia sambesiaca*	1
92	*Philippia pallidiflora*	26	*Terminalia sericea*	11
93	*Pseudolachnostylis maprouneifolia*	1	*Terminalia sp.*	1
94	*Pteleopsis myrtifolia*	20	*Terminalia prunioides*	2
95	*Pterocarpus angolensis*	10	*Turaea Stuhlumanii*	1
96	*Pterocarpus tinctorius*	17	*Vitellariopsis cuneata*	6
97	*Pterocarpus rotundifolius*	8	*Vitex mombassae*	5
98	*Ritchiea albersii*	1	*Vitex sp.*	2
99	*Rhus sp.*	11	*Xeroderris Stuhlumanii*	14
100	*Senna siamea*	4	*Xylotheca tettensis*	2
101	*Senna sp.*	1	*Zanthoxylum holtsianum*	1
102	*Sorindeia obtusifolia*	5	*Ziziphus mucronata*	3
103	*Sclerocarya birrea*	13		
104	*Scorodophleus fischeri*	39		
105	*Spirostachys africana*	6		
106	*Sterculia africana*	9		
107	*Sterculia appendiculata*	5		
108	*Sterculia stenocarpa*	2		
109	*Sterculia quinqueloba*	1		
110	*Strychnos innocua*	1		
111	*Syzygium guineense*	1		
112	*Teclea simplicifolia*	4		
113	*Tamarindus indica*	4		
114	*Terminalia grandifolia*	2		
115	*Terminalia sambesiaca*	3		
116	*Terminalia mollis*	3		
117	*Turraea stuhlmanii*	1		
118	*Vangueria infausta*	2		
119	*Vangueria sp.*	8		
120	*Vernonia subuligera*	4		
121	*Xeroderris stuhlmannii*	17		
122	*Ximenia caffra*	1		
123	*Zanthoxylum chalybeum*	10		

Appendix 3: Soil properties at Kitulang'halo Miombo woodlands, Morogoro-Tanzania

Plot	% SOC	TN (%)	Av. P Bry-1	CEC	Ca^{2+}	Mg^{2+}	K+	Na+	pH	BD
1	1.07	0.09	5.30	22.80	4.10	1.69	0.24	0.12	6.48	1.3
2	0.80	0.08	0.75	35.40	37.67	6.00	0.51	0.15	7.24	1.3
3	0.47	0.06	6.56	18.00	11.99	5.42	0.77	0.14	7.46	1.3
4	0.38	0.04	5.44	37.00	6.35	2.25	0.69	0.16	7.59	1.4
5	0.42	0.04	30.37	10.00	5.41	1.75	0.13	0.12	7.47	1.5
6	0.61	0.06	3.60	11.20	7.29	2.39	0.28	0.16	6.6	1.4
7	1.04	0.09	6.31	20.20	10.49	4.42	0.15	0.17	7.04	1.3
8	0.65	0.05	5.30	18.80	9.92	3.75	0.51	0.15	6.23	1.3
9	0.38	0.03	4.03	14.00	7.67	2.56	0.76	0.16	6.53	1.3
10	1.27	0.10	7.45	10.00	2.59	0.67	0.16	0.14	5.85	1.4
11	1.11	0.09	7.78	8.20	4.29	0.56	0.14	0.18	6.21	1.5
12	0.95	0.08	2.08	10.00	4.47	0.67	0.11	0.15	6.86	1.4
13	3.01	0.20	21.99	17.80	22.86	2.56	0.99	0.17	6.45	1.4
14	2.10	0.13	4.11	13.60	6.92	2.61	0.74	0.17	7.24	1.4
15	1.91	0.13	4.67	14.00	10.30	3.44	1.05	0.16	6.82	1.4
16	1.82	0.12	8.84	9.40	7.11	2.89	0.72	0.16	6.19	1.5
17	1.66	0.11	26.04	19.60	10.11	3.89	0.62	0.19	6.53	1.4
18	1.53	0.13	64.73	19.60	22.86	5.22	0.83	0.19	7.33	1.5
19	0.98	0.08	2.84	13.20	11.43	6.00	0.59	0.18	6.6	1.5
20	0.64	0.07	7.70	11.00	5.79	5.75	0.85	0.21	6.3	1.4
21	0.42	0.06	28.56	16.80	15.38	15.83	1.02	0.18	6.61	1.3
22	0.57	0.06	16.93	16.00	10.30	7.83	0.89	0.16	6.94	1.4
23	1.39	0.11	24.27	36.00	10.49	14.86	0.61	0.18	6.56	1.5
24	0.70	0.07	8.21	16.80	9.55	14.03	0.16	0.21	7.1	1.4
25	0.59	0.06	54.49	26.40	28.12	18.83	1.27	0.23	6.63	1.5
26	2.08	0.15	3.85	11.80	9.55	9.17	0.53	0.18	7.31	1.4
27	1.63	0.12	4.93	16.00	6.92	9.58	0.26	0.21	6.67	1.4
28	1.19	0.09	5.93	14.80	6.73	9.72	0.77	0.21	6.71	1.4
29	1.40	0.13	6.13	14.00	2.78	4.03	0.83	0.20	6.77	1.4
30	0.97	0.09	37.16	22.00	13.46	13.33	1.46	0.22	6.59	1.4

Appendix 4: Soil properties at Kibutuka Miombo woodlands in Liwale District, Tanzania

Plot	% SOC	TN (%)	Av. P Bry-1	CEC	Ca^{2+}	Mg^{2+}	K+	Na+	pH	BD
1	1.17	0.02	3.22	16.60	10.11	3.77	0.42	0.11	5.5	1.3
2	0.6	0.01	33.50	30.20	11.80	2.75	0.36	0.05	6.7	1.2
3	0.53	0.02	4.29	15.60	6.73	2.97	0.64	0.06	6.0	1.3
4	0.4	0.02	5.37	12.20	7.11	2.63	0.48	0.10	5.2	1.7
5	0.35	0.02	28.94	13.20	8.42	2.60	1.14	0.08	6.1	1.6
6	0.92	0.02	6.00	18.80	7.29	2.81	0.95	0.04	6.3	1.4
7	0.71	0.03	20.60	24.40	9.74	2.57	1.24	0.17	6.2	1.5
8	0.49	0.02	2.59	36.60	11.80	13.74	0.26	0.11	6.4	1.6
9	1.07	0.02	4.67	29.20	9.17	2.62	0.69	0.11	5.9	0.9
10	2.2	0.01	6.31	20.80	7.29	2.62	0.63	0.11	5.6	1.2
11	1.49	0.01	4.11	12.20	4.29	2.16	0.28	0.22	5.5	1.7
12	1.04	0.01	15.54	20.40	13.68	2.78	1.04	0.12	6.3	1.6
13	0.62	0.02	8.33	8.60	4.47	1.86	0.43	0.12	6.3	1.2
14	0.49	0.03	5.17	13.80	9.92	2.89	0.53	0.16	5.4	1.3
15	1.13	0.03	4.42	28.70	30.00	4.71	1.53	0.16	5.7	1.4
16	0.98	0.03	2.52	19.00	14.81	3.41	1.14	0.50	5.9	1.5
17	0.74	0.03	2.84	21.60	14.25	4.49	0.94	0.18	6.0	1.5
18	0.59	0.03	2.65	15.40	9.92	4.91	1.82	0.16	6.0	1.5
19	0.56	0.08	7.45	10.60	5.79	2.19	0.87	0.15	6.2	1.5
20	0.65	0.04	6.69	20.20	14.25	3.65	1.14	0.12	6.3	1.5
21	0.6	0.04	5.30	14.80	10.30	5.19	0.56	0.22	6.0	1.3
22	1.6	0.04	18.95	8.40	5.79	1.35	0.35	0.09	5.1	1.4
23	1.04	0.03	14.15	24.60	15.94	5.19	0.56	0.20	5.7	1.8
24	0.89	0.07	13.90	12.80	8.80	2.09	0.36	0.20	5.3	1.6
25	0.77	0.05	29.32	20.40	16.32	3.58	0.28	0.19	6.6	1.5
26	0.86	0.04	7.83	13.80	9.55	2.98	0.42	0.14	5.0	1.7
27	1.49	0.04	8.97	15.60	8.23	2.41	0.95	0.12	6.2	1.2
28	0.82	0.04	7.07	35.20	31.13	3.77	0.85	0.14	6.0	1.6
29	0.68	0.06	13.77	18.20	15.00	4.12	0.89	0.21	6.3	1.3
30	0.55	0.03	6.69	36.20	27.52	4.01	0.37	0.18	6.0	1.5
31	0.45	0.03	2.46	21.20	14.25	2.31	0.39	0.17	5.8	1.5
32	1.54	0.03	3.98	32.20	20.98	7.67	0.79	0.14	6.1	1.2
33	1.03	0.04	7.95	22.20	17.63	5.11	0.52	0.18	6.2	1.4