

***THE POTENTIAL OF ROTATIONAL WOODLOT AND NGITIRI SYSTEMS IN  
CARBON SEQUESTRATION AND SOIL FERTILITY IMPROVEMENT IN MEATU  
DISTRICT, TANZANIA***

**HILDA SAGONDI NGAZI**

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

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**ABSTRACT**

Rotational woodlots and *Ngitiri* fallows have considerable amount of carbon storage and potential for soil fertility improvement though not well quantified. The objectives of this study were to develop allometric models for determination of above-ground carbon, quantify above and below-ground carbon, estimate soil organic carbon stocks and assess soil fertility status in rotational woodlots and *Ngitiri* in Meatu District, Tanzania. In each system, the experiment comprised 3 treatments, replicated 3 times in 8 and 10 year-old *Acacia* fallows. Ninety sample trees were measured for diameter at breast height (DBH) and height, and used in destructive sampling for development of allometric models. Several models were developed and the best fit model based on higher coefficient of determination ( $R^2$ ) and low standard error was used to predict above-ground carbon for all tree components. Soil samples at 20 cm intervals were taken from 100 cm profile at each plot, standard routine soil analysis for organic carbon, nitrogen, phosphorus and potassium was done. The best fit models for *A. tortilis* and *A. polyacantha* were those which used DBH as predictor variable for different tree species. The highest total tree carbon storage under woodlots and *Ngitiri* was  $22.0 \pm 3.14$  and  $17.18 \pm 2.13$  t ha<sup>-1</sup> respectively. In two years *Ngitiri* and woodlots captured between 6.4 to 9.16 and 1.41 to 5.02 t ha<sup>-1</sup> respectively of above-ground carbon. *Ngitiri* and woodlots captured 91.3 and 60.7 t ha<sup>-1</sup> of soil organic carbon respectively in two years. Total nitrogen, inorganic nitrogen and Olsen phosphorus was higher in woodlots than *Ngitiri* while potassium was low in woodlots than *Ngitiri*. The best fit models for predicting above-ground carbon in *Acacia* species are those which used DBH as predictor variables, though height may as well be used in some cases. Rotational woodlots and *Ngitiri* have the potential for carbon storage and soil fertility improvement. Though, *Ngitiri* can sequester more carbon than woodlots while woodlots have higher potential for soil fertility improvement. Therefore,

it is recommended that *Ngitiri* be used for carbon sequestration while woodlots are appropriate for above-ground carbon storage and soil fertility improvement.

**DECLARATION**

**I, HILDA SAGONDI NGAZI**, do hereby declare to the Sokoine University of Agriculture, that this thesis is my own original work and has neither been submitted nor being concurrently submitted for degree award in any other institution.

\_\_\_\_\_

Hilda Sagondi Ngazi  
(PhD candidate)

\_\_\_\_\_

Date

\_\_\_\_\_

Prof. P.K.T. Munishi  
(Supervisor)

\_\_\_\_\_

Date

\_\_\_\_\_

Prof. J.M.R. Semoka  
(Supervisor)

\_\_\_\_\_

Date

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**DEDICATION**

Dedicated to the memory of my father Sospeter Sagondi and my sister Anna Gindu.



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The overall total N is within the range (0.1-0.2 %) rated as low for tropical soils (Landon, 1991; Msanya et al., 2001). Besides, high total N values of 0.3 % in soils under patches of grassland were reported in Meatu District, than total N reported in the present study (Kamwenda, 2006). Soils under Ngitiri in the present study have pH values higher than 8.0 and such levels decrease bacterial activity and consequently nitrification of OM which is most likely cause of low total N (Landon, 1991). 105

On the other hand, findings in this study are contrary to reports documented in other studies. In a 6-year old plantation of *A. senegal* in Sudan at 0.3 m soil depth very low concentrations of total N of 0.027% were reported by Tahir et al., (2009), lower than the overall values of total N ( $0.15 \pm 0.01$  %) in soils under Ngitiri. These differences may be due to difference in tree species and systems management. In addition, the values of total N at the surface soil layer under Ngitiri were higher than total N for pure cultivated sorghum of 0.13% in Sudan (Tahir, et al., 2009). 105

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The overall total N is within the range (0.1-0.2 %) rated as low for tropical soils (Landon, 1991; Msanya et al., 2001). Besides, high total N values of 0.3 % in soils under patches of grassland were reported in Meatu District, than total N reported in the present study (Kamwenda, 2006). Soils under Ngitiri in the present study have pH values higher than 8.0 and such levels decrease bacterial activity and consequently nitrification of OM which is most likely cause of low total N (Landon, 1991). 105

On the other hand, findings in this study are contrary to reports documented in other studies. In a 6-year old plantation of *A. senegal* in Sudan at 0.3 m soil depth very low concentrations of total N of 0.027% were reported by Tahir et al., (2009), lower than the overall values of total N ( $0.15 \pm 0.01$  %) in soils under Ngitiri. These differences may be due to difference in tree species and systems management. In addition, the values of total N at the surface soil layer under Ngitiri were higher than total N for pure cultivated sorghum of 0.13% in Sudan (Tahir, et al., 2009). 105

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**LIST OF ABBREVIATIONS AND ACRONYMS**

AGB	Above-ground biomass
ASB	Alternative to Slash and Burn
BGB	Below-ground biomass
C	Carbon
Ca	Calcium
CEC	Cation Exchange Capacity
cm	Centimeter
CMD	Clean Development Mechanism
CO <sub>2</sub>	Carbon-dioxide
D	Diameter
FAO	Food and Agriculture Organization
g	Gram
GHG	Green House Gas
GIS	Geographical Information system
GPS	Global Positioning System
ha	Hectare
ICRAF	International Centre for Research in Agroforestry
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
kg	Kilogram
m	Metre
Mg	Magnesium
mm	millimetre
Mn	Manganese
MNRT	Ministry of Natural Resources and Tourism

MPTS	Multipurpose tree species	
MRP	Minjingu rock phosphate	
N	Nitrogen	
Na	Sodium	
OC	Organic Carbon	-
OM	Organic Matter	
P	Phosphorus	
Pg	Penta gram	
PBECSA	Programme for Basic Energy and Conservation in Southern Africa	
R <sup>2</sup>	Coefficient of determination	
SE	Standard Error	
SOC	Soil Organic Carbon	
SOM	Soil Organic Matter	
Tg	Tetra gram	
TOC	Total Organic Carbon	
UN	United Nations	
UNFCCC	United National Framework Convention of Climate Change	
US	United States	



## CHAPTER ONE

### 1.0 INTRODUCTION

#### 1.1 Background Information

The total area occupied by forests and woodlands in Tanzania is estimated to be 38.8 million hectares, which is equivalent to 41% of the total land area (PBECSA, 2008). About two thirds of forest and woodland area is covered by woodlands and are found on general lands, whereas, 13.0 million ha of forests and woodlands have been gazetted as forest reserves. The area under private and community forestry ranges from 70,000 to 150,000 ha (Monela *et al.*, 2005).

Forests and woodlands play an important role in the livelihoods of Tanzanians. It is estimated that more than 90% of the population uses biomass energy for cooking and heating. Forests and woodlands also provide non-woody products such as honey, bee wax, fruits, medicines and gum Arabica. They also provide logs for timber, paper, wood-based panels and poles.

Forests and woodlands in Tanzania are a big carbon (C) reservoir, important in mitigating emissions of carbon dioxide (CO<sub>2</sub>), which is a Green House Gas (GHG) used by plants during photosynthesis and implicated in global warming and climate change (Malimbwi *et al.*, 1994; Munishi, 2001; Munishi and Shear, 2004; Munishi and Shirima, 2009; 2010).

In addition forests and woodlands play a critical role in terrestrial C cycle. Active forest management maintain high amount of standing biomass which reduce tropical deforestation and GHG emissions (Fingleton, 2005). Other authors have reported on estimates of biomass in tree stands. For example at Kitulangalo Forest Reserve they reported 4.54 t ha<sup>-1</sup> of

biomass, however, these estimates were low because the trees were small (Malimbwi *et al.*, 1994). On the other hand, it has been reported that estimates of tree biomass including roots was 1055 and 790 t ha<sup>-1</sup> in Usambara and Uluguru montane forests respectively (Munishi, 2001). Since carbon is stored in the above-ground biomass (in dry weight) assuming that 0.5 of the biomass is carbon it is therefore important to estimate stand biomass in tropical forests and woodlands for quantification of carbon (Munishi and Shear, 2004; Baccini *et al.*, 2008; Basuki *et al.*, 2009).

Recently methods for estimating biomass and C stored in terrestrial plant ecosystems have become very important worldwide. These estimates are required to satisfy the requirements of United Nations Convention on Climate Change (1992). Since the Kyoto protocol gained force in 2005 the demand for C credits has been escalating in international markets (Basuki *et al.*, 2009). Governments need this information to report on the state of their national forests (Spercht and West, 2003). Individual forest owners need to quantify the amount of wood they have available or if an open market for sale of sequestered carbon develops the amount of carbon they have available for sale as carbon credits. Therefore, accurate approach for estimating carbon stocks in the above-ground biomass is essential.

The use of allometric models is an accurate approach for estimating carbon stocks in the above-ground biomass (Spercht and West, 2003). Allometry is a technique, which involve relationships between above-ground biomass of trees and tree stem diameter or height and between below-ground biomass and above-ground biomass (Spercht and West, 2003).

Most important, forests and woodlands play an active role in soil fertility improvement (Fingleton, 2005). Soils that develop under natural forests and woodlands are fertile, well structured, and have good water holding capacities (Young, 1997).

Several reports have demonstrated the attractive role of nitrogen (N) fixing trees as sources of N and organic matter (OM) and their potential in soil fertility improvement and maintenance (Pandey, 2007). Nitrogen fixing trees such as *A. polyacantha* and *A. nilotica* have been reported in Shinyanga to fix large quantities of mineralized N (32-82 and 28-73 kg ha<sup>-1</sup>, respectively (Banzi *et al.*, (2002). Besides, *Acacias* are leguminous plants and have the ability to enhance soil fertility, and have nodules on their roots which harbour N-fixing bacteria. The symbiotic N-fixation between bacteria and atmospheric N enhances soil fertility (Dharani, 2006).

On the other hand, forests and woodland resources face enormous pressure from commercialization of cash crops which lead to expansion of cultivation such as replacing forests by annual crops especially cotton, rice and tobacco, increasing fire hazards and illegal harvesting of forest products (Fingleton, 2005; Monela *et al.*, 2005). In addition, forest and woodlands face pressure from human settlements, livestock grazing, mining, frequent resettlement of refugees particularly in western Tanzania. The activities led to deforestation estimated to be 91,000 ha of forests and woodland lost every year (Monela *et al.*, 2005; PBECSA, 2008).

Deforestation results in loss of biological diversity, severe land degradation and leads to desertification, among other things. These problems are acute in arid and semi-arid regions of Tanzania, especially in Shinyanga region and in particular Meatu District (Kamwenda, 2002; Monela *et al.*, 2005; UNFCCC, 2008).

Deforestation may have negative consequences in terms of CO<sub>2</sub> emissions. For example, in Venezuela, forest clearing represents a major source of C emissions accounting for more than 40% of CO<sub>2</sub> emissions (Bonduki and Swisher, 1995). In Africa, deforestation accounts

for nearly 70% of total emissions (FAO, 2005). Studies in northeastern Tanzania, indicated that desertified landscapes had an overall lower soil organic matter (SOM) (Oba *et al.*, 2008). Low SOM suggests that desertification may increase C emissions from degraded lands, which may serve as a source of C emissions (Lal, 2001). In northwestern Tanzania particularly Meatu District exemplifies typical ecosystem degradation caused by land clearing which led to severe deforestation and erosion problems (Otsyina *et al.*, 1997; Kamwenda, 2002; Nnko, 2003).

Alternative ways to reduce deforestation, mitigate GHG emissions and improve soil fertility have been widely acknowledged (Nyadzi, 2004; Munishi and Shear, 2004; Jama and Zeila, 2005). Forest ecosystems such as *Ngitiri* and other forestry-crop systems (agroforestry) have potential to capture and retain large volumes of C over long periods as trees absorb C through photosynthesis process.

*Ngitiri* is a customary land use system in Meatu District, which is an enclosure for management of natural regeneration to enhance biodiversity and livelihood security in the society (Kaale *et al.*, 2003; Monela *et al.*, 2005). Areas of grazing land which have been closed to livestock by the village council or a private landowner are called *Ngitiri* in the local language of the *wasukuma* tribe. This is an example of an indigenous silvopastoral system for land rehabilitation (Jama and Zeila, 2005). *Ngitiri* has great potential in supply of fodder and fuel wood and contributes up to 80% of the total fuel wood consumption (Kamwenda, 1999; Nnko, 2003).

Rotational woodlots is an agroforestry technology which involves growing trees with annual crops in rotation and use the trees to supply fuel wood to replace wood collected from natural woodlands or forests (World Agroforestry Centre, 2009). Management

practices of *Ngitiri* have been adapted in developing rotational woodlots (Otsyina *et al.*, 1997).

Rotational woodlots and *Ngitiri* can mitigate atmospheric CO<sub>2</sub> emissions through C accumulation in the vegetation and soil and thus are implicated positively in climate change as carbon sinks (Munishi *et al.*, 2004; Ajayi *et al.*, 2005; Swamy and Puri, 2005; Jama and Zeila, 2005; Luhende *et al.*, 2006; Nyadzi, *et al.*, 2006a; Kimaro *et al.*, 2007). They also have the potential to improve soil fertility. These potentials are yet to be fully evaluated and the carbon storage and soil fertility status of rotational woodlots and *Ngitiri* remain a significant knowledge gap.

In light of this, five key research questions are addressed in this study: Firstly the aim was to develop allometric models for determination of above-ground C stocks for dominant *Acacia* (*Acacia nilotica*, *Acacia polyacantha* and *Acacia tortilis*). Secondly, to quantify above and below-ground C storage/stocks of *Acacia* fallow. Thirdly, to estimate soil C storage/stocks. Fourthly, to assess soil fertility status in terms of mineral N, available P, exchangeable K and CEC of *Acacia* fallows. Finally, to propose management strategies to reduce CO<sub>2</sub> emissions and improve soil fertility through rotational woodlots and *Ngitiri*.

## **1.2 Problem Statement and Justification**

Forest and land management including *Ngitiri* and agroforestry practices such as rotational woodlots can greatly reduce problems of CO<sub>2</sub> emissions (Munishi, 2001; Munishi *et al.*, 2004; Nyadzi, 2004; Kimaro *et al.*, 2007). Studies in semi-arid areas of eastern and western Tanzania demonstrate the high capacity of planted tree fallows in rotational woodlots compared to native forests to reduce deforestation and sequester atmospheric C which reduces the GHG emissions in the atmosphere (Nyadzi *et al.*, 2003; Kimaro *et al.*, 2007). In

addition, studies in northeastern Tanzania showed that improved land use through seasonal grazing and resting increased soil carbon pools by 50 % in desertified landscapes (Oba *et al.*, 2008).

Despite the importance of rotational woodlots and *Ngitiri* as well as being under high utilization pressure for fuel wood and fodder, little is known about the values of the existing ecosystem services such as potentials in above and below-ground carbon storage, soil organic carbon stocks/storage and soil fertility status (Kamwenda, 1999; Nnko, 2003).

Although these systems have high potential in above and below-ground C storage, their role in carbon storage and sequestration has not been evaluated/quantified. Rotational woodlots were developed in Meatu District to curb deforestation and reverse land degradation (Otsyina *et al.*, 1997). However, its assessment has mainly focused on evaluating the system for firewood and fodder production. In addition, there is still little information on soil organic C stocks/storage potential in rotational woodlots.

In *Ngitiri* most of the assessments have concentrated on fodder dry matter yield and firewood production but not on assessment of above and below-ground C storage and soil organic C stocks/storage. Therefore, there is limited information on above-ground C and soil organic C stocks/storage in *Ngitiri* (Nnko, 2003; Monela *et al.*, 2005).

In addition, very few species-specific allometric models have been developed for quantifying above-ground carbon storage. Therefore, development of allometric models for quantification of above-ground C storage in different tree species of *Acacia* will facilitate estimation of C storage in rotational woodlots and *Ngitiri*.

On the part of soil fertility improvement, most studies in rotational woodlots have concentrated on assessing the improvement of available N and the response of crops to this nutrient (Palm, 1995; Rao and Kwesiga, 2002; Banzi *et al.*, 2002; Nyadzi, *et al.*, 2006b). Many authors have reported substantial changes of soil N under tree based rotations (Nyadzi *et al.*, 2003; Kimaro *et al.*, 2007). Studies in western Tanzania revealed that after tree harvest in a 4-8 year woodlot, soil fertility improved, which resulted to increase in the subsequent maize crop mainly through increased availability of N on top soil layer (Nyadzi *et al.*, 2003). On the other hand, increased crop yield may be enhanced by availability of P and K and other soil key factors such as cation exchange capacity (CEC) and organic carbon (OC) that improve soil physical characteristics (Szott, *et al.*, 1999; Kolawole, *et al.*, 2005).

Rotational woodlots contribute to availability of P, K and other nutrients but its role in enhancing the availability of P and K under Meatu District conditions is still not quantified. Similarly, studies on *Ngitiri* have concentrated on fodder dry matter yield and firewood production but not on soil fertility improvement ((Nnko, 2003; Monela *et al.*, 2005).

### **1.3 Objectives of the Study**

#### **1.3.1 Overall objective**

To assess the potential of rotational woodlots and *Ngitiri* in C sequestration and soil fertility improvement.

#### **1.3.2 Specific objectives**

The specific objectives were to:

- (a) Develop allometric models for determination of above-ground carbon storage/stocks for *A. nilotica*, *A. polyacantha* and *A. tortilis*.

- (b) Quantify above and below-ground C storage/stocks of *A. nilotica*, *A. polyacantha* and *A. tortilis* fallows in rotational woodlots and *Ngitiri* systems.
- (c) Estimate soil C storage/stocks under rotational woodlots and *Ngitiri* systems.
- (d) Assess soil fertility status in terms of mineral N, available P, exchangeable K and CEC of *A. nilotica*, *A. polyacantha*, *A. tortilis* fallows in rotational woodlots and *Ngitiri* systems.
- (e) Propose management strategies to reduce CO<sub>2</sub> emissions and improve soil fertility through rotational woodlots and *Ngitiri* systems.



## CHAPTER TWO

### 2.0 LITERATURE REVIEW

#### 2.1 Definitions

##### (a) Carbon Sequestration

Carbon sequestration refers to removal or capture and storage of carbon from the atmosphere in carbon sinks (such as oceans, forests or soils) through physical or biological processes, such as photosynthesis (Stuart and Gregory, 2009).

##### (b) Rotational Woodlots

Rotational woodlots is an agroforestry technology which involves growing trees with annual crops in rotation and use the trees to supply fuel wood to replace wood collected from natural woodlands or forests (World Agroforestry Centre, 2009).

##### (c) *Ngitiri*

*Ngitiri* is a customary land use system in Meatu District, which is an enclosure for management of natural regeneration to enhance biodiversity and livelihood security in the society (Kaale *et al.*, 2003; Monela *et al.*, 2005).

#### 2.2 Rotational Woodlots

Rotational woodlots was developed recently to curb fuel wood deficit in semi-arid areas of eastern and north-western Tanzania of Shinyanga and Tabora regions (Kamwenda, 2002; Ramadhan *et al.*, 2002; Nyadzi *et al.*, 2003). It is an agroforestry option, which attempts to simulate the traditional fallow system in shifting cultivation where trees contribute to maintaining soil fertility through nutrient cycling during fallow phase (Otsyina *et al.*, 1993). Rotation woodlots do combine effectively the principles of crop

production and forest management hence providing multiple products such as provision of products and services with valuable economic, social and environmental benefits.

Rotational woodlots involves three inter-related phases, namely

- (i) Initial tree establishment phase
- (ii) Tree fallow phase
- (iii) Post-fallow period

### **2.2.1 Initial tree establishment phase**

In rotational woodlots, this phase involves establishment of multipurpose trees in association with food crops. Farmers intercrop trees with crops for the first 2-3 years until canopy closure. However, cropping is discontinued when tree root systems and canopies are fully developed and crop yields are reduced. For example, studies in Shinyanga reported that in the second season after woodlot establishment in *Acacia polyacantha*, *Acacia nilotica* and *Leucaena leucocephala* reduced maize yields by 30.8%, 32.6% and 10.0%, respectively (Otsyina and Asenga (1994). In the third season, trees increased both crown and below-ground structures, yield reductions become very severe amounting to over 50% of sole maize (control). However, duration of the intercropping phase depends on tree species, tree density, and management practices such as branch pruning and type of the associated crop (Otsyina *et al.*, 1996).

### **2.2.2 The tree-fallow phase**

During this phase, cropping is discontinued and trees are allowed to grow for another 2-4 years to produce wood and replenish soil fertility through nitrogen fixation and nutrient retrieval from sub-soil and litter decomposition. However, this may not be seen in an existing fallow since most of nutrient stock will be in the biomass. For example, in a 4-

year fallow of rotation, highest amount of nutrients were accumulated in the biomass of *L. leucocephala* (N, 1158; P, 62; K, 563 kg ha<sup>-1</sup>). These values were two-fold greater than the stand of *A. nilotica* and three-fold higher than that of *Eucalyptus tereticornis* (Toky and Singh, 1995).

Trees are branch-pruned periodically or thinned selectively to widen spacing between trees, and fuel wood can be obtained during this phase. Undergrowth of palatable herbaceous grasses and shrubby species can be encouraged and utilized for feeding livestock. Other value adding outputs for which the system can be used to produce are honey, bee wax and mushrooms. The fallow phase may last for two to four years depending on the tree species, environmental variables such as rainfall and intended use of trees.

### **2.2.3 Post-fallow period**

Trees are harvested and crops intercropped with coppicing tree stumps that produce wood. At the end of the fallow phase, whole plots or parts of the woodlot for the above-ground biomass can be clear felled depending on intended use. Very significant amounts of firewood maybe obtained from fast growing species such as *Leucaena* species and *Acacia* species (*A. polyacantha*, *A. crassicarpa*, *A. julifera* and *A. auriculiformis*). For example, in Shinyanga woodlots at the age of seven years and for trees that was not subjected for pruning earlier produced 89 t ha<sup>-1</sup> for fast growing species such as *L. leucocephala* compared to *A. nilotica* which produced 8 t ha<sup>-1</sup> of wood (Nyadzi, 2004).

Food crops grown following tree harvest, benefit from the increase in soil organic matter, nutrient cycling and N fixed by leguminous trees. For example, studies in Tabora reported that maize following harvest of *A. crassicarpa* in woodlot fallows generally produced greater yields (2 t ha<sup>-1</sup>) than maize after natural fallow (Nyadzi, 2004).

During this phase trees coppice may be pruned to reduce competition for light and nutrients with food crops and provide organic material that is incorporated into the soil. The coppice growth may be used either for fodder or soil fertility improvement. Depending on land availability, the cleared woodlot plots may be cropped for 3-4 years before trees are allowed to regenerate and revert to the fallow phase.

Coppice management systems such as lopping, pruning and whole tree harvest are practised to minimize labour costs while maintaining vigour of trees (Nyadzi, 2004). However, whole tree harvest in turn may have the potential for high nutrient depletion. Studies in India have shown that in rotational woodlots fast growing exotic trees such as *Acacia* species and *Paraserianthes* species resulted in marked loss of nutrients from the site especially when whole tree harvesting was practiced (Kumar *et al.*, 1998). As much as 46% of the total above-ground N was tied up in stem wood of *Acacia* species, another 30% in branches and 23% in the foliage at 8.8 years of age. In *Paraserianthes* species, about 53% of N was tied up in stem. Therefore, during the harvest operation, if the branches and stem alone are removed leaving the foliage and roots at the site, nutrient export from the site could be substantially reduced (Kumar *et al.*, 1998).

#### **2.2.4 Potential of rotational woodlots**

Compared to other agroforestry technologies such as hedgerow intercropping, rotational woodlots is more suitable for semi-arid conditions because sequential cropping arrangements minimize competition for growth resources especially soil moisture and produce higher wood yields due to longer tree fallows ((Rao, 1998; Nyadzi, 2003). Tree species with wider canopies and deep root system could be expected to produce high biomass under limited supply of resources as they can trap water and nutrients from deep soil horizons. For example, studies in semi-arid areas in Morogoro have shown that after

five years of fallow in woodlots *A. crassicarpa* produced high wood yields ( $51\text{Mg ha}^{-1}$ ) at low nutrient cost may be due to high nutrient use efficiency (Kimaro *et al.*, 2007).

### 2.2.5 Sustainability of rotational woodlots

Criteria considered to sustain rotational woodlots were the initial rate of the biomass yield and adaptation to the climate of tree species to be planted. Tree species with low nutrient uptake will sustain the system as small proportions of the nutrients are removed from the soil (Kimaro *et al.*, 2007).

In a six-year old fallow of rotational woodlots, *A. crassicarpa* was reported to sustain the system as it produced 42 and 120 % more wood compared to *A. polyacantha* and *A. nilotica* respectively, but contained considerably less nutrients (Kimaro *et al.*, 2007). For example, wood of *A. crassicarpa* contained 42 % less P, and 60 % less K compared to *A. nilotica* and *A. polyacantha*, respectively. Despite of high production of wood biomass, *A. crassicarpa* contains fewer nutrient elements in its biomass, hence exporting fewer nutrients during harvesting (Kimaro *et al.*, 2007).

Nitrogen-fixing tree species tend to have higher N concentrations in their biomass and their sustainability in terms of N is less critical compared to other nutrients because of biological N-fixation (Deans *et al.*, 2003). For example, *Senna* a non-N fixer grown in fallows of rotational woodlots, captured  $9.5\text{ t C ha}^{-1}$  in biomass on clay soil compared to  $2.1\text{ t C ha}^{-1}$  on sandy soil at Kalunga, Zambia, this shows that the tree species planted on nutrient depleted sandy soil can still support C sequestration and thus sustain the system (Kaonga and Smith, 2009).

### **2.3 Ngitiri**

*Ngitiri*, is a Sukuma word meaning enclosure, and refers to a traditional natural resource management system for dry season fodder reserve among the Sukuma people of Shinyanga region in the north of Tanzania (Hatibu, 2003; Barrow and Mlenge, 2004; Monela *et al.*, 2005).

*Ngitiri* is an example of an indigenous silvopastoral system for land rehabilitation (Jama and Zeila, 2005). It is comprised of an upper stratum dominated by *A. tortilis*, *A. nilotica*, *A. polyacantha* and *A. seyal* and a lower stratum composed of grasses, herbs and forbs (Kamwenda, 2002; Monela *et al.*, 2005). The structure and composition of *Ngitiri* are highly influenced by location, age, management practices and intensity (Kamwenda, 2002).

Vegetation and animals are main components of the *Ngitiri* and their interaction has a significant role in the management and sustainability of the system. There is improvement of biodiversity in the system, noticeably more vegetation because of woodland restoration. Studies in Shinyanga reported that more than a hundred and fifty two tree species, shrubs and climbers are found in the restored *Ngitiri*, in addition, there is an increase of the naturally regenerating indigenous trees being managed on farms (Mlenge, 2002).

#### **2.3.1 Establishment and management of Ngitiri**

Traditional *Ngitiri* were used to provide animal fodder for very young, old and sick animals unable to follow other animals to grazing lands and were usually established on degraded land and around homesteads (Kamwenda, 2002; Hatibu, 2003; Barrow, 2005; UNFCCC, 2008). The *Ngitiri* are of two types and vary in size; those privately owned

occupying an area ranging from 0.2 to 20 ha and the communally owned ranging from 20 to 50 ha (Kamwenda, 2002; Jama and Zain, 2005).

Boundaries are not rigidly marked and physical barriers are not established except that ownership rights are well respected. By-laws enforced by the community protect *Ngitiri* and offenders must pay penalties. At the beginning of the wet season, the *Ngitiri* are closed and the system involves protection of land to allow natural regeneration of indigenous species to take place (Hatibu, 2003). In the dry season when pasture becomes scarce, *Ngitiri* are opened for grazing. Very little management is required during the rainy season other than regular protection from grazing animals (Kamwenda, 1999; Kaale *et al.*, 2003).

### **2.3.2 The potential of *Ngitiri***

*Ngitiri* has proved to be important in range management and forest restoration because it involves the conservation of fallow and rangelands to restore vegetation through controlled livestock grazing (Kamwenda, 2002). In addition, the system alleviates dry season fodder shortages, and protects the environment and improves the livelihoods of the community in Shinyanga Region (Barrow, 2005; UNFCCC, 2008).

As a traditional practice, *Ngitiri* has great potential of improving the ecological conditions of the soils and biodiversity of the sites where trees, grasses, herbs and forbs grow together (Kamwenda, 2002; Jama and Zain, 2005). Trees stabilize the soil because they are usually deep rooted and enrich the surface soil layer with their litter (leaves, flowers, twigs and branches). Furthermore, the extensive ground cover reduces runoff, helps to prevent soil erosion and facilitates water infiltration, percolation and storage in the soil.

*Ngitiri* has the potential to improve the cash income and hence the livelihoods of the rural community including the poor. For instance, it has been reported that, in Shinyanga region over 64% of the households have benefited from *Ngitiri* (Monela *et al.*, 2005). The average income per household per year was US \$ 1,000 which is a significant amount in a rural community (Monela *et al.*, 2005). Notably some cash amount from communal *Ngitiri* have been re-invested in development activities such as schools and dispensaries and individual farmers have used the cash from *Ngitiri* to pay higher education school fees for their children (Monela *et al.*, 2005; Fingleton, 2005).

#### **2.4 Biomass and Carbon Sequestration under Forest Management**

Forests are important C sinks than any other terrestrial ecosystem and they are natural brakes on climate change (Gibbs *et al.*, 2007). In Tanzania, like elsewhere in the tropics, forests and woodland are a big carbon reservoir, important in mitigating emissions of CO<sub>2</sub> and implicated on global warming and climate change (Malimbwi *et al.*, 1994; Munishi, 2001; Munishi and Shear, 2004; Tokar *et al.*, 2007).

Deforestation and forest degradation is the main source of GHG emissions in most countries in the tropics (Tokar *et al.*, 2007). In 1990's the amount of CO<sub>2</sub> released to the atmosphere through deforestation was estimated to be 15-20% of the annual GHG emissions per year (Houghton, 2005). For example, clearing of forests in Venezuela, accounts for 40% of CO<sub>2</sub> emissions in the country (Bonduki and Swisher, 1995). Deforestation accounts for 70% of the total emissions in Africa (FAO, 2005). In Tanzania, it is estimated that 91,000 ha of forests and woodland are lost every year through deforestation releasing tons of CO<sub>2</sub> to the atmosphere (Monela *et al.*, 2005).



The main C pools in tropical forest ecosystems are the living biomass of trees and understorey vegetation and the dead mass of litter, woody debris and soil organic matter (SOM) (Gibbs *et al.*, 2007). The C stored in the above-ground biomass of trees is the largest pool and the most directly affected by deforestation and degradation. However, the below-ground biomass is also considered to be important as it has a significant contribution on the C stocks of the forest biomass (referred to as the above and below-ground biomass in this study). The below-ground biomass is estimated to be 20-30% of the above-ground tree biomass (Malimbwi *et al.*, 1994; Lasco and Suson, 1999; Ramankutty *et al.*, 2007). Estimating C in above-ground biomass is the most important step in quantifying C stocks and fluxes from tropical forests (Munishi and Shear, 2004; Northup *et al.*, 2005; Gibbs *et al.*, 2007).

Rotational woodlots and *Ngitiri* can also mitigate atmospheric CO<sub>2</sub> and GHG emissions. Carbon emissions may be reduced through emission avoidance or conserving existing C pools on the land and C sequestration (Munishi, 2001; Munishi and Shear, 2004).

The amount of C sequestered depends largely on the technology put in place, tree species, management practises and soil depth (Swamy and Puri, 2005; Ajayi *et al.*, 2005). Studies in Tabora indicated that different tree species in rotational woodlots affected C sequestration differently due to their biomass allocation patterns (Nyadzi *et al.*, 2003). Total C in foliage plus wood of *Acacia* species ranged from 13.3 to 30.3 Mg ha<sup>-1</sup> for 5 years fallow (Nyadzi, *et al.*, 2006a). Biomass of above-ground parts of *Leucaena* species increased from 4 kg ha<sup>-1</sup> in the first year to 64 kg ha<sup>-1</sup> in the sixth year rotational woodlots fallow (Lasco and Suson, 1999). At Kitulangalo Forest Reserve in Tanzania, it was observed that *Acacia nilotica* was second most abundant in terms of numbers (112 stems ha<sup>-1</sup>) in miombo woodland but the biomass was not high (4.54 t ha<sup>-1</sup>) because the

trees were small Malimbwi *et al.*, (1994). In addition, *Acacia* as a genus had 28% of the total biomass, however, *Albizia* species, *Acacia polyacantha* and other *Acacia* species represented the least abundant species in the miombo woodland (Malimbwi *et al.*, 1994). It has been observed that long-term fallows ( $\geq 5$  years) sequestered 32.6 - 73.9 tons ha<sup>-1</sup> of C compared to 3.0 - 8.9 t ha<sup>-1</sup> of short fallows ( $\leq 5$  years) of N-fixing tree species (Ajayi *et al.*, 2005).

In agroforestry systems, roots play a significant role in increasing the below-ground C pool because they comprise 25% to 30% of total tree biomass (Lasco and Suson, 1999). In miombo woodlands, it has been found that only 20% of the biomass was in the roots and the variation between species was very little (Malimbwi *et al.*, 1994). However, the 20% biomass obtained did not reflect a particular significant role of miombo woodland roots in storing atmospheric C compared to other forest types. Only limited biomass studies are reported especially those involving root excavations because they are expensive in terms of time and financial resources (Malimbwi *et al.*, 1994). As a result, most of the studies on roots have mainly focused on competitive interactions between trees and crops for moisture and nutrients (Lose *et al.*, 2003).

## **2.5 Quantification of Terrestrial Carbon**

Recently, the need for accurate information on biomass in tropical forests and plantations has become an important global agenda (Hiratsuka *et al.*, 2003; Zianis and Radoglou, 2006). In addition, estimates of C stocks within different land management systems are important elements in the design of land use systems that protect or sequester C (Woomer and Palm, 1998).

Direct quantification of C stocks in above-ground biomass requires destructive harvest, drying and weighing the biomass. Carbon content is estimated to be 50% of the dry biomass (Munishi and Shear; 2004; Gibbs *et al.*, 2007; Baccini *et al.*, 2008). Though accurate, destructive methods are labour intensive, expensive, destructive and impractical in remote areas or shrub lands, woodlands and forests (Chave *et al.*, 2005; Northup. *et al.*, 2005; Gibbs *et al.*, 2007).

An alternative method is to collect non-destructive measurements of tree components (eg. height, canopy dimensions, stem diameter), and relate these measurements to biomass with allometric equations developed from destructive sampling of trees from a range of size classes (Northup *et al.*, 2005). Nonetheless, develop volume models for different tree species and determine biomass from the wood density hence carbon stocks (Munishi and Shear, 2004).

These allometric models are quick, accurate and allow non-destructive estimates of above-ground biomass over a large area as compared to destructive harvest method. Therefore, allometric relationships have gained importance for estimating above-ground biomass used to quantify C stocks in a large area of forests without employing destructive harvesting.

### **2.5.1 Allometric models**

Aerial photography satellite, imagery and destructive sampling are methods used for forest biomass estimation. General and local biomass tables and allometric equations are developed for forest biomass estimation. Allometric equations provide attractive means for estimation of C pools in forest biomass because they are based on: existing information, variables which can be easily measured such as diameter at breast height

(DBH), total height (H) and girth at 10 cm height, crown length (Spercht and West, 2003; Zianis and Radoglou, 2006).

The development of allometric equations is based on destructive sampling of selected individuals covering the whole range of tree size and then fitted in the data collected in the field to provide estimates of biomass at plot level (Zianis and Radoglou, 2006). Allometric relationships have also been developed to estimate stem volume and biomass at stand level using DBH, H or DBH and H (Malimbwi *et al.*, 1994; Chamshama *et al.*, 2004; Munishi and Shear, 2004; Northup *et al.*, 2005).

Stand volume and stem biomass have been proved to be a good predictor of various forest parameters in the past, it has not been routinely measured in national forest inventories. However, these are limited to tree species. Shrub biomass is an important component of the total biomass especially in natural forest (Karki, 2002). Due to lack of methodology and difficulty in calculation, in some cases they are omitted and this results in underestimation of the total biomass (Karki, 2002). The formula for calculating the basal area of a shrub is the same as that used for tree biomass estimation which may over or under estimate the biomass depending on species (Palm, 2003).

Of the three allometric regression relationships, mixed species allometric equations are moderately accurate for making non-destructive estimates of above-ground biomass (Spercht and West, 2003). However, species-specific allometric equations that describe the relationships between tree species and biomass are more accurate and flexible (Spercht and West, 2003; Zianis and Radoglou, 2006). Though, use of regional or site-specific allometric equations where possible can as well be accurate. Species size-

biomass relationship may differ as tree change allocation pattern in response to disturbance, climatic and edaphic conditions (Northup *et al.*, 2005; Tobin *et al.*, 2006).

Many authors have reported species-specific allometric equations. For example; six different equations for six popular tree species were developed and one allometric equation for *Acacia harpophylla* was reported (Scanlan,1991; Spercht and West 2003) Some equations use DBH as a predictor variable whereas others use both DBH and height. A general biomass estimation allometric equation  $AGB = a (D^2)^b$  (where: AGB = above-ground biomass, a and b regression coefficients, a = y intercept and also a constant) from 26 sample trees using DBH as predictor variable was developed and reported to estimate above-ground biomass of *Acacia mangium* (Hiratsuka *et al.*, 2003).

However, there are problems with existing allometric models;

- (a) they are species-specific, each species requiring the application of its own regionally desired equation
- (b) they are not applicable in the same locality because of the narrow range of variables such as DBH
- (c) they are not applicable to the same species in different localities due to different climates and edaphic conditions.

In addition, they commonly over estimate biomass of old mature stands and have not been developed for an entire age sequence particularly in young afforested stands, which are important (Tobin, *et al.*, 2006).

Very few models have been developed for different tree species. However, eight equations were developed using DBH and height to estimate biomass and volume of

different tree components (stem, branch and roots) for 26 species in a forest reserve of miombo woodland (Malimbwi *et al.*, 1994). Six different equations were developed for estimating stem, branch and total tree biomass for 30 tree species commonly occurring in miombo woodlands (Chamshama *et al.*, 2004). Regression equations were developed to predict above-ground biomass, C and N content from stem and canopy for 10 shrub species common to subtropical thorn parklands (Northup *et al.*, 2005).

Based on literature I therefore developed carbon allometric models for estimating C stocks in above-ground tree components of dominant *Acacia* species.

### **2.5.2 Evaluation of allometric models**

In order to evaluate models many regression equations are developed before applying accuracy measures used to select the best model. Several authors have reported on accuracy measures applied in selecting best models (Makridakis *et al.*, 1998; Specht and West, 2003). Analysis of accuracy measures plays a major role in the selection of the best model as they deal with the error term. In any prediction, the aim is to reduce the error by reducing the gap between the actual and predicted values. Linear regression when used to a set of predictor variables against dependent variable gives many accuracy measures, but in this study, only three reliable accuracy measures were used; standard error (SE), coefficient of determination ( $R^2$ ), and overall F-value.

The coefficient of determination shows the percentage of the variation in dependent variable explained by the independent variables (Makridakis *et al.*, 1998). The regression equation is more accurate if it gives a lower value of SE and higher value of  $R^2$  (Malimbwi *et al.*, 1994; Chamshama *et al.* 2004; Spercht and West, 2003). It is argued that allometric models developed for biomass estimation based on only one response

variable (height) their accuracies is questionable (Harrington, 1979). In addition, too small sample size, even if  $R^2$  value is higher, the model may not be statistically sound. However, in such context when using regression analysis alternative hypothesis can be tested that the slope of the regression line is statistically significantly different from zero at the general accepted confidence level of 95%. Therefore, the model is accepted when the calculated F-value is greater than tabulated F-value at 95 % confidence level. Hence, the model with higher F-value can be selected as the best among the many models developed and evaluated (Maraseni *et al.*, 2005).

In addition, higher F-values,  $R^2$  and lower SE values sometimes do not guarantee the robustness of the model. The model can be improved by removing predictor variables that have no statistically significant contribution to the model. On individual coefficient of determination ( $a$ ,  $b$  and  $c$ ) t-test tells if the coefficient is statistically significant from zero in the presence of other predictor variables. The predictor variable whose coefficient value is statistically not different from zero could be removed from the model (Maraseni *et al.*, 2005). In addition, the intercept can be used even if its value is non-significant at zero (P-values lower than 0.05) as it does not cost extra money when included but it helps the prediction power of the model (Maraseni *et al.*, 2005).

### **2.5.3 Estimation of stand biomass and carbon in forest**

In order to estimate biomass and C in stand trees in any forest, measurements of DBH, height (H) and crown cover are taken at plot level. Thereafter, allometric models adapted or developed maybe fitted in the stand data collected in the field to provide estimates of biomass at plot level (Zianis and Radoglou, 2006). The biomass is computed per hectare and 50% of the biomass is estimated as C as reported by many authors (Munishi and Shear 2004; Baccini *et al.*, 2008; Basuki *et al.*, 2009). Studies in Philippines showed that

natural forests have a C density of 563 t ha<sup>-1</sup> in above-ground biomass (Lasco *et al.*, (2005). Bush lands and tree plantations have lower C densities of 200 t ha<sup>-1</sup>. In Tanzania, studies have reported tree biomass including roots of 1055 t ha<sup>-1</sup> and 790 t ha<sup>-1</sup> in Usambara and Uluguru montane forests, respectively (Munishi, 2001).

## 2.6 Soil Organic Carbon

Terrestrial ecosystems such as soils have a potential to sequester large amounts of C, which slow down the increase of atmospheric CO<sub>2</sub> concentrations. Soil organic matter is assumed to contain 50% C as SOC (Ardo and Olsson, 2004). Land use changes that degrade terrestrial resources will continue to be dominant drivers of environmental change in semi-arid areas for future decades (Scholes and van Breemen, 1997). These degraded semi-arid areas have a large potential to sequester C in the soil, which is preferred to storage in above-ground vegetation due to longer residence times (Lal *et al.*, 1999).

Changes in land use maybe net emitters or net sinks of atmospheric CO<sub>2</sub> which offer possibilities to sequester C in the soil and thereby mitigate the increase of atmospheric CO<sub>2</sub> as well as improve soil fertility. Studies in Sudan show that land under fallow for 30 years and followed by 30 years of continuous cultivation results into decrease in SOC depending on cultivation intensity (Ardo and Olsson, 2004). During fallow periods, about 4 g per m<sup>2</sup> year<sup>-1</sup> of SOC was sequestered. However, changing an intensely cropped area to permanent grassland would sequester 1–2 g of SOC per m<sup>2</sup> year<sup>-1</sup>. Continuous cultivation decreased the low soil carbon levels further (Ardo and Olsson, 2004).

Some studies had estimated that between 0.6 and 2 Pg C year<sup>-1</sup> could be sequestered by large-scale application of appropriate land management in the world's degraded lands



(Batjes, 1999). In addition, other authors estimated the attainable sink in dry lands to be 1.0 Pg C year<sup>-1</sup> over the next 50 years (Squires, 1998). Desertification control could globally sequester 0.9 – 1.9 Pg C year<sup>-1</sup> for 25 – 50 years (Lal, 2001).

Woodland canopies contribute significantly to C sequestration in dry land ecosystems (Traore *et al.*, 2007). The degree of accumulation of organic matter in the soil depends on the relationship between organic carbon inputs and the decomposition of litter. The quantity and quality of litter fall, and fine root decomposition contributes to enhancement of organic carbon from natural ecosystems (Traore *et al.*, 2007). *Acacia* species are perennials and return larger quantities of litter than annual grass species; therefore they sequester more carbon in the soil. In *A. polyacantha* there was more total OC (12 g C kg<sup>-1</sup> of soil) than in other *Acacia* species and gives more organic carbon in root litter (Traore *et al.*, 2007).

Studies in eastern Burkina Faso showed that native *Acacia* species contribute to improving C and N levels in cambisol and vertisol due to organic input and a reduction in nutrient leaching under their canopies (Traore *et al.*, 2007). The fine texture of cambisols and vertisols influence significantly the microbial processes. The clay content contributes to microbial biomass protection and OM stability that favors great sequestration of OC (Traore *et al.*, 2007). Sustainable management of *Acacia* stands and their introduction in degraded land afforestation can significantly improve the amount of C and N held in stand biomass and ecosystems regeneration (Traore *et al.*, 2007).

Most studies in agroforestry systems, which show the improvements of SOC have concentrated on changes in the top soil layer of 0–20 cm (Kang *et al.*, 1999; Takimoto *et al.*, 2009). For example, studies in Senegal's Sahel transition zone reported higher SOC

(25.35 t C ha<sup>-1</sup>) in the 0-40 cm soil profile under mixed scattered trees of *Acacia tortilis*, and *Balanites aegyptiaca* (Kang *et al.*, 1999).

However, several studies have reported soil C contents at deeper soil layers up to 100 cm. For example, in Seqou region of Mali, it is reported that soil C contents in four systems, across three depths ranged from 1.33 - 4.69 g kg<sup>-1</sup> in parklands, 1.11 - 4.42 g kg<sup>-1</sup> in live fence, 1.87 - 2.30 g kg<sup>-1</sup> in fodder bank, and 3.69 - 5.30 g kg<sup>-1</sup> in abandoned land correlated positively with silt and clay (Takimoto *et al.*, 2009). In Zambia, studies indicated that, SOC stocks to 200 cm depth ranged from 64.7 t ha<sup>-1</sup> under non-coppicing fallows to 184 t ha<sup>-1</sup> in 10-year old coppicing fallows (Kaonga and Smith, 2009).

In addition, agroforestry practices are efficient strategies used to improve SOM stocks, atmospheric C sequestration and soil quality (Diekow1 *et al.*, 2005). They reduce SOM losses by diminishing the mineralization and the erosion processes and can even increase the SOM stocks (Diekow1 *et al.*, 2005).

## **2.7 Soil Fertility and Fallow Systems**

Although much has been studied on *Ngitiri* in Tanzania, very little is known about the potential of the system with regard to soil fertility improvements. However, studies on *in situ* conservation of natural fallows and indigenous silvipastoral system from elsewhere may be comparable to the *Ngitiri* (Jama and Zain, 2005).

### **2.7.1 Fallow growing periods and soil fertility improvement**

The use of fallow periods is the only measure taken to improve soil fertility in areas where traditional agriculture is common (Craig, 1991). In Sudan, land is conventionally cultivated for 4–6 years and then left as fallow for 15–20 years. During the last few

decades, the length of the fallow periods has been reduced (Craig, 1991). This reduction may be caused by an increased demand for food; reduced crop yield due to decreasing precipitation, soil degradation and an increased desire to grow cash crops (Olsson, 1993).

Some authors had reported that SOM decreases with conversion of land management practices such as natural land converted to cultivated land (Wright, 2009). Continuous cultivation without addition of organic matter decreases SOM and N. In Burkina Faso, continuous cultivation of millet on sandy soils has been reported to slowly deplete soil N and P (Krogh, 1997). In Niger, significant increases of C and N with fallow age on sandy soils were observed (Wezel and Boecker, 1998). During the fallow periods, SOM increased and the natural regeneration of *Acacia senegal* and other *Acacia* species were common. In Tanzania, an increase in SOC and N with age of fallow was reported (Nyadzi *et al.*, 2003). Other environmental benefits of fallow periods with trees include low soil temperatures, high soil moisture, high SOC, greater fuel wood production and shade for grazing animals (Abril and Bucher, 2001; Nyadzi *et al.*, 2004).

SOM has favorable effects on the chemical, physical, and thermal properties of the soil, as well as on its biological activity. Soil quality is improved by an increased SOM content through better water-holding capacity, improved micro aggregate structure, preventing erosion, and providing a stabilizing effect on the soil structure (Batjes, 1999; Lal *et al.*, 1999). Soil organic matter is also an important determinant of the cation exchange capacity of soils (Batjes, 1999).

The length of the fallow growing period in large part determines the quantity of biomass produced and nutrients recycled. Studies in Nigeria, observed that three-year natural fallows accumulated more P compared to *Pueraria phaseoloides* fallow systems (9.4 kg

ha<sup>-1</sup> and 7.4 kg ha<sup>-1</sup>, respectively) (Kolawole *et al.*, 2005). For instance, maize and cassava P uptake increased with increase in fallow period due to biomass and nutrient (especially N and P) accumulation (Kolawole *et al.*, 2005). In Northern Cameroon, it had been reported that a 5-year *A. polyacantha* fallow had a much greater effect on maize and sorghum yields than intercropping (Ganry *et al.*, 2001). A maize yield of 3.0 t ha<sup>-1</sup> was observed in cultivated land after fallow of *A. polyacantha* the yield was high compared with maize yields of 0.5 to 1.0 t ha<sup>-1</sup> harvested in a cultivated land after herbaceous fallow. The higher crop production after *A. polyacantha* fallow is due to higher N storage in the soil and nitrogen fixation by the tree species.

Many authors had reported on soil fertility improvement and crop response to nutrients in long and short-term fallows of rotational woodlots and planted tree species in arid and semi- arid areas (Palm, 1995; Szott *et al.*, 1999; Banzi *et al.*, 2002; Nyadzi *et al.*, 2006b). For instance studies reported that the yield response of crops following fallows depends on the biomass and N accumulation by fallows (Szott *et al.*, 1999). An increase in soil inorganic N was reported in a 5-year tree fallow phase of *A. polyacantha*, *L. leucocephala* and *A. nilotica* ranging from 51 to 87 kg N ha<sup>-1</sup> (Banzi *et al.* 2002). In addition, organic inputs of various tree legumes applied at 4.0 t ha<sup>-1</sup> can supply enough N for maize grain yields of 4.0 t ha<sup>-1</sup> though they could not supply enough P and K to support such maize yields over time (Palm, 1995).

On the other hand, few studies have quantified some soil fertility aspects especially as relates to soil inorganic P, K, OC and CEC in rotational woodlot fallows. For example, a two-year non-coppicing fallows of *Cajanus* species and *Sesbania* species maintained a positive soil inorganic P balance which was 33 kg P ha<sup>-1</sup> and 32 kg P ha<sup>-1</sup> respectively (Mafongoya *et al.*, 2005).

### 2.7.2 Soil fertility improvement under trees

Trees can increase the availability of nutrients through increased release of nutrients from SOM and recycled organic residues. Agroforestry trees such as *Acacia* spp have a potential to provide N in quantities sufficient to support moderate crop yields through N<sub>2</sub> fixation and retrieval of nitrate from deep soil layers (Nyadzi *et al.*, 2003).

In Sudano Sahelian zone, enrichment of total OC in *Acacia* habitat was reported (Traore *et al.*, 2007). Indeed total OC under *Acacia* canopies, ranged from 7.5 to 12 g kg<sup>-1</sup> of soil. In addition, total N under *Acacia* canopy was 0.5 -1.11 g kg<sup>-1</sup> of soil.

### 2.7.3 Nutrients and organic matter accumulation

Several authors have extensively reviewed the concepts and practices of soil fertility improvement by trees (Palm, 1995; Lal, 2001). Many studies have shown that soil fertility improvement is linked to the growth of deep-rooted trees and shrubs, which recycle plant nutrients from lower soil layers and build up the SOM. Agroforestry techniques and natural forests can improve soil fertility by providing OM through litter fall from trees and shrubs grown *in situ*, particularly from N fixing legumes (Sanchez, 1995; Fingleton, 2005; Mkangwa *et al.*, 2007). A general vertical distribution of nutrients from upper to lower soil horizons ranked in the order: P>K>Ca>Mg>Na was reported by Jobbagy and Jackson (2001). Nutrients cycled by plants such as P and K were reported to be more concentrated in the upper (0-20 cm) soil layer as compared to nutrients less limiting to plant growth such as sodium.

Some studies have reported on soil organic C at 0-15 cm depth after 5-year hedgerow intercropping with *L. leucocephala* to be 12.3 g kg<sup>-1</sup> of soil under the hedgerow and 9.4 g kg<sup>-1</sup> of soil, between the hedgerows as compared to 5.9 g kg<sup>-1</sup> of soil in the control

without a hedgerow (Kang, 1997).

In northern Senegal studies in a widely spaced *Acacia senegal* plantations aged between 3 and 18 years reported SOM, N, P and K concentrations to be higher in surface horizons close to stems (Deans *et al.*, 1999). Concentrations of N = 0.0222 %, P = 0.0064 %, K = 4.38 mg (100 g)<sup>-1</sup> and SOM = 0.999 % (dry weight) were higher beneath tree canopies than in open ground between trees (N = 0.0132%, P = 0.0057%, K = 3.75 mg (100 g)<sup>-1</sup> and SOM = 0.881 % (dry weight)). The concentrations decreased significantly as distance from tree stems and depth in soil increased (Deans *et al.*, (1999). In addition, highest percentage differences in concentrations of nutrients and SOM at differing depths in soil were found for extractable K. The concentration of extractable K (6.99 mg 100 g<sup>-1</sup>) was four times higher in the top 0-10 cm of soil than it was at 50-100 cm depth (1.73 mg 100 g<sup>-1</sup>).

#### **(i) Nitrogen dynamics**

Nitrogen is the primary element that most often limits plant growth in many terrestrial ecosystems, and competition between plants and microbes for this nutrient is powerful (Hodge *et al.*, 2000). Most of the soil N occurs in organically bound forms, which need to be mineralized to inorganic N (ammonium or nitrate) to be available for uptake by plants. A small fraction of the total N less than 10 percentage in most cases may be mineralized during the short rotation of a fast-growing tree plantation (Miller, 1995, Hawkins *et al.*, 2000).

In addition, the dynamics of N differ from place to place as influenced by different tree species and land management systems. For example, studies in dry lands of Sudan have shown a significant change in stocks and dynamics of N after conversion of 6-year old

*Acacia senegal* plantation to crop land and the highest stock depletion for N was 53 % (Tahir *et al.*, 2009). In Tanzania, coffee home gardens are mostly interplanted with *Grevillea* tree species, but N was reported to be the most limiting macro nutrient in small scale holder farms in coffee growing areas, which attributed to low crop productivity ( $200 \text{ g tree}^{-1} \text{ year}^{-1}$ ) (Semoka *et al.*, 2005).

## **(ii) Phosphorus dynamics**

After nitrogen, phosphorus is the most limiting nutrient for plants in many tropical soils (Smith, 2000). It is an important plant macro nutrient, which constitutes 0.2 % of a plant's dry weight. Low availability of P in bulk soil restricts plant uptake (Harrier and Watson, 2003).

Cycling of P from organic materials is normally insufficient to meet the P requirements of crops, as the extractable soil P levels recycled in most organic materials are below  $10 \text{ mg P kg}^{-1}$  soil considered as threshold for plant needs (Okalebo, 1987). For example, in the southern highlands of Tanzania it has been reported that the use of crop rotation, manure application and use of crop residues to replenish P in the soil do not increase crop yields, due to insufficient P supplied by the materials (Lisuma *et al.*, 2006).

Numerous studies have reported an increase of P replenishment in soil after combining organic materials with Minjingu phosphate rock (MPR). Minjingu phosphate rock of 0, 25, 50 and  $75 \text{ kg P ha}^{-1}$  when combined with organic materials (chicken manure, farm yard manure, maize stover and compost manure) and applied at a rate of  $2 \text{ t ha}^{-1}$  (air dry weight) is a viable option for P replenishment (Waigwa *et al.*, 2003). Increased rates of MPR with or without organic material increased dry matter yields of maize linearly. However, chicken manure combined with  $50 \text{ kg P ha}^{-1}$  as MPR produced the highest

(27.9 g pot<sup>-1</sup>) dry matter yield of maize, thus MPR used is a reactive and effective source of P for plant growth (Semoka *et al.*, 1992; Waigwa *et al.*, 2003). Phosphorus was reported to accumulate in litter fall of *Tephrosia vogelii* (3.7 kg ha<sup>-1</sup>) and stem (7.1 kg ha<sup>-1</sup>) after adding 80 kg P ha<sup>-1</sup> as MPR (Mkangwa *et al.*, 2007).

In fact most studies have reported little or no benefit of trees on extractable inorganic soil phosphorus. Several authors had found no significant difference in available soil P under hedgerow intercropping with *L. leucocephala* and *Dactyladenia barteri* as compared to a control without trees or with *Faidherbia albida* (Siaw, 1991; Weil and Mughogho, 1993). Some studies have reported a decrease in extractable inorganic P under trees, probably because of P storage in tree biomass (Hagggar *et al.*, 1991). Therefore sustained crop production in agroforestry systems on P-deficient soils will significantly require external P input (Buresh and Tian, 1998; Khanna, 1998).

However, a slight favourable effect of 4-year old trees (*Senna siamea*, *Leucaena leucocephala*, *Acacia leptocarpa* and *Acacia auriculiformis*) on extractable P at 0-15 cm soil depth during the fallow phase was reported (Kang, 1997). In addition, compared with control alley cropping of *Leucaena* species and *Gliricidia* species gave nine times mean values for recycled P (Kang, 1997). Trees might have access to soil P from unstable pools inaccessible or exploited by crops (Hands *et al.*, 1995). In addition, studies in western Kenya reported that rotation of unfertilized maize with *Sesbania sesban* rather than continuous maize cropping could to a small degree increase the availability of P (Buresh *et al.*, 1997). The *S. sesban* fallow also increased the maize yield on this P-deficient soil but it did not eliminate P deficiency in subsequent maize crops.



**(iii) Potassium dynamics**

The total amount of potassium (K) in soils varies broadly from less than 0.01% to about 4%, and it is usually about 1%. Clays may contain 2% to 4% potassium. The direct source of K for crops is from soil solution. Its availability to plants mainly depends on the K<sup>+</sup> ion concentrations close to the root zone, on the rate at which K<sup>+</sup> ions are transported through the soil solution to the root surface, on the replenishment of the solution by adsorption from exchange sites on the soil colloids and on the level to which the plant roots ramify through the soil (Wild, 1988).

Studies reported increased N and K in the surface soil as *Acacia senegal* plantations aged (Deans *et al.*, 1999). In 15 years of fallow period, N accumulation added on top soil layer (0-10 cm) was estimated to be 300 kg ha<sup>-1</sup>, K was 50 kg ha<sup>-1</sup>, and using estimates of N uptake by *Sorghum bicolor* crops of 7 g m<sup>-2</sup>, the N accumulated may provide good sorghum yields for at least four successive cropping seasons (Deans *et al.*, 1999).

## CHAPTER THREE

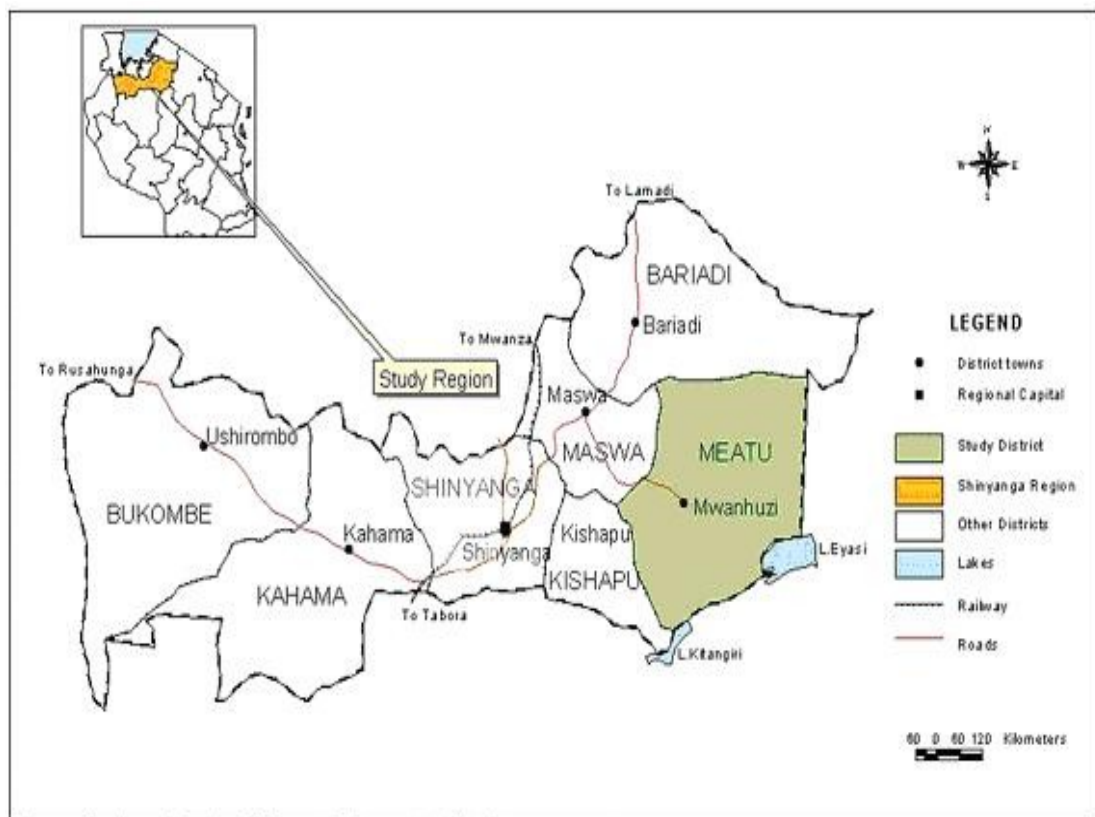
### 3.0 MATERIAL AND METHODS

#### 3.1 Materials

##### 3.1.1 Site Description

###### 3.1.1.1 Location

The study was conducted in Meatu District, Shinyanga Region in Tanzania (Fig.1). Meatu District is located 155 km East of Shinyanga town. It lies within a semi-arid zone between latitudes  $3^{\circ}$  -  $4^{\circ}$  south and longitudes  $34^{\circ}8'$  -  $34^{\circ}49'$  east and at an altitude of 1000-1500 m above sea level (Otysina *et al.*, 1997). The district covers about 8,835 km<sup>2</sup>, of which 50 % are reserved areas (Otysina *et al.*, 1997).



**Figure 1: Map of Shinyanga Region showing location of Meatu District, Tanzania.**

In addition, Meatu District is bordered by Bariadi District in the north, Maswa and Kishapu Districts in the west, Arusha Region in the east, Tabora and Singida Regions in the south.

### **3.1.1.2 Climate**

The area has a semi-arid tropical type of climate with a unimodal rainfall distribution. The rainy season is from November to April with a peak in March. The total annual precipitation ranges from 600 mm in the north to 800 mm in the south with an average of 450 mm. Annual temperatures ranges from 27.6<sup>0</sup> C to 30.2<sup>0</sup> C. with an average of 22.7<sup>0</sup>C (Nnko, 2003).

### **3.1.1.3 Soils**

In general, soils in Meatu District are mainly red to yellowish, freely drained tropical soils classified as Chromic Cambisols, according to the FAO classification (Nnko, 2003). However, soils at the experimental site are classified as Cambisols, which vary with climate, topography, depth or stoniness. The soils have a wide variety of agricultural uses including crop production to include cotton, sorghum, maize, millets, groundnuts, sunflower, chickpeas (De Pauw, 1984) and *Ngitiri* for provision of fuel wood and dry season fodder (Kamwenda, 1999).

### **3.1.1.4 Vegetation**

Natural vegetation was originally woodland and bushland with species such as *Acacia* species *Branchystegia* species, *Albizia* species, *Commiphora* species and *Dalbergia* species (Monela *et al.*, 2005). During tsetse fly and quelea quelea bird eradication programme in 1920's and 1930's, large areas of land were cleared of bushes and trees (Otsyina *et al.*, 1996). Since then deforestation and bush clearing have continued. As a

result, many areas are tree less except for few *Acacia* species and baobab trees (Monela *et al.*, 2005).

Today, the vegetation has gradually reverted to an open grassland savanna, characterized by short grasses with scattered shrubs (4-6 m high), and dominant tree species are *Acacia* mainly, *A. tortilis*, *A. polyacantha*, *A. nilotica*, *A. drepanolobium* and *A. senegal* (Otsyina, 1994; Monela *et al.*, 2005). Besides the *Acacia* stands, other indigenous tree species occurring in the savanna are *Balanites aegyptica*, *Albizia amara* and *Adansonia digitata* (Mbuya *et al.*, 1994). The grassland diversity is largely dominated by *Pennisetum* species, *Hyperhenia rufa*, *Cynodon dactylon* and *Cenchrus* species which are grazed by livestock.

## **3.2 Methods**

### **3.2.1 Experiments**

The experiments were carried out in established rotational woodlots at Mwambegwa village and in an existing *Ngitiri* at Mwamishale village starting from August, 2007. Information on rotational woodlots and *Ngitiri* characteristics and clarification of the ages of systems were gathered from farmers by conducting informal interviews with the land-owners (Plate 1).



**Plate 1: Informal interviews with the land-owners at Mwamishale in Meatu District, Tanzania.**

Destructive sampling technique was used to develop allometric equations, which were later used to estimate C stocks in above-ground tree components. Measurements on stand trees, soil sampling and observations were carried out in sample plots of the farms.

### **3.2.2 Experimental design**

Table 1 illustrates the layout of the experiment, treatments, sample plots and the experimental design. Two systems (rotational woodlots and *Ngitiri*) each with two different fallow periods (eight and ten years) were used in this study. The experiment comprised of three treatments namely, *A. nilotica*, *A. polyacantha*, *A. tortilis*. The plots were replicated three times, making thirty six sample plots.

**Table 1: Layout of main and sub-plot treatments**

BLOCK I											
Rotational woodlots						<i>Ngitiri</i>					
8 years			10 years			8 years			10 years		
1	2	3	1	2	3	1	2	3	1	2	3

BLOCK II											
Rotational woodlots						<i>Ngitiri</i>					
8 years			10 years			8 years			10 years		
1	2	3	1	2	3	1	2	3	1	2	3

BLOCK III											
Rotational woodlots						<i>Ngitiri</i>					
8 years			10 years			8 years			10 years		
1	2	3	1	2	3	1	2	3	1	2	3

Numbers 1-3 denote treatments; 1 = *A. nilotica* 2 = *A. polyacantha*, 3 = *A. tortilis*,

The design used was split split plot. Eighteen sample plots of 625m<sup>2</sup> size were established in each system (Plate 2). A plot in the *Ngitiri* was considered a treatment only when it had 75% coverage by trees of one among the tree species selected as treatments (Plate.3).



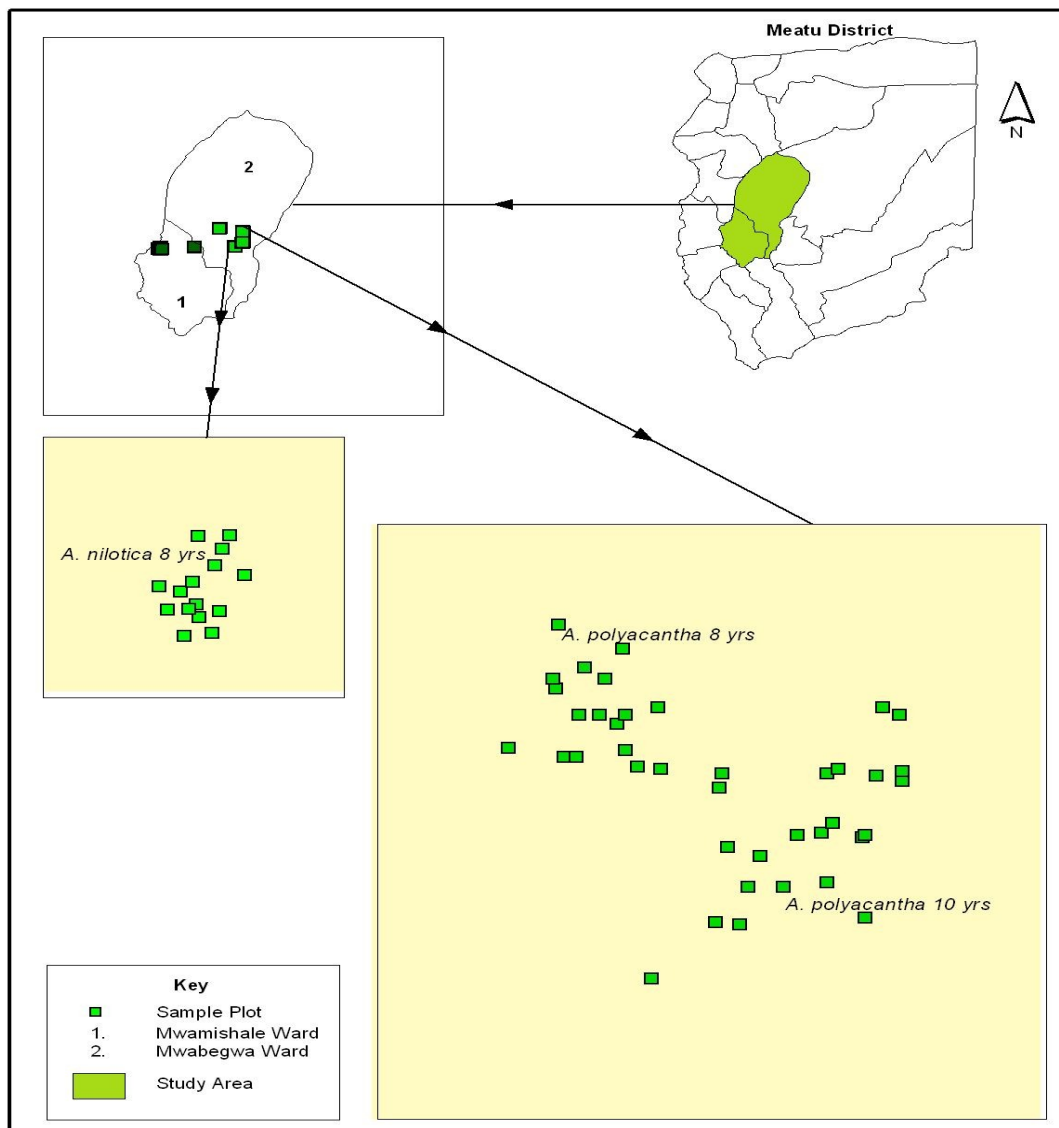


**Plate 2: Establishment of sample plots in a Ngitiri at Mwamishale village in Meatu District, Tanzania.**



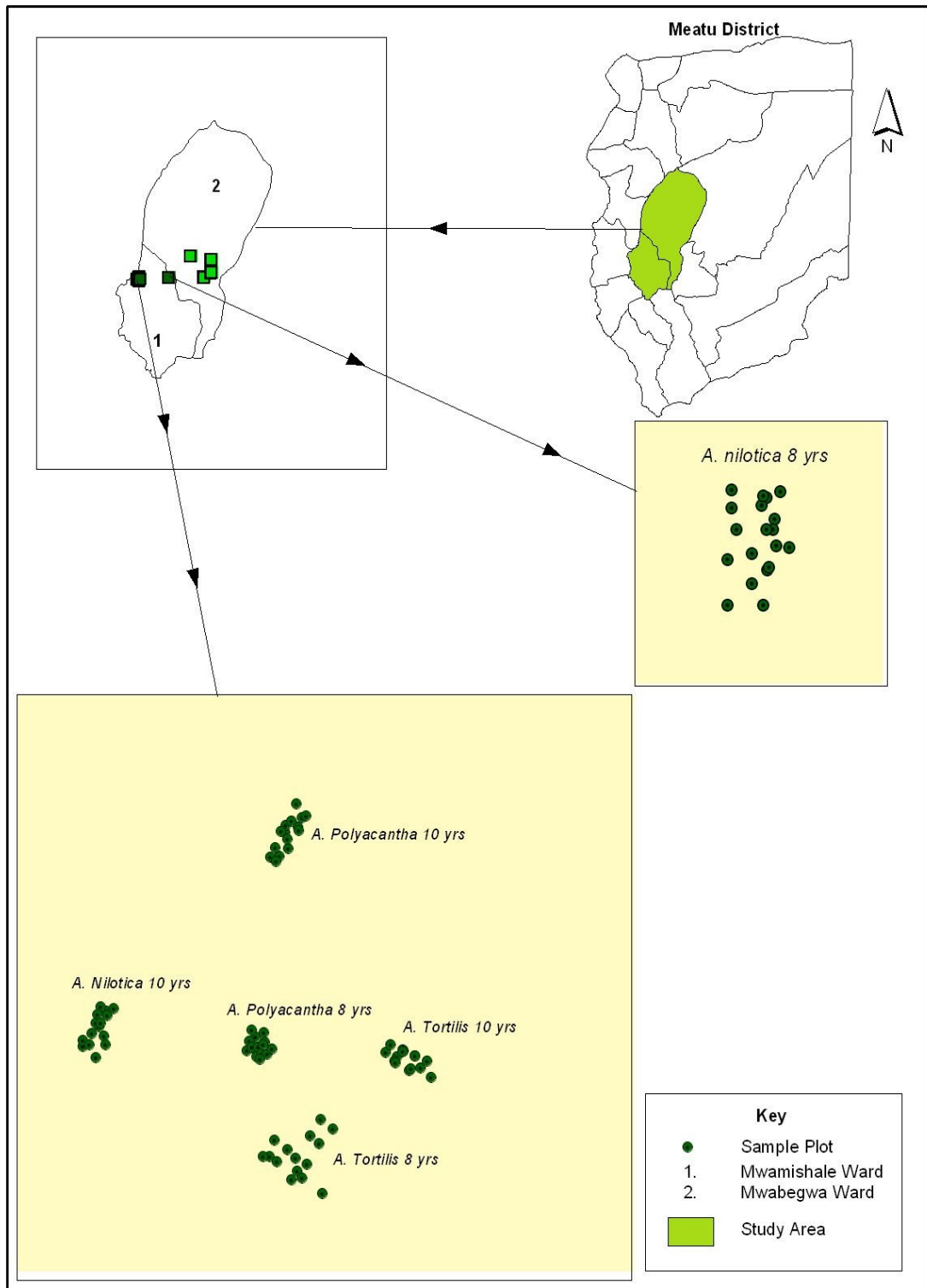
**Plate 3: A treatment of *A. tortilis* fallows in a Ngitiri at Mwamishale village in Meatu District, Tanzania.**

A global positioning system (GPS) receiver was used to take points in all sample plots to assist in correctly locating the plots in the imageries and for ground truthing (Figures 2-3). Figure 2 shows the sample plots of *A. nilotica*, *A. polyacantha* under rotational woodlots fallows being located in Mwambegwa ward while sample plots in *Ngitiri* occur in Mwamishale ward. Figure 3 illustrates *A. nilotica*, *A. polyacantha* and *A. tortilis* fallows and their corresponding ages in *Ngitiri*.



**Figure 2: Sample plots in rotational woodlots at Mwambegwa village in Meatu District, Tanzania.**





**Figure 3: Sample plots in *Ngitiri* at Mwamishale village, in Meatu District, Tanzania.**

### **3.3 Data Collection, Laboratory Procedures and Analysis**

#### **3.3.1 Allometric models**

##### **(a) Sampling for allometric model development**

Three different tree species namely *A. tortilis*, *A. nilotica* and *A. polyacantha*, were selected to reflect the dominance of species occurring in natural woodland in the study area (Monela *et al.*, 2005). Ninety (90) trees (*A. tortilis* (31), *A. nilotica* (27) and *A. polyacantha* (32)) were sampled randomly in the Bomani forests located in Mwanhuzi ward (Fig.1) in Meatu District. Sampling was restricted to trees with DBH ranging from 5 to 40 cm basing on diameter ranges measured in stand trees in sample plots for both systems. Tree height and DBH were measured using Haga hypsometer and diameter tape.

The selected trees were felled at 0.3 m above the ground, divided into three components, which were stem, branches, leaf and/or twigs. The stem and branches were cut into billets of 2-3 m depending on the length. Each component was then weighed separately in the field for green weight and recorded. Depending on thickness, the branches were classified in three diameter groups termed as primary (10 cm), secondary (5 cm), and tertiary (2 cm) branches. Wood discs of 2 cm thick were cut from the middle part of the different sections of the stem and branches. Samples were weighed immediately to determine green weight and recorded. For Leaves and/or twigs, a representative sample of 50 gm was taken from each tree and weighed, thereafter taken to the laboratory for analysis.

##### **(b) Data collected**

Tree height, diameter at breast height, field green weight and sub samples green weight were collected.

### (c) Laboratory procedures

Sub-samples collected in the field were taken to the laboratory for biomass analysis. Leaves and/or twigs sub-samples were oven dried to constant weight at 70°C. Stem and branches sub-samples were oven dried at 105°C to constant weight in order to determine the oven-dry weights. Biomass ratio was computed as the ratio between the oven dry weight and oven green weight.

The following formulas were applied in computing biomass and C in trees.

$$\text{Biomass} \cdot \text{ratio} = \frac{\text{Sub-sample} \cdot \text{Oven} \cdot \text{Dry} \cdot \text{Weight}}{\text{Sub-sample} \cdot \text{Green} \cdot \text{Weight}} \dots\dots\dots(1)$$

$$\text{Biomass} = \text{Biomass} \cdot \text{ratio} \cdot \times \cdot \text{Field Green Weight} \cdot (\text{kg} \cdot \text{tree}^{-1}) \dots\dots\dots(2)$$

$$\text{Carbon} \cdot \text{in} \cdot \text{tree} = (\text{kg} \cdot \text{tree}^{-1}) = \text{Biomass} \cdot \times \cdot 0.5 \dots\dots\dots(3)$$

Tree C was computed as 50% of the biomass (Munishi and Shear, 2004; Baccini *et al.*, 2008; Basuki *et al.*, 2009).

### (d) Data analysis

The computed C for each tree component (stem, branch and leaves/or twigs) was regressed against the tree DBH and H to develop C allometric equations that was used in computing C based on easily measured tree parameters such as DBH. Data was log transformed to equalize the variances over the entire range of C values, which satisfies the prerequisites of linear regression. The criteria (accuracy measures) used to select the best fit models were highest coefficient of determination ( $R^2$ ), lowest standard error (SE) of y estimated values (Malimbwi *et al.*, 1994) and minimum residual value or intercept coefficient  $a$  (Munishi and Shear, 2004). Overall F-value at 95% confidence level was considered for upgrading of the best fit models.

The following are the general forms of functions (Philip, 1983) fitted to the collected data hence models developed:

1.  $Y = a + bDBH$
2.  $Y = a + bDBH + cH$
3.  $Ln(Y) = a + bLnDBH$
4.  $Ln(Y) = a + bLnDBH + cLn(H)$

Where:

$Y$  = Carbon (kg tree<sup>-1</sup> component)

$DBH$  and  $H$  = Diameter at Breast Height (cm) and total tree Height (m) respectively, and they are predictor variables.

$a$ ,  $b$  and  $c$  = regression coefficients;  $b$  and  $c$  corresponds to each  $DBH$  and  $H$  value for multiple ranges

$a$  = y intercept and also a constant

#### **(e) Regression analysis**

Regression equations were developed from data of the 90 trees harvested from destructive sampling using the linear regression procedures of Excel Micro Soft Windows version 2003. First, the raw data was graphed to visually assess the relationships between  $C$  and predictor variables ( $DBH$  and  $H$ ). Using both raw and logarithmically transformed data,  $C$  was first modeled as a linear function of each predictor variable. Logarithmic transformations (natural logarithm) were applied to the raw data as it was necessary to account for the non-constant variance. Finally, logarithmic units were converted to arithmetic units to obtain the realistic  $C$  content (Van *et al.*, 2000),

### **3.3.2 Estimation of above and below-ground carbon**

#### **(a) Tree measurements of stand biomass**

Species identification and tree measurements were done in all sample plots. All trees in the rotational woodlots plots were measured for DBH and height. For *Ngitiri* plots, only trees with  $DBH \geq 5$  cm were measured for DBH and height. Trees with  $DBH \leq 5$  cm were counted and recorded. Tree height was measured using Haga hypsometer and diameter was measured with a diameter tape. In both systems, diameter ranges measured in stand trees for all sample plots were recorded and used as a standard measure of DBH in destructive sampling.

#### **(b) Data collected**

Data collected from the sample plots to estimate above ground carbon were tree height and diameter at breast height.

#### **(c) Data analysis**

The developed best fit selected allometric models were used to predict above-ground C in all tree components. Tree height and DBH were fitted in the allometric models to estimate the above-ground C. Below-ground C was computed as 30% of total tree C. All data was organized in excel and analyzed statistically and all mean values of above and below-ground was reported with a standard error on tables and standard deviations of means in error bars in figures.

### **3.3.3 Soil sampling**

Soil sampling was done in November and December 2007 in rotational woodlots and *Ngitiri* plots in Mwambegwa and Mwamishale villages respectively. Soil samples were taken from a profile 100 cm deep. A pit was dug to a depth of 100 cm at the centre of

each plot but one meter away from a tree trunk to avoid accumulation of organic matter. Soil samples were collected at five different depths; 0-20, 20-40, 40-60, 60-80 and 80-100 cm. Soil cores were used to collect samples for bulk density determination.

### 3.3.4 Bulk density, total organic carbon and soil texture

#### (a) Laboratory procedures

Soil analysis to determine bulk density and texture and total organic carbon were done in the Soil Science Department laboratory of Sokoine University of Agriculture from March 2008 to July 2009. For determination of bulk density (BD) soil cores were weighed and soil moisture content was determined gravimetrically by oven drying a sub-sample at 105°C for 48 hours.

#### (b) Data analysis

The BD was then, computed as a ratio of the oven dry weight to soil core volume for each sample and expressed in g cm<sup>-3</sup>.

$$\text{Bulk density } gcm^{-3} = \frac{\text{Oven Dry Weight (g)}}{\text{Soil Core Volume (cm}^3\text{)}} \dots \dots \dots (4)$$

Nonetheless, bulk density was used to convert soil volumes (g kg<sup>-1</sup>) to soil mass within a given area (t ha<sup>-1</sup>) and soil depth (Kaisi *et al.*, 2005).

Determination of Total Organic Carbon (TOC) followed the wet oxidation method of Walkely-Black (Nelson and Sommers, 1982). Percentage TOC was converted to SOC concentrations (g C kg<sup>-1</sup> of soil).

Soil texture was determined by hydrometer method after dispersing soil samples with sodium hexametaphosphate as described by Okalebo *et al.*, (2002).

All data for SOC was organized in excel and analyzed statistically and all mean values was reported with a standard error on tables and standard deviations of means in error bars in figures.

### **3.3.5 Soil sampling for determination of soil fertility key elements**

#### **(a) Laboratory procedures**

Soil samples were taken from a profile which was dug to a depth of 100 cm at the centre of each plot but one meter away from a tree trunk to avoid accumulation of organic matter. Soil samples were collected at five different depths; 0-20, 20-40, 40-60, 60-80 and 80-100 cm. Soil samples were packed in well labeled paper bags and sent to the laboratory for analysis. Soil samples were air dried, ground using a mortar and pestle and sieved through a 2 mm mesh sieve. Thereafter, the soil samples were analyzed for organic carbon (OC), pH (water), available P, exchangeable K, available N, total N, CEC and texture.

Soil fertility parameters were selected and analysed in this study namely; soil pH (water), Olsen P, total N, inorganic N, exchangeable K, and Cation Exchange Capacity.

Soil reaction, pH (water) was measured in 1:25 soil to solution ratio (Okalebo *et al.*, 2002). Soil acidity was tested prior to other chemical analysis in order to select appropriate method for analysis of available P. In this case, the pH levels in many samples in this study were very high above 7.5. Therefore, available P in the soil was determined using Olsen method (Olsen and Sommers, 1982). Total N was determined

by the micro Kjeldal method (Okalebo *et al.*, 2002). Inorganic nitrogen (Ammonium N and Nitrate N) was determined using calorimetric method (Anderson and Ingram, 1993; Okalebo *et al.*, 2002). Exchangeable K was extracted using acidified ammonium acetate (Rhodes, 1982) and read on an atomic absorption spectrophotometer. Cation exchange capacity (CEC) was determined by the ammonium-extraction method (Okalebo *et al.*, 2002).

#### **(b) Data analysis**

All data was organized in Excel and values reported in means, standard deviations and standard error to show the variations within the means and the sample population respectively.



## CHAPTER FOUR

### 4.0 RESULTS AND DISCUSSION

Carbon stocks/storage in dominant *Acacia* species and soils under fallows of rotational woodlots and *Ngitiri* are reported and discussed in this study. As there were no allometric models for determination of C stocks in different tree components of *A. nilotica*, *A. polyacantha* and *A. tortilis*, carbon prediction allometric models were developed as part of this study. This was followed by presentation of C stocks in above and below-ground components of the three *Acacia* species and SOC stocks under fallows of the same species in rotational woodlots and *Ngitiri*. Finally, results for soil fertility status under rotational woodlots and *Ngitiri* are presented and discussed.

#### 4.1 Allometric Models for Determination of Carbon Storage/Stocks in *Acacia* Species

Carbon stored in biomass of tropical forests and woodlands are needed as these forests and woodlands are undergoing faster rates of change worldwide and reliable estimates are few (Brown, 1997) particularly the woodlands enriched with *Acacia* species in Tanzania. Accurate estimation of biomass in tropical forests is crucial for many reasons, to include commercial exploitation of timber and the global carbon cycle. Of particular importance in the global carbon cycle is estimation of the total above-ground carbon with accuracy sufficient to establish the increase or decrease in C stored over short period of time from 2 to 10 years (Basuki *et al.*, 2009).

Forty eight (48) allometric models was developed for estimation of C stored in different tree components of *A. nilotica*, *A. polyacantha* and *A. tortilis*. Among the

developed models, only nine were selected as best to predict C stocks in the *Acacia* species.

#### 4.1.1 Species-specific allometric models

##### (i) Allometric Models for *A. nilotica*

Table 2 shows the developed allometric models for prediction of above-ground C in *A. nilotica*. All models developed to estimate above-ground C for stem, branches and leaves and/or twigs for *A. nilotica* explain well the relationship between DBH, height and tree C with the coefficient of determination ( $R^2$ ) ranging from 0.67 to 0.91.

The highest  $R^2$  and the lowest SE values for the models developed to estimate stem and branch C was associated with models, which applied both DBH and H as predictor variables. Both models selected for estimation of stem and branch C of *A. nilotica* had high  $R^2$  (0.83 and 0.89, respectively), implying that log transformation linear regression is appropriate for prediction of stem and branch C in *A. nilotica*. The best fit model selected for *A. nilotica* stem was  $Y = 0.047 \text{ DBH}^{2.03}$  and for branches was  $Y = 0.006 \text{ DBH}^{2.891}$ .

The model that would be selected for estimation of leaves C in and/or twigs in *A. nilotica* had DBH and H as the predictor variables. However, the model had a negative intercept and could not be accepted as the best model. Instead the model with DBH as predictor variable ( $Y = 0.011 \text{ DBH}^{1.629}$ ) was selected as the best fit model for estimation of C in leaves and/or twigs of *A. nilotica*.

**Table 2: Allometric models and their goodness of fit for estimation of stem, branch and leaf and/or twig C in *A. nilotica* (n = 27)**

Dependent variable	Model	Allometric relationship	R <sup>2</sup>	SE	F-value	P-value
Stem C	1	Y= -12.346+1.869 DBH	0.67	9.93	49.78	*
	2	Y= -20.325+1.591 DBH+1.931H	0.70	9.59	28.15	*
	3	<b>Y= 0.047 DBH<sup>2.03</sup></b>	<b>0.83</b>	<b>1.61</b>	<b>118.8</b>	<b>**</b>
	4	Y= 0.026 DBH <sup>1.666</sup> H <sup>0.855</sup>	0.85	1.56	70.26	<b>**</b>
Branch C	1	Y= -33.455 + 3.86 DBH	0.81	14.13	105.1	<b>**</b>
	2	Y= -36.31 + 3.78 DBH + 0.691 H	0.81	14.37	50.88	*
	3	<b>Y= 0.006 DBH<sup>2.891</sup></b>	<b>0.89</b>	<b>1.67</b>	<b>208.3</b>	<b>***</b>
	4	Y= 0.003 DBH <sup>2.529</sup> H <sup>0.846</sup>	0.91	1.62	117.7	<b>**</b>
Leaf and/or twig C	1	Y= -3.218 + 0.439 DBH	0.80	1.66	98.53	*
	2	Y= -3.674 + 0.423 DBH + 0.111H	0.80	1.68	48.04	*
	3	<b>Y= 0.011 DBH<sup>1.629</sup></b>	<b>0.75</b>	<b>1.72</b>	<b>77.77</b>	*
	4	Y= 0.006 DBH <sup>1.629</sup> H <sup>1.223</sup>	0.78	1.69	39.94	*

Y = Carbon, DBH = diameter at breast height, H = tree height, SE = Standard error, R<sup>2</sup> = coefficient of determination, bolded number = best fit model P<0.05=\*, P< 0.01= \*\*, P< 0.001=\*\*\*

## (ii) Allometric Models for *A. polyacantha*

Table 3 shows the allometric models for prediction of C in different tree components of *A. polyacantha*. All four models fitted for estimation of C in *A. polyacantha* for different tree components explained well the relationship between tree C and the predictor variables of DBH and height with the coefficient of determination (R<sup>2</sup>) ranging from 0.60 to 0.97.

The highest R<sup>2</sup> and the lowest SE values for the models developed to estimate stem and branch C was obtained in models which applied both DBH and height as predictor variables. However, the models that combine the two variables had low F-value and were not selected as best because models are accepted when the F-value is higher and can be selected as the best among the many models developed and evaluated (Maraseni *et al.*, 2005).

Both best fit models selected for estimation of stem and branch C ( $Y = 0.009 \text{ DBH}^{2.658}$  and  $Y = 0.019 \text{ DBH}^{2.368}$  respectively) of *A. polyacantha* had higher coefficient of determination ( $R^2$ ) and low SE, implying that log-transformed linear regression models are more appropriate for prediction of stem and branch C in *A. polyacantha*.

The model  $Y = 0.026 \text{ DBH}^{1.718}$  that used DBH as the predictor variable was accepted as the best model for prediction of leaf and/or twigs C in *A. polyacantha*, because of its higher coefficient of determination ( $R^2$ ), low SE and higher F-value.

**Table 3: Allometric models and their goodness of fit for estimation of stem, branch and leaf and /or twig C in *A. polyacantha* (n = 32)**

Dependent variable	Model	Allometric relationship	$R^2$	SE	F-value	P-value
Stem C	1	$Y = -38.799 + 4.058 \text{ DBH}$	0.84	15.81	162.5	**
	2	$Y = -52.90 + 2.90 \text{ DBH} + 3.70 \text{ H}$	0.87	14.65	97.69	**
	3	<b><math>Y = 0.009 \text{ DBH}^{2.658}</math></b>	<b>0.95</b>	<b>1.38</b>	<b>608.9</b>	<b>***</b>
	4	$Y = 0.005 \text{ DBH}^{2.028} \text{ H}^{1.105}$	0.97	1.29	487.6	<b>***</b>
Branch C	1	$Y = -28.188 + 3.028 \text{ DBH}$	0.70	17.91	70.54	*
	2	$Y = -26.21 + 3.19 \text{ DBH} - 0.52 \text{ H}$	0.70	18.19	34.22	*
	3	<b><math>Y = 0.019 \text{ DBH}^{2.368}</math></b>	<b>0.90</b>	<b>1.54</b>	<b>269.2</b>	<b>***</b>
	4	$Y = 0.016 \text{ DBH}^{2.213} \text{ H}^{0.273}$	0.90	1.55	132.1	**
Leaf and/or twig C	1	$Y = -2.709 + 0.409 \text{ DBH}$	0.60	3.04	44.72	*
	2	$Y = -2.165 + 0.45 \text{ DBH} - 0.14 \text{ H}$	0.60	3.08	21.87	*
	3	<b><math>Y = 0.026 \text{ DBH}^{1.718}</math></b>	<b>0.80</b>	<b>1.60</b>	<b>120.8</b>	<b>**</b>
	4	$Y = 0.031 \text{ DBH}^{1.898} \div \text{H}^{0.317}$	0.80	1.60	59.50	*

Y = Carbon, DBH = diameter at breast height, H = tree height, SE = Standard error,  $R^2$  = coefficient of determination, bolded number = best fit model  $P < 0.05 = *$ ,  $P < 0.01 = **$ ,  $P < 0.001 = ***$

### (iii) Allometric Models for *A. tortilis*

Table 4 shows the allometric models developed to estimate stem, branches and leaf and/or twig C in *A. tortilis*. All models developed to estimate C in stem and branches for *A. tortilis* explain well the relationship between tree C and the predictor variables

of DBH and height with the coefficient of determination ranging from 0.60 to 0.96. The highest  $R^2$  and the lowest SE values for the models developed to estimate stem and branch C were obtained in models which used DBH and H as predictor variables. However, models that combine two variables had low F-value and would not be accepted as the best. This is according to hypothesis that a model is accepted when the calculated F-value is greater than tabulated F-value at 95 % confidence level consequently the model with higher F-value can be selected as the best among many models developed and evaluated (Maraseni, 2005).

The best fit model for estimation of stem and branch C ( $Y = 0.035 \text{ DBH}^{2.246}$  and  $Y = 0.017 \text{ DBH}^{2.554}$  respectively) was the one that uses log-transformed DBH as the predictor variable. Both models selected for estimation of stem and branch C for *A. tortilis* had higher  $R^2$  and low SE, implying that log-transformation linear regression is convenient for prediction of stem and branch C in *A. tortilis*.

The model which use DBH as the predictor variable  $Y=0.034+\text{DBH}^{2.036}$  was accepted as the best model for estimation of leaves and/or twigs C in *A. tortilis* because it had higher  $R^2$ , low SE and higher F-value.

In all best selected models DBH was the only predictor variable that fitted well the prediction of carbon for all species based on their higher  $R^2$ , low SE and higher F-value.

**Table 4: Allometric models and their goodness of fit for estimation of stem, branch and leaf and/or twig C of *A. tortilis* (n = 31)**

Dependent variable	Model	Allometric relationship	$R^2$	SE	F-value	P-value
Stem C	1	$Y = -18.779+2.588 \text{ DBH}$	0.88	6.72	220.8	**

	2	Y = -19.43+2.546 DBH+0.198 H	0.88	6.83	106.7	**
	<b>3</b>	<b>Y = 0.035 DBH<sup>2.246</sup></b>	<b>0.96</b>	<b>1.26</b>	<b>700.9</b>	<b>***</b>
	4	Y = 0.028 DBH <sup>2.074</sup> H <sup>0.363</sup>	0.96	1.26	361.7	**
Branch C	1	Y= -31.450+3.843 DBH	0.80	13.93	113.4	*
	2	Y= -28.427+4.037 DBH+0.92 H	0.80	14.14	55.11	*
	<b>3</b>	<b>Y= 0.017 DBH<sup>2.554</sup></b>	<b>0.92</b>	<b>1.47</b>	<b>325.6</b>	<b>**</b>
	4	Y = 0.013 DBH <sup>2.306</sup> H <sup>0.523</sup>	0.92	1.47	185.6	**
Leaf and/or twig C	1	Y= -8.867+1.401DBH	0.35	13.75	15.49	*
	2	Y=-18.82+0.766DBH+3.019H	0.39	13.58	8.81	*
	<b>3</b>	<b>Y= 0.034 DBH<sup>2.036</sup></b>	<b>0.81</b>	<b>1.64</b>	<b>127.1</b>	<b>**</b>
	4	Y = 0.030 DBH <sup>1.920</sup> H <sup>0.243</sup>	0.82	1.66	61.84	**

Y = Carbon, DBH = diameter at breast height, H = tree height, SE = Standard error, R<sup>2</sup> = coefficient of determination, bolded number = best fit model P<0.05=\*, P< 0.01= \*\*, P< 0.001=\*\*\*

#### (iv) Best fit species-specific allometric models for estimation of carbon in different tree components

The best species-specific allometric models for estimation of above-ground C for different tree components for *Acacia* are shown in Table 5. In general the coefficient of determination (R<sup>2</sup>) was greater than 0.50 for all best fit models for C estimation in all tree components of all *Acacia* that indicates a good fit. Other parameters like SE and F-value were also used in selection of best model. For example, SE was slightly higher for *A. nilotica* compared to *A. tortilis* and *A. polyacantha* for the best models developed for C estimation of all tree components.

**Table 5: Summary of best fit species-specific allometric models for estimation of carbon in different tree components of *Acacia* species in Meatu District, Tanzania**

Species	Dependent variable	Relationship	R <sup>2</sup>	SE	F-value	P-value
<i>A. nilotica</i>	Stem C	Y = 0.047 DBH <sup>2.03</sup>	0.83	1.61	118.8	**
	Branch C	Y= 0.006 DBH <sup>2.891</sup>	0.89	1.67	208.3	***
	Leaf and/or twig C	Y= 0.011 DBH <sup>1.629</sup>	0.75	1.72	77.83	*

<i>A.polyacantha</i>	Stem C	Y=0.009 DBH <sup>2.658</sup>	0.95	1.38	608.9	***
	Branch C	Y=0.019 DBH <sup>2.368</sup>	0.9	1.54	269.2	***
	Leaf and/or twig C	Y=0.026 DBH <sup>1.718</sup>	0.8	1.60	120.8	**
<i>A.tortilis</i>	Stem C	Y= 0.035 DBH <sup>2.246</sup>	0.96	1.26	700.7	***
	Branch C	Y= 0.017 DBH <sup>2.554</sup>	0.92	1.47	325.6	***
	Leaf and/or twig C	Y= 0.034 DBH <sup>2.036</sup>	0.81	1.64	127.1	**

Y = Carbon, DBH = diameter at breast height, H = tree height, SE = Standard error, R<sup>2</sup> = coefficient of determination, bolded number = best fit model P<0.05=\*, P< 0.01= \*\*, P< 0.001=\*\*\*

On the other hand, models for leaf and/or twig had lower coefficient of determination and high standard error suggesting that linear regression relationships are more suitable for allometric models for C prediction in stem and branch compared to leaf and/or twig.

Furthermore, all best selected models to estimate C for all tree components in all species used DBH as a predictor variable because most of these relationships had higher F-value which added more strength to the model (Maraseni *et al.*, 2005). For example, log transformed model which used DBH and H as predictor variables was selected to predict stem and branch C for *A. nilotica* had the highest R<sup>2</sup> and lowest SE values (Table 2), but the relationship was rejected, because H as an individual coefficient in the regression was not significant at the general accepted confidence level of 95 % (Maraseni *et al.*, 2005).

Therefore accuracy measure suggests that prediction of C in different tree components of *Acacia* tree species is well explained using single predictor variable (DBH). These results are in agreement with findings which reported that DBH was the most suitable regressor for estimation of C in trees (Zians and Radoglou, 2006; Basuki *et al.*, 2009).

The SE was high in all best fit allometric relationships for C estimate in leaf and/or twig for all tree species indicating that there is more variation in this tree component, possibly caused by difficulty in undertaking measurements and sampling of leaf and/or twigs compared to other tree components.

**(v) Allometric models for estimation of total tree carbon**

Table 6 shows the allometric models developed to estimate total C in the trees of different species. The models developed for estimation of total C for *A. polyacantha* and *A. tortilis* used only DBH as the predictor variable, though *A. nilotica* had its best relationship developed by using both DBH and H as the predictor variables.

The best fit model to estimate total tree C for *A. tortilis*, and *A. polyacantha* were fitted using log-transformed DBH as predictor variable. The best fit relationship for estimation of C in *A. nilotica* used log-transformed DBH and H as predictor variables, ie.  $Y = 0.026 \text{ DBH}^{2.064} \text{ H}^{0.769}$ . These findings are in agreement with results reported by Tobin *et al.*, (2006) that estimates of C in biomass using allometric models based on DBH were most reliable, particularly after inclusion of crown height. However, other authors argued that adding more variables does not always improve the relationship (Basuki *et al.*, 2009). This suggests that careful evaluation of the model is important when using multiple predictor variables.

In addition, tree H measurements are often difficult to make because tree tops are hidden by the canopy layer (Chave *et al.*, 2005). Tree inventories are very valuable in ecological research, but may not have been recorded. For these reasons it is claimed that DBH was the simple predictive predictor variable which provided the most robust estimation of C in above-ground biomass (Chave *et al.*, 2005; Zians and Radoglou, 2006).



**Table 6: Allometric models for estimation of total tree C in species-specific *Acacia* species (n ≥ 30)**

Species	Model	Allometric relationship	R <sup>2</sup>	SE	F-value	P-value
<i>A. nilotica</i>	1	Y = -49.02 + 6.17 DBH	0.82	21.42	116.7	**
	2	Y = -60.3 + 5.77 DBH + 2.73H	0.83	21.36	59.3	*
	3	Y = 0.045 DBH <sup>2.393</sup>	0.89	1.54	200.5	***
	4	<b>Y = 0.026 DBH<sup>2.064</sup> H<sup>0.769</sup></b>	<b>0.91</b>	<b>1.51</b>	<b>116.6</b>	<b>**</b>
<i>A. polyacantha</i>	1	Y = -69.70 + 7.50 DBH	0.85	28.55	170.1	**
	2	Y = -81.27 + 6.55 DBH + 3.04H	0.84	28.51	85.8	*
	3	<b>Y = 0.04 DBH<sup>2.429</sup></b>	<b>0.97</b>	<b>1.27</b>	<b>916.2</b>	<b>***</b>
	4	Y = 0.028 DBH <sup>2.08</sup> H <sup>0.612</sup>	0.98	1.24	566.7	***
<i>A. tortilis</i>	1	Y = -66.68 + 7.35 DBH + 2.30H	0.86	21.73	193.6	***
	2	Y = 0.076 DBH <sup>2.337</sup>	0.87	21.97	94.9	*
	3	<b>Y = 0.055 DBH<sup>2.078</sup> H<sup>0.545</sup></b>	<b>0.95</b>	<b>1.32</b>	<b>536.7</b>	<b>***</b>
	4	Y = 0.055 DBH <sup>2.078</sup> H <sup>0.545</sup>	0.95	1.31	289.5	***

Y = Carbon, DBH = diameter at breast height, H = tree height, SE = Standard error, R<sup>2</sup> = coefficient of determination, bolded number = best fit model P < 0.05 = \*, P < 0.01 = \*\*, P < 0.001 = \*\*\*

The developed allometric relationships in this study show that diameter at breast height (DBH) is the only appropriate predictor variable in predicting above-ground C of all tree components of *Acacia* species and total above-ground C in *A. tortilis* and *A. polyacantha*. The variable is easy to measure and available in standard forest inventory. Inclusion of H does not improve the performance of the models with exception of prediction of total above-ground C for *A. nilotica*. Therefore, allometric models developed from this study can be used in predicting above-ground C for estimation of C stocks in different tree components of *Acacia* species.

#### **4.2 Carbon Storage in Above and Below-ground Biomass and Soil Organic Carbon under Rotational Woodlots and *Ngitiri***

The mean C storage in different tree components of above and below-ground biomass in rotational woodlots and *Ngitiri* are presented in this section. In addition, the means

of SOC in different soil depth under rotational woodlot and *Ngitiri* are reported. The influence of fallow periods on above-ground, below-ground C storage and SOC in rotational woodlots and *Ngitiri* are presented.

#### **4.2.1 Carbon storage in rotational woodlots**

##### **(a) Carbon storage in above and below-ground biomass in woodlots**

Table 7 shows mean values of above and below-ground carbon and total tree carbon storage/stocks in different tree species under rotational woodlots. *A. nilotica* had the highest total tree C of  $22.0 \pm 3.14 \text{ t ha}^{-1}$ . These estimates are relatively higher than reported above-ground C of  $20 \text{ t ha}^{-1}$  in southern miombo woodlands (Munishi *et al.*, 2010). The high value of C storage in the woodlots is attributed to the intact conditions with minimum human disturbance because ownership rights are well respected by the community (Kamwenda, 1999). For example, studies suggest that intact tropical forests may be acting as significant sinks for atmospheric CO<sub>2</sub> (Stephens *et al.*, 2007; Phillips *et al.*, 2008; Lewis *et al.*, 2009). Forests and woodlands that have been subjected to human disturbances such as harvesting medicines, fuelwood and wild fire tend to have lower biomass and C storage than their potential (Munishi and Shear, 2004). On the other hand, estimates of total tree C in this study are comparably lower to estimates in other studies (Munishi and Shear, 2004; Munishi and Shirima, 2010). Higher estimates of total C storages in trees of  $517 \text{ t ha}^{-1}$  and  $384 \text{ t ha}^{-1}$  was reported for the Usambaras and Ulugurus, respectively (Munishi and Shear, 2004). Estimates of total tree C storage in Chome Nature Reserve were  $159.5 \text{ t ha}^{-1}$  approximately seven times of the estimates in *A. nilotica* woodlots (Munishi and Shirima, 2010). These disparities may be associated with differences in size and composition of trees (Munishi and Shear, 2004).

**Table 7: Means of above and below-ground carbon storage in different tree species under rotational woodlots in Meatu District, Tanzania**

Tree species	Carbon Storage (t ha <sup>-1</sup> )					
	Above-ground C		Below-ground C		Total Tree C	
	Mean	±SE	Mean	±SE	Mean	±SE
<i>A. nilotica</i>	16.92	2.20	5.08	0.94	22.00	3.14
<i>A. polyacantha</i>	12.17	2.29	3.65	0.98	15.82	3.27
<i>A. tortilis</i>	11.07	1.94	3.32	0.83	14.39	2.76

±SE are standard error of means

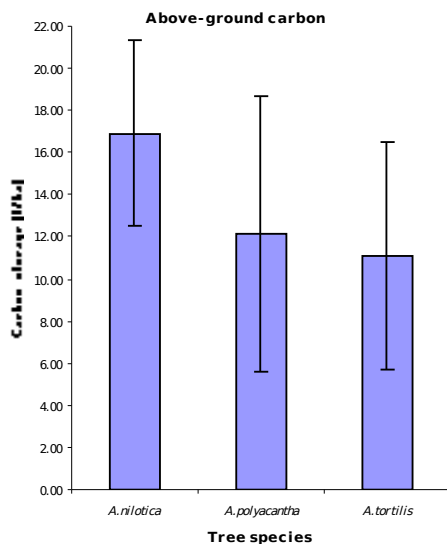
Different tree species contribute differently in C storage potential, where *A. nilotica* contributed the highest total tree C of  $22.0 \pm 3.14$  t ha<sup>-1</sup> followed by *A. polyacantha* had  $15.82 \pm 3.27$  t ha<sup>-1</sup> and *A. tortilis* had the least amount of  $14.39 \pm 2.76$  t ha<sup>-1</sup>. This difference may be attributed to the growing habits of tree species in degraded soils. Tree species with wide canopies as well as extensive and deep root systems are likely to produce high biomass under limited supply of growth resources due to superior acquisition capacities (Kimaro *et al.*, 2007). *Acacia nilotica* grows very fast during the early stage of growth, accumulates more carbon, therefore contributed more C compared to other tree species.

*A. nilotica* in forests of tropical India had total biomass estimates of 84.46 t ha<sup>-1</sup> (42.23 t C ha<sup>-1</sup>) which is twice as much as the estimates in this study. Size and composition of trees in a forest has an influence on total C storage in the system (Mutanal *et al.*, 2007). In primary forest, 70% of total C comes from trees with diameter greater than 30 cm (Roxburgh *et al.*, 2006). Low values of total C storage in *A. nilotica* in this study compared to other studies can be attributed to existence of small trees with diameters below 30 cm, which influences the amount of carbon in these ecosystems. However, total C stocks accumulated by *A. nilotica* in this study

were higher, almost twice to estimates of 26 t ha<sup>-1</sup> of biomass (13 t C ha<sup>-1</sup>) for *A. nilotica* under rotational woodlots in Mkundi village, Tanzania (Kimaro *et al.*, 2007).

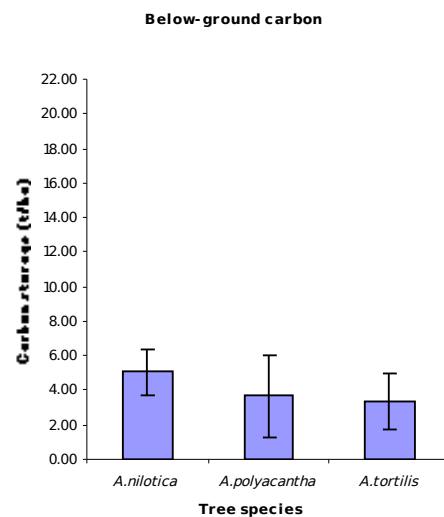
The C stocks stored by *A. polyacantha* in this study were lower compared to 18 t ha<sup>-1</sup> reported in Mkundi, Tanzania (Kimaro *et al.*, 2007). These differences may be caused by varying degrees in land degradation and the management of the systems (Unruh *et al.*, 1993; Kaonga and Smith, 2009).

Figures 4a and b shows the mean values of estimated above and below-ground C stocks in different tree species under rotational woodlots. *Acacia nilotica* had the highest above and below-ground C storage followed by *A. polyacantha* and *A. tortilis*.



Error bars are standard deviations of means

**Fig. 4a**



**Fig. 4b**

**Figure 4: Means of above and below-ground carbon storage in different tree species under rotational woodlots in Meatu District, Tanzania.**

Estimates of above ground C stocks ( $11.07 \pm 1.94$  to  $16.92 \pm 2.20$  t ha<sup>-1</sup>) for different species of *Acacia* in this study are within the range for agroforestry systems in Africa (3-15 t ha<sup>-1</sup>) (Sanchez, 1999), though higher than those reported for tropical systems which ranged from 1.5 to 3.5 t ha<sup>-1</sup> (Montagnini and Nair, 2004). Studies at Msekera and Chipata Zambia estimated C stocks of 5.4 t ha<sup>-1</sup> in above-ground and 1.97 t ha<sup>-1</sup> below-ground C accumulated in *Acacia angustissima* in 10-year improved fallows (Kaonga and Smith, 2009). These differences are presumably due to variations in management systems and nature of trees species.

Table 8 illustrates carbon storage potential of different tree components in rotational woodlots. Among the tree components, branches contributed the highest C storage, followed by stem, root and Leaf and/or twig. Stem C storage of  $2.97 \pm 1.0$  to  $7.06 \pm 2.10$  t ha<sup>-1</sup> were comparable to those published for improved fallows at Kalunga in Zambia of 1.4–7.5 t ha<sup>-1</sup> (Kaonga and Smith, 2009). Leaf and/or twig C storage were higher ( $1.22 \pm 0.3$  to  $2.95 \pm 1.0$  t ha<sup>-1</sup>) than those (0.4–1.8 t ha<sup>-1</sup>) reported for improved fallows in Zambia (Kaonga and Smith, 2009). Such disparities in C storage for tree components could be attributed to differences in tree species, fallow periods and management system (Unruh *et al.*, 1993).

**Table 8: Carbon storage potential of different tree components in rotational woodlots in Meatu District, Tanzania**

Tree species	Carbon Storage (t ha <sup>-1</sup> )							
	Stem		Branch		Leaf and/or twig		Root	
	Mean	±SE	Mean	±SE	Mean	±SE	Mean	±SE
<i>A.nilotica</i>	7.06	2.1	8.27	3.0	1.59	0.5	5.08	0.92
<i>A.polyacantha</i>	5.79	3.2	5.15	2.3	1.22	0.3	5.79	3.2
<i>A.tortilis</i>	2.97	1.0	5.16	2.3	2.95	1.0	3.32	0.35

SE (±) is standard error of means

Root C storage/stocks of  $3.32 \pm 0.35$  to  $5.08 \pm 0.92$  t ha<sup>-1</sup> are higher than those reported for rotational fallows of 0.8 to 3.7 t ha<sup>-1</sup> at Kalunga and Msekera (Kaonga and Smith, 2009).

In rotational fallows, the amount of C stored in tree biomass depends on the tree species and the fate of stem biomass at the end of tree fallow (Kaonga and Smith, 2009). Branches of *A. nilotica* contributed the highest C storage followed by *A. tortilis* and *A. polyacantha*. On the other hand, stems of *A. nilotica* and *A. polyacantha* and roots of *A. nilotica* contributed the highest carbon. Leaf and/or twig C storage for *A. tortilis* was relatively higher compared to *A. nilotica* and *A. polyacantha* which contributed the lowest carbon stocks.

Tree species contributed different amounts of C storage in components because of different growth characteristics. Branches of *A. nilotica* and *A. tortilis* contributed the highest C storage suggesting that there is a higher C gain in the crown because they form many branches with large crowns. Stems of *A. nilotica* are conical and short in length (5-6 m) hence accumulating less carbon overtime. The shape of the crown in *A. tortilis* is umbrella with many branches, which attributes to greater biomass (Dharani, 2006). The stem is straight pole like and short implying less carbon. Carbon storage was  $8.27 \pm 3.0$  t ha<sup>-1</sup> and  $5.16 \pm 2.3$  t ha<sup>-1</sup> in branches of *A. nilotica* and *A. tortilis* respectively. This component is commonly harvested for firewood before maturity. This implies that C stored in branches is lost while trees are still undergoing active growth.

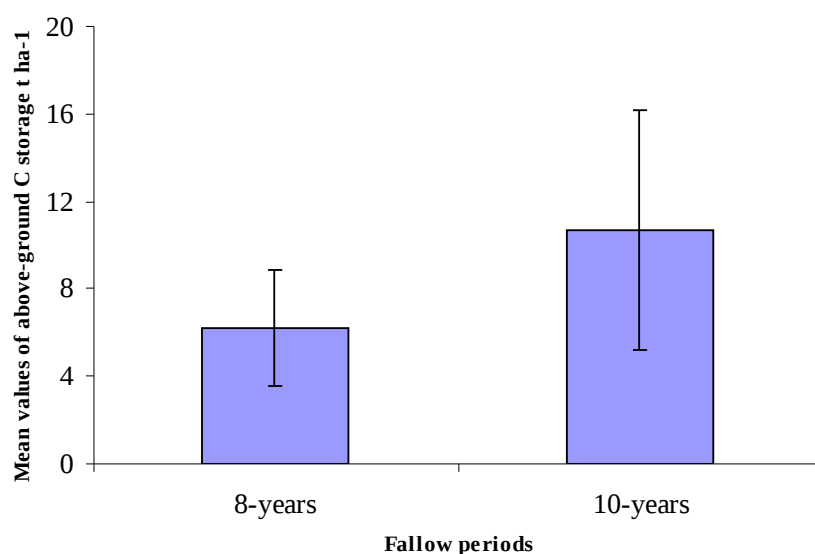
Higher C storage in stems of *A. polyacantha* is attributed to the tree characteristics. The stem is straight relatively thin and grows to a height between 3 and 25 m

(Dharani, 2006). For that reason, harvesting the stem for firewood at the end of tree fallow in rotational woodlots may result in a considerable loss of C storage from the system (Kaonga and Smith, 2009). This implies that potential for long-term storage in above-ground C in *A. polyacantha* may be limited unless harvested stem is processed into long-term wood products such as yolks for ox carts, poles for building and handles for hand hoes.

Leaf and/or twigs comprise a relatively low amount of C in rotational woodlots for all tree species. However, C storage in leaf and/or twigs was  $2.95 \pm 1.0 \text{ t ha}^{-1}$  in *A. tortilis* which was highest compared to other *Acacia* species. This suggests that *A. tortilis* produces leaves throughout the year and does not shed leaves, which ensures continuous photosynthesis and growth therefore higher C accumulation. Leaf and/or twig C storage in *A. polyacantha* was  $1.22 \pm 0.3 \text{ t ha}^{-1}$ . These trees shed leaves during dry season resulting into slow growth and hence low annual C accumulation. *Acacia nilotica* had  $1.59 \pm 0.5 \text{ t ha}^{-1}$  leaf and/or twigs C reflecting species characteristics which comprises of thorns and few leaves. Therefore, estimation of leaf and/or twigs C storage should adequately account for annual leaf fall or litter production and species characteristics (Otieno *et al.*, 2005).

#### **(b) Influence of fallow periods on above-ground carbon storage in woodlots**

Table 9 illustrates the change in above-ground C with increase in fallow periods. Carbon storage increased with increase in fallow periods (Figure 5a). In 8-year fallow, the overall mean C storage was  $6.21 \pm 0.63 \text{ t ha}^{-1}$  and increased to  $10.64 \pm 1.02 \text{ t ha}^{-1}$  in the 10-year fallow showing an increment of  $4.43 \text{ t ha}^{-1}$ .



Error bars are standard deviations of means

**Figure 5a: Influence of fallow periods on carbon stocks in above-ground rotational woodlots in Meatu District, Tanzania.**

The overall mean values of above-ground C storage in 8 and 10-year fallow periods is higher than those values reported for nitrogen fixing tree species in Zambia that in fallows  $\leq 5$  years which sequestered 3.0 - 8.9 t ha<sup>-1</sup> of C (Ajayi *et al.*, 2005).

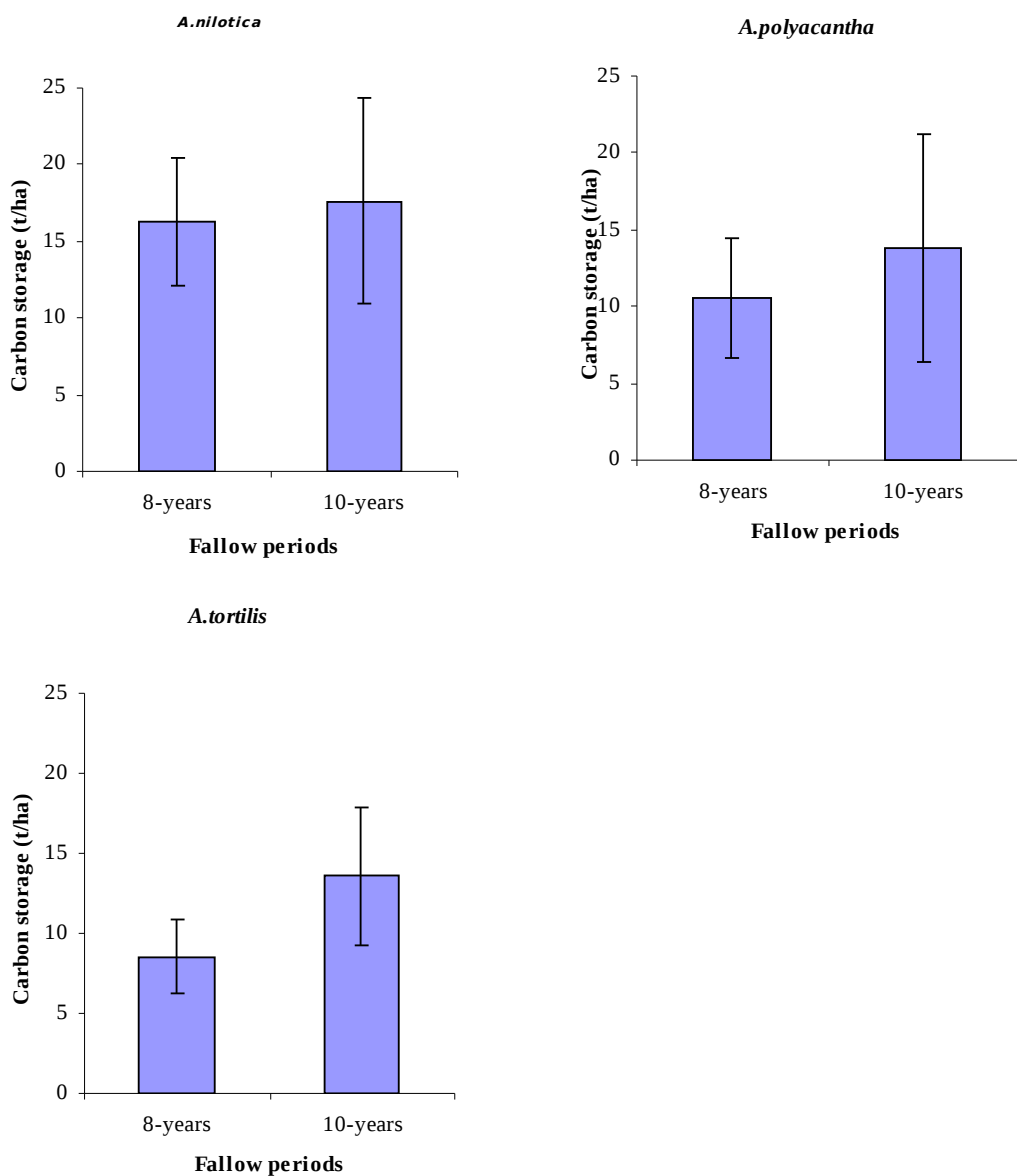
**Table 9: Influence of fallow periods on above-ground carbon storage in tree species under rotational woodlots in Meatu District, Tanzania**

Fallow periods	Carbon Storage (t ha <sup>-1</sup> )					
	<i>A.nilotica</i>		<i>A.polyacantha</i>		<i>A.tortilis</i>	
	Mean	±SE	Mean	±SE	Mean	±SE
8-years	16.22	1.70	10.53	2.26	8.56	2.59
10-years	17.63	5.35	13.81	4.31	13.58	2.24
<b>Change-C</b>	<b>+1.41</b>		<b>+2.28</b>		<b>+5.02</b>	

SE (±) is standard error of means



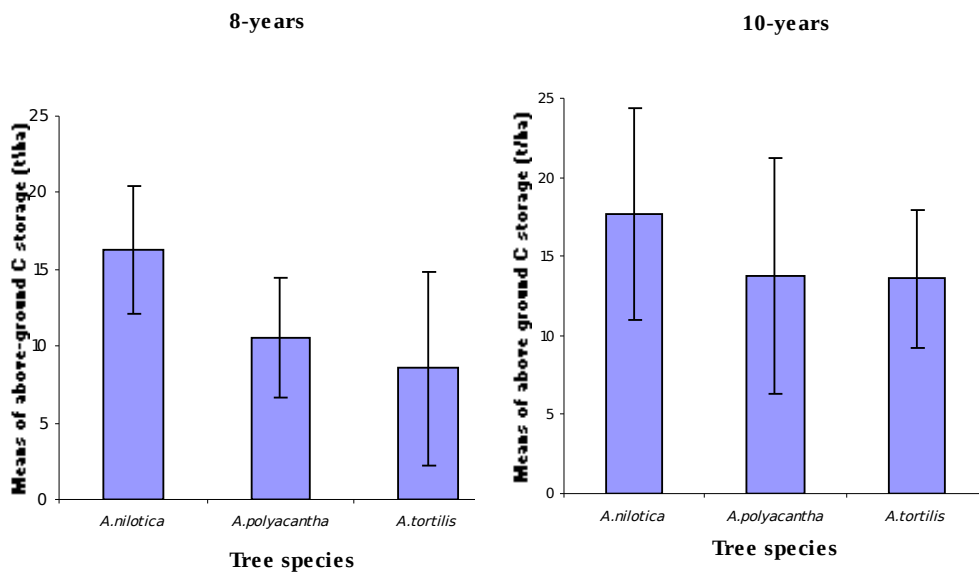
For all tree species, above-ground C storage increased with increase in fallow periods (Figure 5b). *A. tortilis* had the highest increase followed by *A. polyacantha* and *A. nilotica* within the 2 year period. The greater increment of C storage contributed by *A. tortilis* in woodlots is due to its deep rooting system which is able to maximize carbon gain when soil water is abundant and adjusting water uptake during drought, thus minimize water loss and make it available later in the season (Otieno *et al.*, 2005). This enables the tree to grow and increase its C storage. Similar findings for *A. tortilis* have been reported in the savanna regions of Kenya (Otieno *et al.*, 2005).



Error bars are standard deviations of means

**Figure 5b: Influence of fallow periods on carbon accumulation by different tree species in rotational woodlots in Meatu District, Tanzania**

For the 8-year fallows, *A.nilotica* had the highest C storage followed by *A. polyacantha* and *A. tortilis* (Fig. 6). On the other hand, for 10-year fallows, *A. polyacantha* and *A. tortilis* had almost the same carbon storage while *A. nilotica* maintained its lead in carbon storage (Fig. 6). This suggests that *A. nilotica* grows fast during the initial stages of growth and as the tree ages the carbon decreases as it loses some parts through senescence, unlike to *A. tortilis*, which gains C as the tree ages due to its dense wood.



Error bars are standard deviations of means

**Figure 6: Influence of 8 and 10-year fallows on above-ground carbon storage by different tree species in rotational woodlots in Meatu District, Tanzania.**

**(c) Soil organic carbon in woodlots**

Table 10 shows mean values of SOC stocks in different soil depths under rotational woodlots. Woodlots under *A. tortilis* contributed the highest SOC of  $159.5 \pm 4.58$  t ha<sup>-1</sup> in 100 cm soil depth followed by *A. polyacantha* ( $123.8 \pm 5.08$  t ha<sup>-1</sup>) and *A. nilotica* ( $94.9 \pm 0.43$  t ha<sup>-1</sup>).

The SOC stocks in this study contributed by different tree species in 100 cm depth under woodlots is within the range to SOC estimates reported in a 10-year non-coppicing fallows (*Tephrosia vogelli*, *Cajanus cajan* and *Sesbania sesban*) at Kalichero, Zambia. The estimated SOC ranged from 64.7 t ha<sup>-1</sup> to 184 t ha<sup>-1</sup> (Kaonga and Smith, 2009) which was almost similar to the range of SOC ( $94.9 \pm 0.43$  to  $159.5 \pm 4.58$  t ha<sup>-1</sup>) estimated in rotational woodlots in this study.

**Table 10: Means of soil organic carbon stocks (t ha<sup>-1</sup>) in different soil depths under rotational woodlots in Meatu District, Tanzania**

Soil depth (cm)	Tree species					
	<i>A. nilotica</i>		<i>A. polyacantha</i>		<i>A. tortilis</i>	
	Mean	SE (±)	Mean	SE (±)	Mean	SE (±)
0-20	34.03	3.58	50.05	12.13	68.15	11.26
20-40	28.37	3.84	32.60	4.75	37.33	4.46
40-60	12.78	2.20	17.00	4.56	24.22	4.39
60-80	9.87	1.96	12.42	1.16	18.13	1.69
80-100	9.88	2.15	11.77	2.81	11.67	1.1

SE (±) is standard error of means

In addition, the total SOC levels in this study are comparably higher than those for miombo woodlands and fallows reported in south-central Africa (Walker and

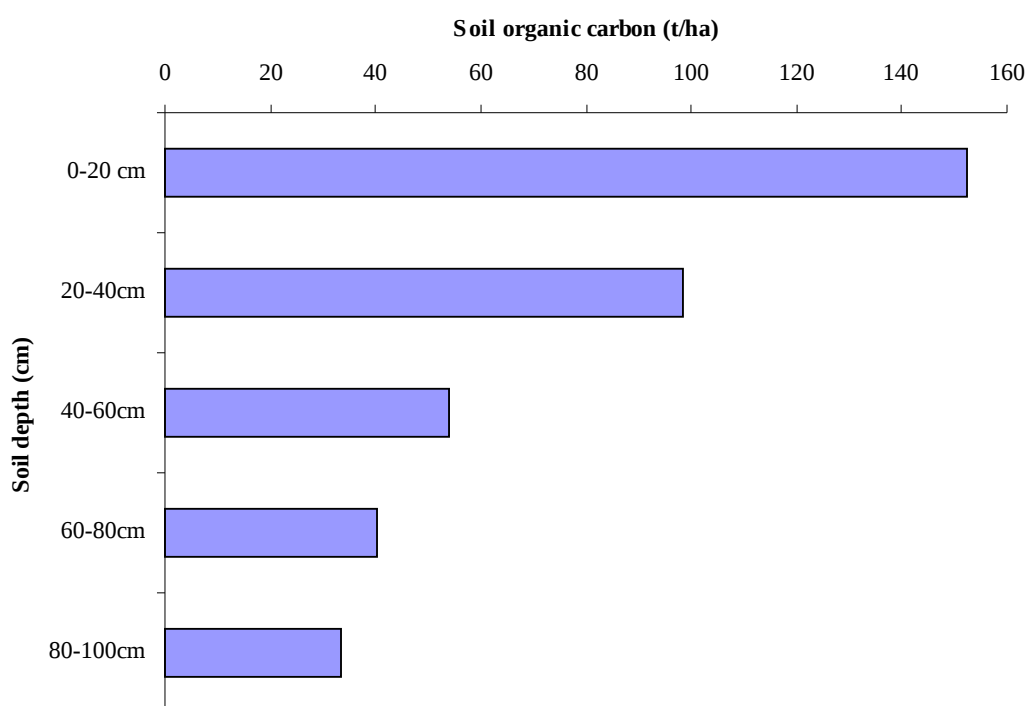
Desanker, 2004). The difference is attributed to the fact that the estimates in the other studies were based on soil analysis to 150 and 200 cm depth as opposed to 100 cm in this study.

The total C stocks in soils under woodlots of *A. tortilis* ( $159.5 \pm 4.58 \text{ t ha}^{-1}$ ) were within the reported range of 130.0–160.0  $\text{t ha}^{-1}$  of the expected amount of C in the first top metre of tropical soils (Jobbagy and Jackson, 2000). This potential for *A. tortilis* to contribute high SOC stocks can be attributed to tree characteristics and system management. It is a slow grower, therefore in soils under rotational woodlots, roots penetrate easily because the soil is tilled during woodlot establishment and therefore they grow fast and accumulate more organic matter.

Soil organic carbon decreased with soil depths, with highest amounts in the surface soil layers (0-20 and 20-40 cm) and small content in deep soils. Soil organic carbon on the top surface (0-20 cm) was  $152.2 \pm 8.99 \text{ t ha}^{-1}$ , on 20-40 cm was  $98.3 \pm 4.35 \text{ t ha}^{-1}$  and  $33.3 \pm 2.02 \text{ t ha}^{-1}$  in the depths of 80-100cm (Fig. 7).

Surface soils have higher amount of SOC and decrease with increasing depth because the OM is restricted on the top soil. Most of the litter falls on surface soil and is decomposed by microbes which are active on surface soil. In sub soil the microbial activities decreases due to increased bulk density which reduces aeration leading to low decomposition of OM hence low SOC in lower horizons. On average 60% of the C is found above 40 cm and more than 40% in the top 20 cm (Walker and Desanker, 2004). These findings are in agreement with observations in the present study for the reason that the top soil layer (0-20 cm) had higher SOC stocks of  $152.2 \pm 8.99 \text{ t ha}^{-1}$ . However, SOC storage in this study are low compared to estimates of  $418 \text{ t ha}^{-1}$  and

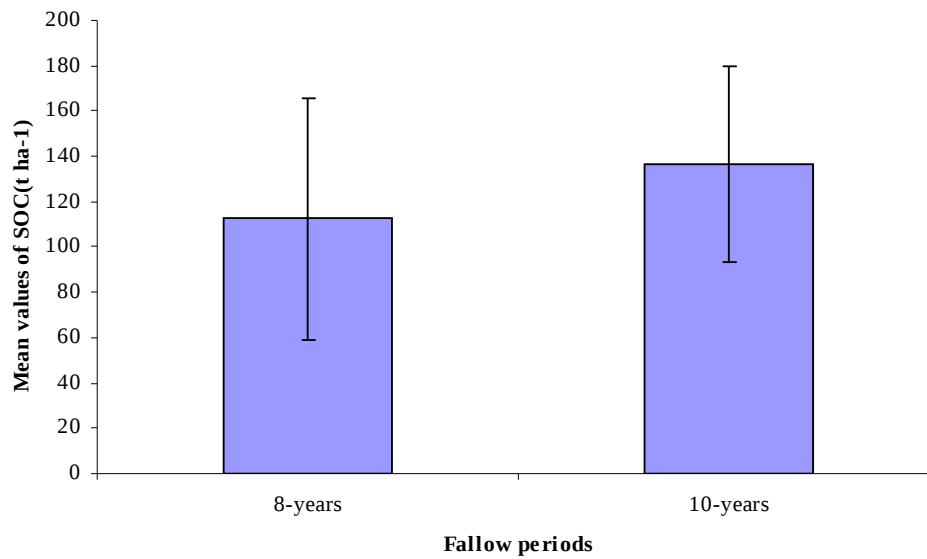
295 t ha<sup>-1</sup> in the 0-30 cm soil depth reported in Usambara and Uluguru montane forests respectively, in the Eastern Arc mountains (Munishi and Shear, 2004). This difference could be attributed to massive accumulation of litter and absence of wildfire in other studies. However, species composition, location of slope and nature of tree species could result to the differences (Munishi and Shear, 2004).



**Figure 7: Soil organic carbon stocks in different soil depths under rotational woodlots in Meatu District, Tanzania.**

**(d) Influence of fallow periods on soil organic carbon in woodlots**

Table 11 illustrates change in SOC with increase in fallow period. Overall mean values of SOC under rotational woodlots was  $112.68 \pm 12.56$  t ha<sup>-1</sup> for the 8-year and  $136.68 \pm 10.22$  t ha<sup>-1</sup> in the 10-year fallow periods (Fig. 8) which is an increment of 24 t ha<sup>-1</sup> over the 2 years. The increase in SOC was for both fallow periods.



Error bars are standard deviations of means

**Figure 8: Influence of fallow periods on soil organic carbon under rotational woodlots in Meatu District, Tanzania.**

Findings in this study are in agreement with those reported that there was more C on surface soil layers in the miombo region of south-central Africa than was in other tropical deciduous forests or savannas (Jobbagy and Jackson, 2000; Walker and Desanker, 2004). Highest soil organic carbon pools of between 119.2 -131.9 t ha<sup>-1</sup> was reported under plantations in the Caribbean lowlands of Costa Rica and the corresponding increase in sub surface soil layers was 33.3, 35.8 and 64.2% in 1, 3 and 6-year plantations, respectively (Jimenez *et al.*, 2007).. The soil organic carbon stocks were less compared to the total SOC in this study. These disparities are attributed to differences in tree species and management of woodlots and plantations.

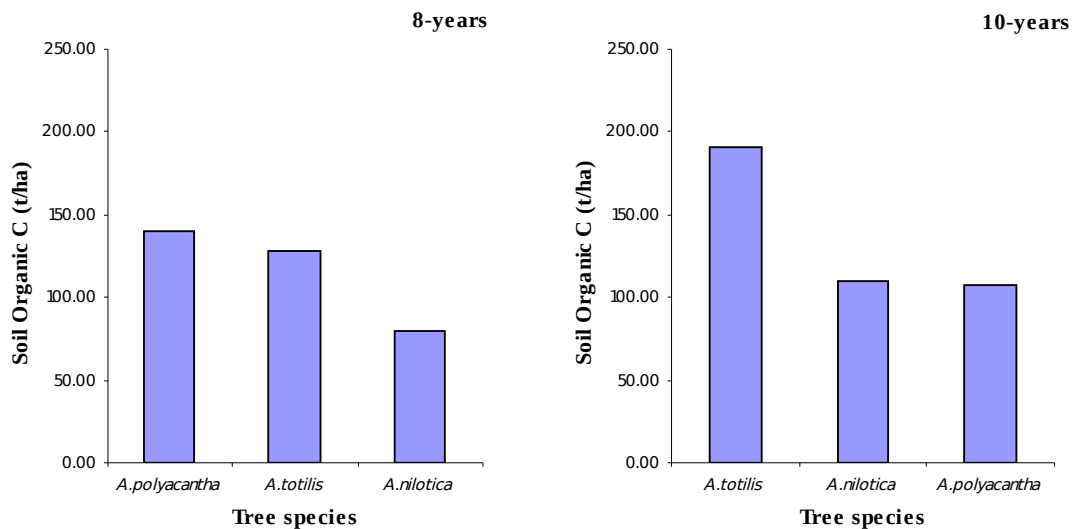
**Table 11: Influence of fallow periods on soil organic carbon under rotational woodlots in Meatu District, Tanzania**

Soil depth (cm)	Soil Organic Carbon (t ha <sup>-1</sup> )		Change Increment
	8-years	10-years	
0-20	137.1	167.4	+ 30.3
20-40	91.9	104.7	+ 12.8
40-60	51.0	57.0	+ 6.1
60-80	39.3	41.5	+ 2.2
80-100	28.6	38.0	+ 9.4

Soils in surface horizons (0-20 and 20-40 cm) increased by 30.3 t ha<sup>-1</sup> and 12.8 t ha<sup>-1</sup> in the 8-year and 10-year fallow periods respectively. The increment in the 40-60 and 60-80 cm depth was 6.1 t ha<sup>-1</sup> and 2.2 t ha<sup>-1</sup> respectively. In the lower horizon (80-100 cm) SOC decreased but with a relatively higher increment than the sub-soil.

Similar observations were reported that SOC was higher in the surface (61%) and sub surface (44%) soil horizons over different years of plantation (Gupta *et al.*, 2009). The higher SOC on the surface horizons may be attributed to the litter fall, which occurred at the beginning of dry season. In addition, decomposition of the litter to OM takes place mainly on the surface layers.

Soil organic carbon was higher in both fallow periods, although it was relatively low in 8-year compared to 10-year fallow. Woodlots of *A. polyacantha* had higher amount of SOC in 8-years followed by *A. tortilis* and *A. nilotica* (Fig. 9). In 10-year fallow period, SOC was higher in the *A. tortilis* followed by *A. nilotica* and *A. polyacantha* woodlots.



Error bars are standard deviations of means

**Figure 9: Influence of 8 and 10-year fallow periods on soil organic carbon under rotational woodlots in Meatu District, Tanzania.**

These results are in agreement with findings in other studies (Msanya *et al.*, 2003; Walker and Desanker, 2004; Kimaro *et al.*, 2007). In Mkundi village, Tanzania soil organic carbon in tree fallows of *A. polyacantha* and *A. mangium* were higher (0.8–1.3%) and raised close to those in natural Miombo woodlands after a 5-year fallow period (Kimaro *et al.*, 2007). Soil organic carbon under *A. mangium* of 1.3% and *A. nilotica* of 1.1% was higher than in soils under natural fallow of 0.9% (Kimaro *et al.*, 2007). On the other hand, the results are similar to those reported from natural Miombo soils of semi-arid areas of Tanzania (Msanya *et al.*, 2003). This improvement is usually associated with litter accumulation and fine root turn over during the fallow period (Walker and Desanker, 2004).



#### 4.2.2 Carbon storage in *Ngitiri*

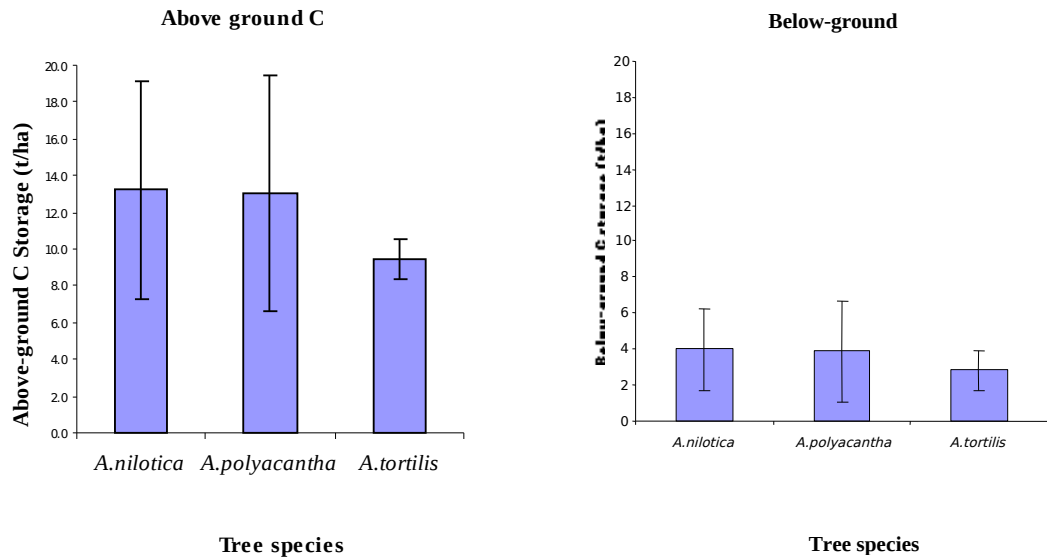
##### (a) Above and below-ground carbon storage in *Ngitiri*

Table 12 illustrates mean values of above and below-ground C stocks and total tree carbon storage/stocks in different tree species under *Ngitiri*. Different species contributed different amount of C storage in *Ngitiri*. *A. nilotica* accumulated  $13.22 \pm 1.49$  t ha<sup>-1</sup> of the above-ground C in the *Ngitiri* followed by *A. polyacantha* ( $13.01 \pm 4.30$  t ha<sup>-1</sup>) and *A. tortilis* ( $9.44 \pm 2.39$  t ha<sup>-1</sup>) (Fig.10).

**Table 12: Means of above and below-ground carbon stocks in tree species under *Ngitiri* in Meatu District, Tanzania**

Tree species	Above-ground C		Below-ground C		Total Tree C	
	Mean	±SE	Mean	±SE	Mean	±SE
<i>A.nilotica</i>	13.22	1.49	3.97	0.64	17.18	2.13
<i>A.polyacantha</i>	13.01	4.30	3.90	0.63	16.91	6.14
<i>A.tortilis</i>	9.44	2.39	2.83	0.42	12.27	3.42

SE (±) is standard error of means



Error bars are standard deviations of means

**Figure 10: Means of above and below-ground carbon storage in different tree species under *Ngitiri* in Meatu District, Tanzania.**

Findings in this study are in a range well with other reported studies (Kauri *et al.*, 2002). Similar total carbon storage in above-ground parts of *A. nilotica* has been reported in silvopastoral systems on a sodic soil in Kurukshetra, northwestern India, ranging from 6.80 to 18.55 t ha<sup>-1</sup> (Kauri *et al.*, 2002). However, root C in this study for *A. nilotica* was relatively higher (3.97 ± 0.64 t ha<sup>-1</sup>) than in other studies which ranged between 1.48 to 3.66 t C ha<sup>-1</sup> (Kauri *et al.*, 2002). It may be pointed out that *Acacia nilotica* had relatively low root C in other studies because the soils had pH ≥ 10 (Kauri *et al.*, 2002).

Table 13 shows C storage potential in tree components in *Ngitiri*. Carbon storage in the stem was about 15.55 t ha<sup>-1</sup>, branches stored almost the same quantities (15.82 t

ha<sup>-1</sup>) while leaf and/or twig had the lowest C (4.21 t ha<sup>-1</sup>). These findings are similar to those reported in Longisonte forest reserve, southern highlands miombo who reported higher stem C storage (53%) compared to branches (47%) (Munishi *et al.*, 2010).

Branches of *A. nilotica* contributed the highest C storage of  $6.92 \pm 3.3$  t ha<sup>-1</sup> while *A. polyacantha* and *A. tortilis* contributed relatively lower carbon storage of  $5.21 \pm 2.3$  t ha<sup>-1</sup> and  $3.79 \pm 2.5$  t ha<sup>-1</sup> respectively. On the other hand, tree stem and roots contributed the highest carbon storage for *A. polyacantha* and *A. nilotica*. The leaf and/or twig C for *A. tortilis* was relatively higher ( $2.09 \pm 1.2$  t ha<sup>-1</sup>) compared to other *Acacia* species. Branches of *A. nilotica* ranked first among *Acacia* species for C storage in the ecosystem. The tree species is relatively small to medium, usually single stemmed, branching from low down to the trunk and tends to produce many branches under favorable conditions (Dharani, 2006). As a result, its C storage potential is comparably higher than other *Acacia* species.

Stem of *A. polyacantha* had higher C storage in the ecosystem compared to other *Acacia* species in *Ngitiri*. This difference may be attributed to its large size, which had an influence on C storage in the *Ngitiri*. Most *A. polyacantha* in *Ngitiri* had diameters  $\geq 30$  cm, and in Missouri, 70% of total C comes from trees with diameter larger than 30 cm (Roxburgh *et al.*, 2006). This might contribute to the high values of C storage in the stem. *Acacia nilotica* and *A. tortilis* had diameter in the range between 5 and 30 cm, which had impact on the C stocks in the stem.

**Table 13: Means of carbon storage potential in different tree components under *Ngitiri* in Meatu District, Tanzania.**

Tree species	Carbon stocks (t ha <sup>-1</sup> )							
	Stem		Branch		Leaf and/or twig		Root	
	Mean	±SE	Mean	±SE	Mean	±SE	Mean	±SE
<i>A. nilotica</i>	5.16	1.3	6.92	3.3	1.14	0.2	4.0	0.51
<i>A. polyacantha</i>	6.83	3.7	5.21	2.3	0.98	0.5	3.9	0.32
<i>A. tortilis</i>	3.56	2.2	3.79	2.5	2.09	1.2	2.83	0.5

SE (±) is standard error of means

Values of C storage contributed by leaf and/or twig of  $2.09 \pm 1.2$  t ha<sup>-1</sup> was slightly higher in *A. tortilis* than in other species. This suggests that *A. tortilis* produces leaves in larger quantity throughout the year and during sampling both old and new leaves were taken in the measurement. Studies in the savanna of Kenya, estimated total litter production of *A. tortilis* to an average of 2300 kg ha<sup>-1</sup> per year (Haro and Oba, 1993).

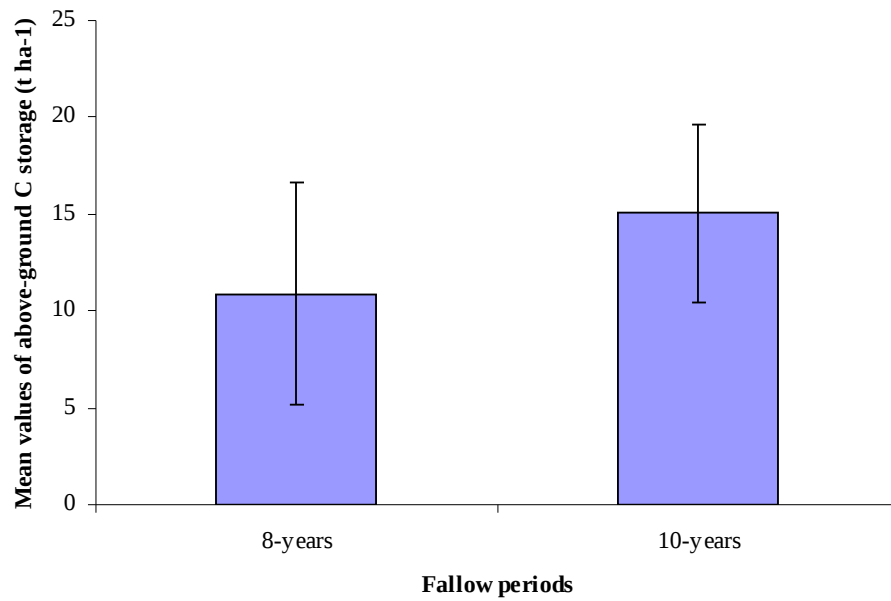
#### **(b) Influence of fallow periods on above-ground carbon storage**

Table 14 shows the change in above-ground C storage between 8 and 10 year old fallow under *Ngitiri*. The overall mean of above-ground C storage under *Ngitiri* in the 8-year fallow was  $10.86 \pm 5.74$  t ha<sup>-1</sup> and in the 10-year fallow increased to  $15.06 \pm 4.58$  t ha<sup>-1</sup> which is an increment of 4.20 t ha<sup>-1</sup> (Fig. 11).

**Table 14: Fallow periods and above-ground carbon storage under Ngitiri in Meatu District, Tanzania**

Fallow periods	Carbon Storage (t ha <sup>-1</sup> )					
	<i>A. nilotica</i>		<i>A. polyacantha</i>		<i>A. tortilis</i>	
	Mean	±SE	Mean	±SE	Mean	±SE
8-years	10.02	2.26	5.72	0.36	4.86	2.89
10-years	16.42	2.57	20.30	0.86	14.02	2.63
<b>Change in C</b>	<b>+6.40</b>		<b>+14.58</b>		<b>+9.16</b>	

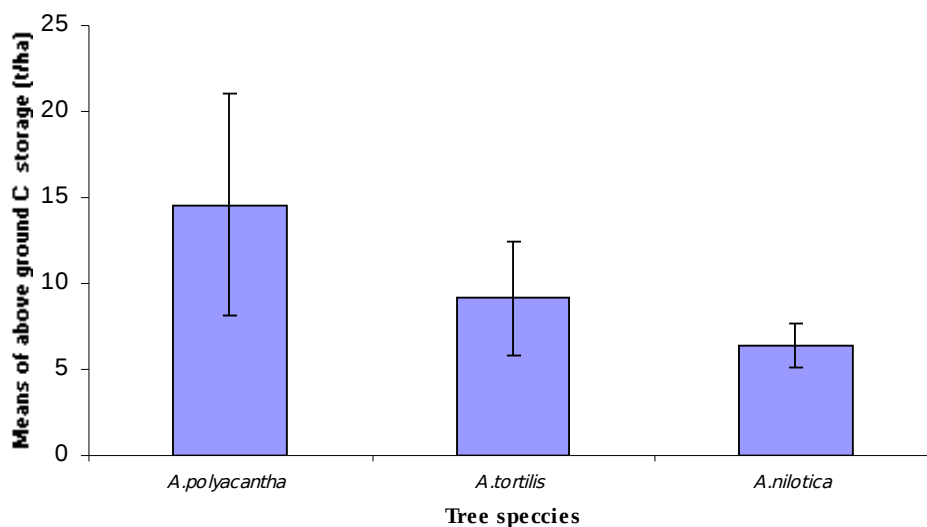
These findings had lower overall mean values of above-ground C storage of  $10.86 \pm 5.74$  t ha<sup>-1</sup> and  $15.06 \pm 4.58$  t ha<sup>-1</sup> which contributed to the ecosystem in 8 and 10-year fallow periods compared to those reported in other studies (Jong *et al.*, 1995). In addition, the increment of 4.20 t ha<sup>-1</sup> between the two fallow periods is lower to other studies. For example, in systems such as taungya, improved tropical fallows and coffee plantations have potential for above-ground C storage which ranges between 130–181 t C ha<sup>-1</sup> after 25 years of fallow period showing an increment of 51 t C ha<sup>-1</sup> (Jong *et al.*, 1995; Soto-Pinto *et al.*, 2009). For other studies it has been reported that natural fallow systems could store from 14 to 191 t C ha<sup>-1</sup> in 2 and 25 years respectively (Soto-Pinto *et al.*, 2009). Biomass accumulation apparently depends on fallow age and tree species (Mafongoya and Dzowela, 1999). These factors could account for the differences between findings in this study and those reported in other studies.



Error bars are standard deviations of means

**Figure 11: Influence of fallow periods on above-ground carbon storage under *Ngitiri* in Meatu District, Tanzania.**

For all tree species C storage in above-ground tree components increased with increasing fallow periods. *A. polyacantha* had the highest increase of 14.58 t C ha<sup>-1</sup> followed by *A. tortilis* by 9.16 t C ha<sup>-1</sup> and *A. nilotica* 6.4 t C ha<sup>-1</sup> (Fig. 12).



Error bars are standard deviations of means

**Figure 12: Means of 8 and 10-year fallow periods on above-ground carbon storage by different species under *Ngitiri* in Meatu District, Tanzania.**

The consistent increase in C storage contributed by all *Acacia* species indicate that as the tree ages biomass and carbon accumulated over time. The small increment in *A. nilotica* suggests that the species does not accumulate as much biomass/carbon as it grows and hence reduces the carbon gain. It might as well be due to utilization pressure. In Meatu District, branches of *A. nilotica* are commonly harvested for fuel wood at the early stage because of its fast growth potential thus ability to accumulate large quantities of biomass, and growing to sizes that can be suitable for fuel wood in the early stages of growth.

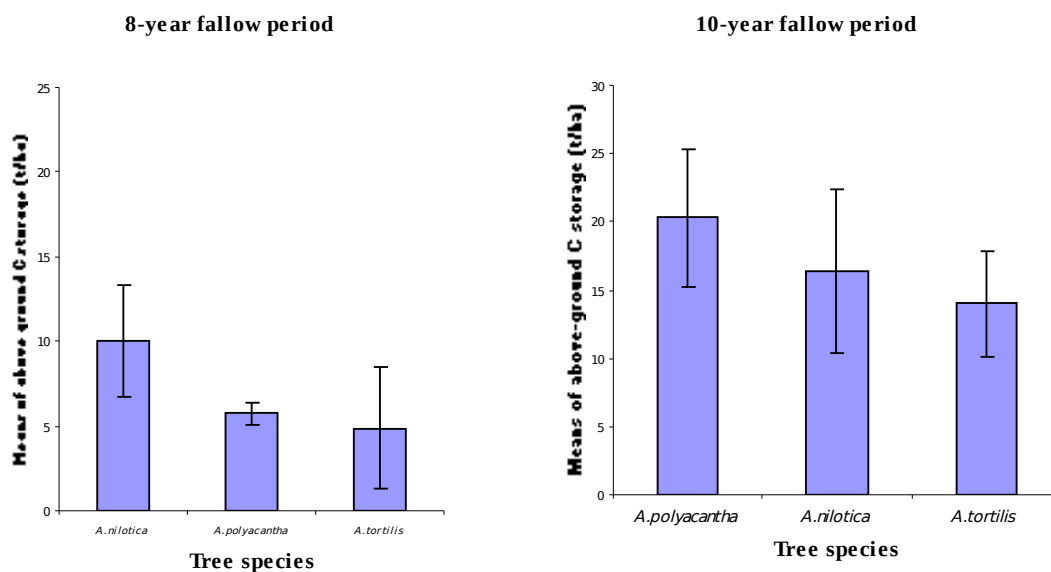
On the other hand, *A. nilotica* had accumulated the highest C storage in 8-year fallow while *A. tortilis* had the lowest carbon storage (Fig.13). In the 10-year fallows, *A.*

*polyacantha* contributed the highest C storage while *A. tortilis* had the lowest (Fig. 13).

*Acacia polyacantha* a fairly small to very large robust tree 3-25 m high (Dharani, 2006) usually occurring near stream banks in *Ngitiri*, ranked first in contributing to above-ground C in the ecosystem after 10-year fallow period. Consequently, its size makes it accumulate C storage as the *Ngitiri* ages compared to other *Acacia* species.

The low proportion of above-ground C contributed by *A. tortilis* in both fallow periods may be attributed to its size and environmental conditions. *A. tortilis* is a medium to large sized tree up to 20 m sometimes grows as a small shrub or bush and usually found where there has been disturbance by man or livestock (Dharani, 2006). In the *Ngitiri* *A. tortilis* is found on hillsides and seriously degraded habitats, therefore during early stage of growth the tree faces pressure from both human and livestock disturbance. In addition, the hillsides have poor and shallow soils, which impart retardation to tree growth compared to other *Acacia* species occurring under *Ngitiri*.





Error bars are standard deviations of means

**Figure 13: Influence of 8 and 10-year fallow periods on above-ground carbon from different species under *Ngitiri* in Meatu District, Tanzania.**

**(c) Soil organic carbon in *Ngitiri***

Table 15 shows SOC in different depths for the different *Acacia* species. Soils in 100 cm depth under *A. nilotica* had the highest amount of SOC of  $178.5 \pm 25.91$  t C ha<sup>-1</sup> than *A. polyacantha* of  $148.3 \pm 21.65$  t ha<sup>-1</sup> and *A. tortilis* of  $80.06 \pm 19.88$  t C ha<sup>-1</sup>.

The SOC estimated in this study under *Ngitiri* is higher than estimates of 21–74 t C ha<sup>-1</sup> in abandoned land and 18–140 t C ha<sup>-1</sup> for miombo woodlands in Mozambique (Williams *et al.*, 2008). These differences in SOC stocks might be attributed to management of the systems and the nature of tree species ((Unruh *et al.*, 1993; Mafongoya and Dzowela, 1999). Under *Ngitiri*, the land is protected by traditional by-laws, which help to minimize disturbance caused by humans and livestock.

**Table 15: Means of soil organic carbon in different soil depths under Ngitiri in Meatu District, Tanzania**

Tree species	Soil organic C (t ha <sup>-1</sup> )									
	0-20 cm		20-40cm		40-60cm		60-80cm		80-100cm	
	Mean	±SE	Mean	±SE	Mean	±SE	Mean	±SE	Mean	±SE
<i>A. nilotica</i>	39.70	4.23	36.18	1.52	37.42	7.39	27.45	1.87	37.72	11.13
<i>A. polyacantha</i>	39.40	9.46	37.05	2.89	26.20	2.83	23.44	2.65	22.18	4.16
<i>A. tortilis</i>	26.30	9.02	17.53	3.58	12.20	3.39	11.15	2.01	12.88	1.88

SE (±) is standard error of means

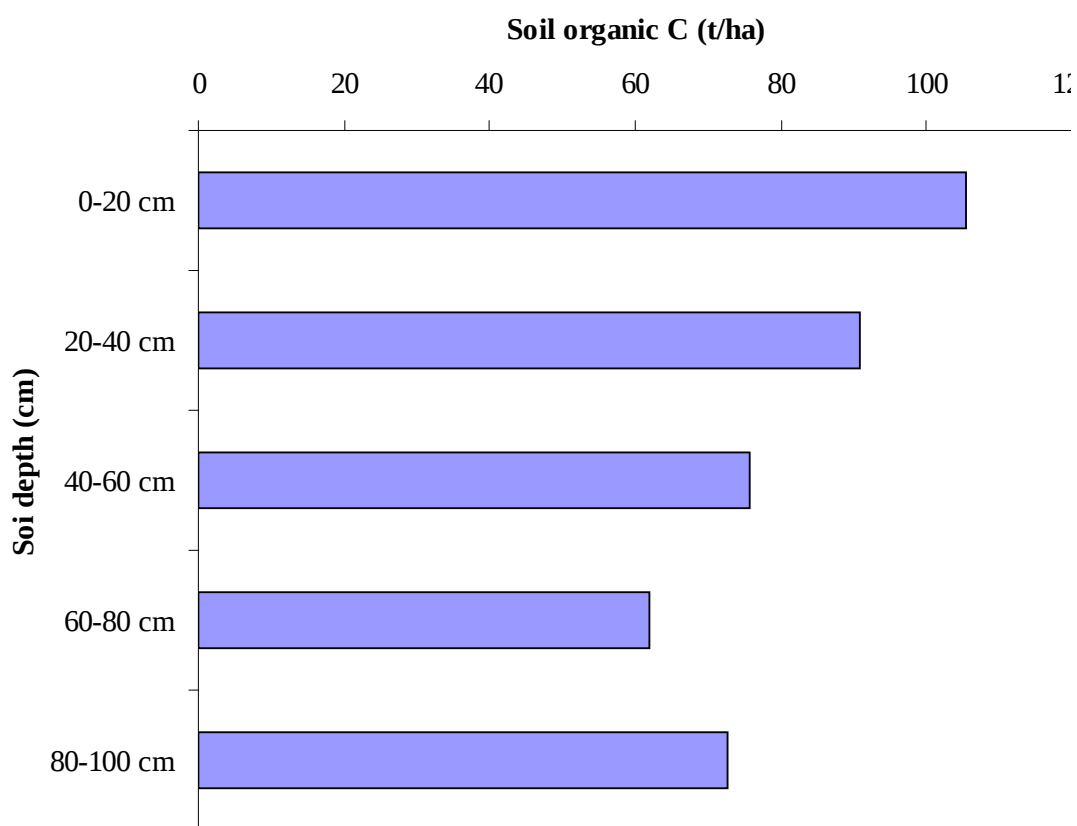
The total SOC of  $178.5 \pm 25.91$  t C ha<sup>-1</sup> in 100 cm soil depth under *A. nilotica* dominated Ngitiri was higher than the reported range of 130.0–160.0 t ha<sup>-1</sup> from other studies of the expected amount of C in the first metre of tropical soils (Jobbagy and Jackson, 2000). This potential for *A. nilotica* to contribute high SOC storage may be attributed to tree characteristics and system management. In areas with minimum human and livestock disturbance, *A. nilotica* grows fast, accumulates organic matter in the soil, which microbes decompose eventually increasing the SOC. On the other hand, *A. nilotica* have been reported to perform well in alkaline soils which in most cases are fertile leading to fast growth and accumulation of OM hence higher soil organic carbon (Goel and Behl, 1996; Charturved and Behl, 1996).

Soil organic carbon was inversely proportional to soil depth so the amount decreased with increasing soil depth. The carbon stocks in the surface soil layer (0-20 cm) were the highest (105.4 t ha<sup>-1</sup>), which decreased to 90.76 t ha<sup>-1</sup>, 75.82 t ha<sup>-1</sup> and 62.04 t ha<sup>-1</sup> in subsequent soil depths. However, the deep soil horizon (80-100 cm) had highest stocks of SOC of 72.78 t ha<sup>-1</sup> compared to the previous depths (Fig. 14). This later change could be due to presence of roots in the lowest horizon, which decomposed hence increase in SOC. In addition, horizon of 80-100 cm could have been previously

occurring on surface however, with time soil deposited and occupied lowest horizons while retaining its SOC from the surface soil.

The surface soil layer in this study have higher total SOC of 105.4 t C ha<sup>-1</sup> but comparably lower to the reported range of 130.0–160.0 t ha<sup>-1</sup> in the first metre of tropical soils (Jobbagy and Jackson, 2000).

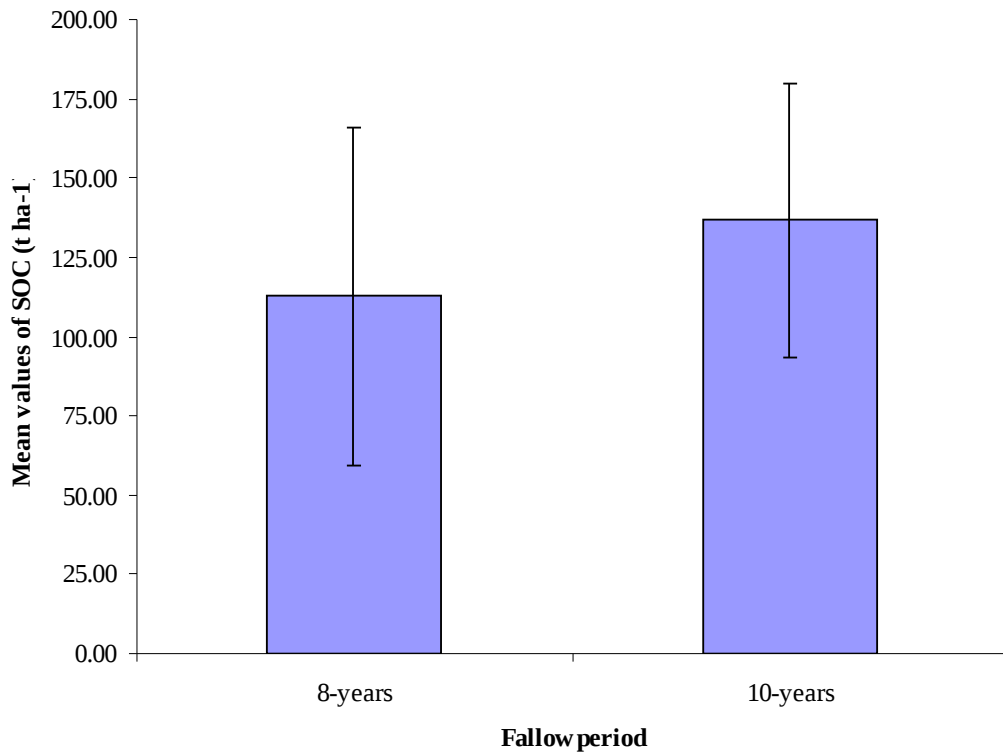
Many studies have reported higher estimates of SOC in the surface soil layer than lower horizons. Soil organic carbon storage of 418 t ha<sup>-1</sup> and 295 t ha<sup>-1</sup> in 0-30 cm depth was reported in Usambara and Uluguru montane mountains respectively (Munishi and Shear, 2004). In addition, estimates of 427 t ha<sup>-1</sup> of SOC was reported in the Uluguru and Chome Nature Reserve in the Eastern Arc mountains, but higher (277.3 t ha<sup>-1</sup>) than that in Iyondo Forest Reserve of the Kilombero Nature Reserve (Munishi and Shirima, 2009; Munishi and Shirima, 2010). These differences are attributed to species composition and location, nature of tree species, and also the variability in climatic and edaphic conditions (Mafongoya and Dzwela, 1999). In addition, high amount of SOC may be attributed to the management systems which, among other functions, minimize soil disturbance and erosion (Paustian, 2000).



**Figure 14: Soil organic carbon in different soil depth under Ngitiri in Meatu District, Tanzania.**

**(d) Influence of fallow periods on soil organic carbon in Ngitiri**

The overall mean values of soil C stocks in the 8-year fallows was  $112.68 \pm 12.56 \text{ t C ha}^{-1}$  and  $136.68 \pm 10.22 \text{ t C ha}^{-1}$  in the 10-year fallow period (Fig. 15) which is an increase of  $24.0 \text{ t C ha}^{-1}$ . The overall SOC of both fallow periods in this study is higher than the total SOC pools reported in a 7-year old taungya and improved fallow systems which accumulated  $130 \text{ Mg C ha}^{-1}$  and  $120 \text{ Mg C ha}^{-1}$  respectively (Soto-Pinto *et al.*, 2009). This disparity may be attributed to many factors such as fallow age and nature of tree species but management seems also to be crucial in C storage (Soto-Pinto *et al.*, 2009).



Error bars are standard deviations of means

**Figure 15: Influence of fallow periods on soil organic carbon under *Ngitiri* in Meatu District, Tanzania.**

Tables 16 illustrate changes in SOC with increase in fallow periods. In all soil depths, the SOC was lower for the 8-year fallow than the 10-year fallow.

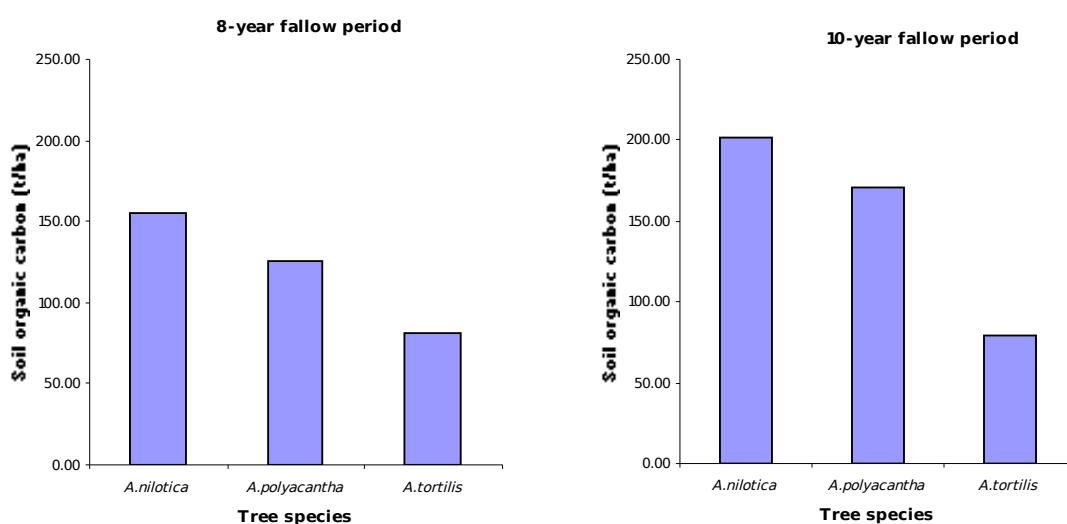
**Table 16: Soil organic carbon and fallow periods under *Ngitiri* in Meatu District, Tanzania**

Soil depth (cm)	Soil organic carbon (t ha <sup>-1</sup> )		
	8-year	10-year	Increment
0-20	101.20	119.00	+ 17.80
24-40	81.40	93.13	+ 11.73
40-60	66.94	82.70	+ 15.76
60-80	59.24	64.83	+ 5.60
80-100	52.57	93.00	+ 40.43

The surface soil layer (0-20 cm) contributed the highest SOC and increased by 17.8 t ha<sup>-1</sup> between the fallow periods. Soil organic carbon decreased with depth in the 20-40, 40-60 and 60-80 cm. However, in each soil depth below the top soil (0-20 cm) SOC storage/stocks increased by 11.73 t ha<sup>-1</sup>, 15.76 t ha<sup>-1</sup> and 5.6 t ha<sup>-1</sup> respectively in 10-year fallows. The increment in SOC between the two fallows at 80-100 cm depth was 40.43 t ha<sup>-1</sup> and was the highest among previous soil depths.

The observation in this study that SOC decreased with depth is in agreement with other published studies (Power, 2004; Soto-Pinto *et al.*, 2009). Most marked differences in SOC occur in the upper soil layer (Power, 2004). For example, studies in Chiapas, Mexico under traditional fallow reported higher SOC (56.1 t ha<sup>-1</sup>) on surface soil layer (0-10 cm), and the corresponding increase in each sub surface soil layers was 36.5 and 28.1 t ha<sup>-1</sup> in the 10-20 and 20-30 cm soil depth respectively (Soto-Pinto *et al.*, 2009). In a 7-year period taungya and improved fallow, the systems accumulated one-third of SOC previously predicted to be reached in 25 years (Jong *et al.*, 2000). Although their age was unknown, traditional fallows also demonstrated the same potential (Soto-Pinto *et al.*, 2009).

Soil organic carbon increased with increasing fallow periods for *A. nilotica* and *A. polyacantha*, but decreased in *A. tortilis* with increasing fallow periods (Fig. 16). In both fallow periods, *A. nilotica* accumulated higher amount of SOC followed by *A. polyacantha* and *A. tortilis*. These results are well in agreement with the findings in other studies (Kimaro *et al.*, 2007). For example, SOC in tree fallows of *A. polyacantha* and *A. mangium* were higher (0.8–1.3%) and close to those in natural Miombo woodlands after a 5-year fallow period (Kimaro *et al.*, 2007).



Error bars are standard deviations of means

**Figure 16: Influence of 8 and 10-year fallow periods on soil organic carbon under *Ngitiri* in Meatu District, Tanzania.**

#### 4.3 Soil Fertility Improvement under Rotational Woodlot and *Ngitiri*

*Acacia* fallows are potential sources of nutrients for soil fertility improvement in rotational woodlot and *Ngitiri*. In this section, levels of soil nutrients for total N, inorganic N, Olsen P and exchangeable K in different depths are reported. The quantities of these soil nutrients on different depth (0-100 cm) are presented. In

addition, the influence of fallow periods on soil inorganic N, Olsen P and exchangeable K under woodlots and *Ngitiri* are reported and discussed.

#### **4.3.1 Effects of rotational woodlots and fallow periods on soil nutrients**

##### **(a) Total nitrogen, inorganic nitrogen, Olsen phosphorus and exchangeable potassium at different depths under rotational woodlots**

Table 17 shows results for total N, inorganic N, Olsen P and exchangeable K in the surface soil layer (0-20 cm). Higher concentration of total N of  $0.31\% \pm 0.034$  were observed in soils under *A. tortilis* ( $0.31\% \pm 0.034$ ) compared to  $0.18\% \pm 0.02$  in *A. polyacantha* and  $0.14\% \pm 0.21$  in *A. nilotica*.

The total N for *A. tortilis* was within the general range of total N (0.2-0.5%) rated as medium for tropical soils (Landon, 1991; Msanya *et al.*, 2001). However, the values of total N under *A. nilotica* and *A. polyacantha* fallow are lower than those reported in patches of grassland of 0.3% in Meatu District and in cultivated soils (0.22%) before woodlots establishment in rural Shinyanga (Ngazi, 1997; Kamwenda, 2006)). In addition, low levels of total N of 0.154 % was found in more than 8-year old woodlots of *A. auriculiformis* in Kerala, India compared to values of total N in soils under *A. polyacantha* and *A. tortilis*, however, higher than in soils under *A. nilotica* in this study (Kumar *et al.*, 1998). These disparities may be due to difference in nature of trees species, and management of systems.

Among the tree species, soil inorganic N under *A. polyacantha* was  $118.2 \pm 22.94$  mg  $\text{kg}^{-1}$  of soil and that of *A. nilotica* was  $117.1 \pm 9.26$  mg  $\text{kg}^{-1}$  of soil this was comparatively higher than in *A. tortilis* of  $101.1 \pm 10.20$  mg  $\text{kg}^{-1}$  of soil.



**Table 17: Mean values of total N, inorganic N, Olsen P and exchangeable K in soil depths 0-20 cm in rotational woodlots in Meatu District, Tanzania**

Tree species	TN (%)		Inorganic N (mg kg <sup>-1</sup> )		Olsen P (mg kg <sup>-1</sup> )		Exch. K (cmol kg <sup>-1</sup> )	
	Mean	±SE	Mean	±SE	Mean	±SE	Mean	±SE
<i>A.nilotica</i>	0.14	0.21	117.1	9.26	36.8	9.26	0.41	0.07
<i>A.polyacantha</i>	0.18	0.02	118.2	22.94	53.2	22.94	0.70	0.16
<i>A.tortilis</i>	0.31	0.03	101.1	10.20	18.4	10.20	0.94	0.30

TN = total nitrogen, Olsen P = available phosphorus by Olsen method and Exch. K = exchangeable potassium. SE (±) is standard error of means

Trees in managed land use systems frequently cause favourable changes in soil chemical properties. For example in this study, means of soil inorganic N of different *Acacia* species under woodlots which ranged between  $101.1 \pm 10.20$  to  $118.2 \pm 22.94$  mg kg<sup>-1</sup> of soil the value that was higher than natural grass fallow ( $9.03$  -  $17.2$  mg kg<sup>-1</sup> of soil) in surface soil layer (0-30 cm) reported in Shinyanga (Banzi *et al.*, 2002). The higher soil inorganic N found in *Acacia* species than in natural grass fallow is most likely caused by N fixation by the trees, decomposition of tree residues and trapped atmospheric dust. In addition, N enrichment due to decomposition of understorey herbaceous litter could also be a factor (Buresh and Tian, 1998).

On the other hand, highest inorganic N of  $12.51$ - $28.5$  mg kg<sup>-1</sup> of soil in *A. polyacantha* than in soils under *A. nilotica* ( $9.73$ - $25.37$  mg kg<sup>-1</sup> of soil) was reported in Shinyanga (Banzi *et al.*, 2002). These results are similar to findings in this study. *Acacia* species have a potential to provide N in quantities sufficient to support moderate crop yields through N<sub>2</sub> fixation and retrieval of nitrate from deep soil layers. *Acacia* species in Africa (except the subgenus *Aculeiferum Monacantha*) are able to develop nodules with N fixing bacteria and mycorrhizae that improve N status of the soil (Harrier *et al.*, 1997).

The average soil Olsen P under woodlots was  $36.1 \pm 16.87$  mg kg<sup>-1</sup> of soil. Concentrations of soil Olsen P were different among species: *A. polyacantha* ranked first, *A. nilotica* ranked second and *A. tortilis* had the lowest phosphorus levels.

Most studies have reported little or no benefit of trees in respect of extractable inorganic soil phosphorus. Contrary to this study which reported higher mean values of Olsen P ranged between  $18.4 \pm 10.20$  to  $53.2 \pm 22.94$  mg kg<sup>-1</sup> of soil, some studies have reported a decrease in extractable inorganic P under trees, probably because of P storage in tree biomass (Haggard *et al.*, 1991; Hamidou, 1996). For example, low available P of 4.7 mg kg<sup>-1</sup> of soil in surface soil layer of 0-25 cm was reported in a five-year old mixed woodlots of *L. leucocephala* and *A. polyacantha* in Meatu District, Tanzania (Hamidou, 1996). This variation could be due to differences in age of woodlots and nature of species. *L. leucocephala* grows very fast unlike to the *Acacia nilotica* and *A. tortilis*, P in the soil could have been removed and stored in the tree biomass hence low P in the soil.

In addition, Olsen P in the soil surface under *Acacia* woodlots was higher for *A. polyacantha* followed by *A. nilotica* and *A. tortilis* but normally sufficient to meet the P requirements of crops because the values are above 10 mg P kg<sup>-1</sup> of soil, which is considered as threshold for plant needs (Okalebo, 1987; Landon, 1991; Msanya *et al.*, 2001).

Low values of available P of 4.1 mg kg<sup>-1</sup> of soil in 0-30 cm soil depth in patches of grassland was reported in Meatu District compared to values of Olsen P for all *Acacia* fallows in the woodlots (Kamwenda, 2006). In addition, lower values of 8.6

mg kg<sup>-1</sup> soil of available P in top soil layer cultivated before woodlots establishment was reported in rural Shinyanga than P values reported in the present study (Ngazi, 1997). The high P in soils under woodlots could be caused by nutrient cycling due to deep root system of *Acacia* species and decomposition of litter on surface soil, unlike to grasses they have shallow root system and the litter produced on surface soil is low compared to trees. This indicates that *Acacia* species have ability for soil enrichment through litter fall and improvement in the soil organic matter than patches of grassland and cultivated soil.

Phosphorus and Potassium (K) are known to be efficiently cycled by plants, and generally their concentrations in the top soil layer is reported to be higher than in patches of grassland and cultivated soils (Ngazi, 1997; Kamwenda, 2006; Tahir *et al.*, 2009). Concentrations of soil exchangeable K on the surface soil layer under woodlots averaged to  $0.68 \pm 0.14$  cmol (+) kg<sup>-1</sup> of soil, in the top soil layer (0-20 cm). These values are higher than exchangeable K (0.52 cmol (+) kg<sup>-1</sup> of soil) in cultivated soils before woodlots establishment in rural Shinyanga (Ngazi, 1997). Exchangeable K reported in the present study is higher than the values of 0.6 cmol (+) kg<sup>-1</sup> of soil found in soils under patches of grassland reported in Meatu District by Kamwenda (2006). The low levels of K in patches of grassland and cultivated soils could be caused by soil erosion due to absence of trees and leaching beyond root zone, as well as to the harvest of K in grass and the crops cultivated before woodlots establishment.

On the other hand, low soil exchangeable K under *A. nilotica* of  $0.41 \pm 0.07$  cmol (+) kg<sup>-1</sup> of soil reported in this study compared to that of  $0.70 \pm 0.16$  cmol (+) kg<sup>-1</sup> of soil in *A. polyacantha* and *A. tortilis* woodlots ( $0.94 \pm 0.30$  cmol (+) kg<sup>-1</sup> of soil) could be attributed to differences in nutrient uptake efficiency between different tree species,

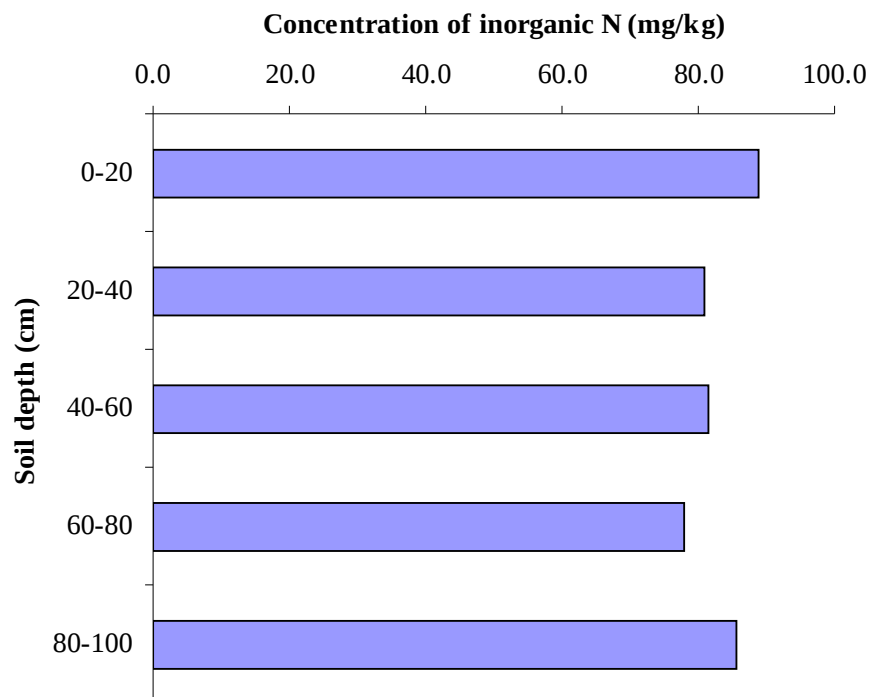
erosion and leaching on surface soil layer following low undergrowth (Kimaro *et al.*, 2007).

*Acacia nilotica* was the most efficient in K uptake; because this species produced the highest above-ground C (Table 7) at lowest nutrient “costs”. Its K-uptake efficiency was two times higher than that of *A. tortilis*. The variation in nutrient uptake efficiency among species may be attributed to several reasons related to uptake, transport, and utilization within plants (Kimaro *et al.*, 2007). For example, higher rates of nutrient re-translocation during either vegetative or reproductive growth, increase nutrient use efficiency due to better utilization of organically bound nutrients for growth (Marschner, 1995). This mechanism probably accounted for the observed species variability in K uptake since *A. nilotica* usually has faster vegetative growth (Dharani, 2006) that may reflect high nutrient re-translocation rates. Figures 17-19 show concentrations of soil inorganic N, Olsen P and exchangeable K in *Acacia* woodlots at different soil depths. The concentration of soil inorganic N, Olsen P and exchangeable K decreased with soil depth.

Under woodlots soil inorganic N was highest at the top soil layer than sub soil. Concentrations of N declined rapidly with depth, below 80 cm the values changed only slightly with depth. The amount of soil inorganic N in the top 20 cm depth was 88.7 mg kg<sup>-1</sup> of soil, declining to 77.9 mg kg<sup>-1</sup> of soil, at 60-80 cm and increased to 85.5 mg kg<sup>-1</sup> of soil, at 80-100 cm soil horizon. These results are in agreement with studies in Tabora and Morogoro which reported decrease in quantities of soil inorganic N with increase in depth in the sub soil however, quantities of N increased in the lowest horizon (Nyadzi *et al.*, 2003; Msanya *et al.*, 2003). This later change is presumably due to presence of roots in the lowest horizon which decomposed, and

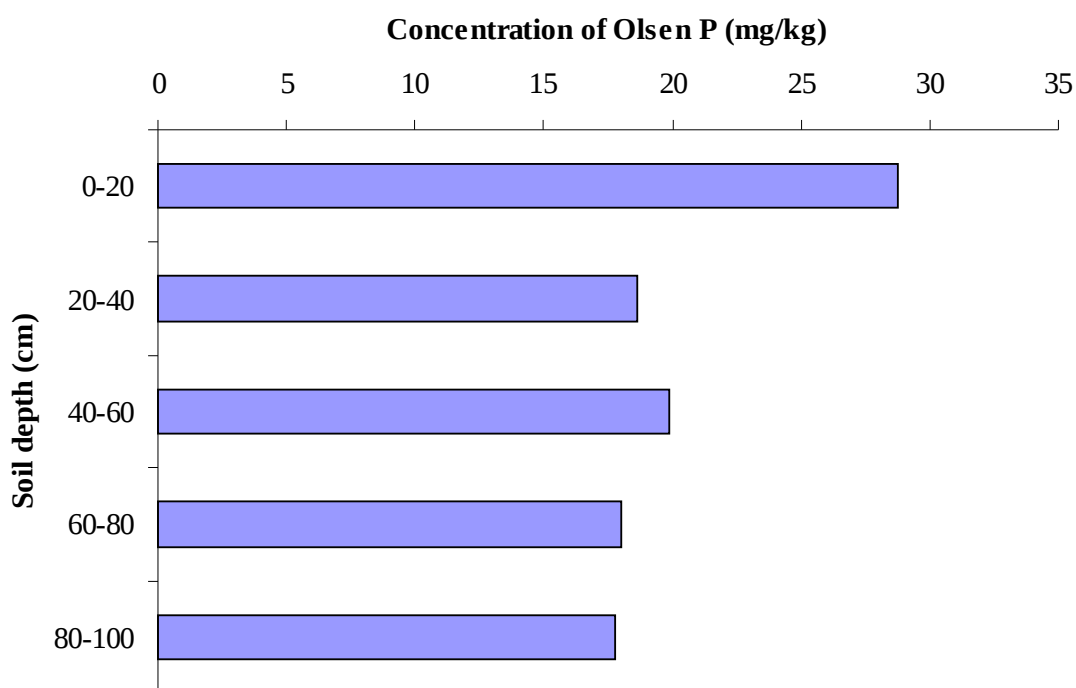
*Acacias* are able to develop nodules with N-fixing bacteria and mycorrhiza, which improve the N status of soil (Haggar *et al.*, 1991).

In addition, inorganic N under soils in woodlots of *A. crassicarpa* was reported to be higher in the two top soil horizons than in the lower horizons and was much lower under trees than natural fallow (Nyadzi *et al.*, 2003). The inorganic N in *A. crassicarpa* was in the order of 2.24, 1.97, 1.54, 1.17 mg kg<sup>-1</sup> of soil, while the natural fallow was 10.10, 3.37, 1.88 and 1.1 mg kg<sup>-1</sup> of soil, in 0-15, 15-30, 30-50 and 50-100 cm, respectively (Nyadzi *et al.*, 2003). The lower inorganic N below 30 cm depth under the woodlots and natural fallows was likely to have resulted from uptake by the roots of trees and the natural vegetation.



**Figure 17: Soil inorganic nitrogen at different soil depths in rotational woodlots of *Acacia* species in Meatu District, Tanzania.**

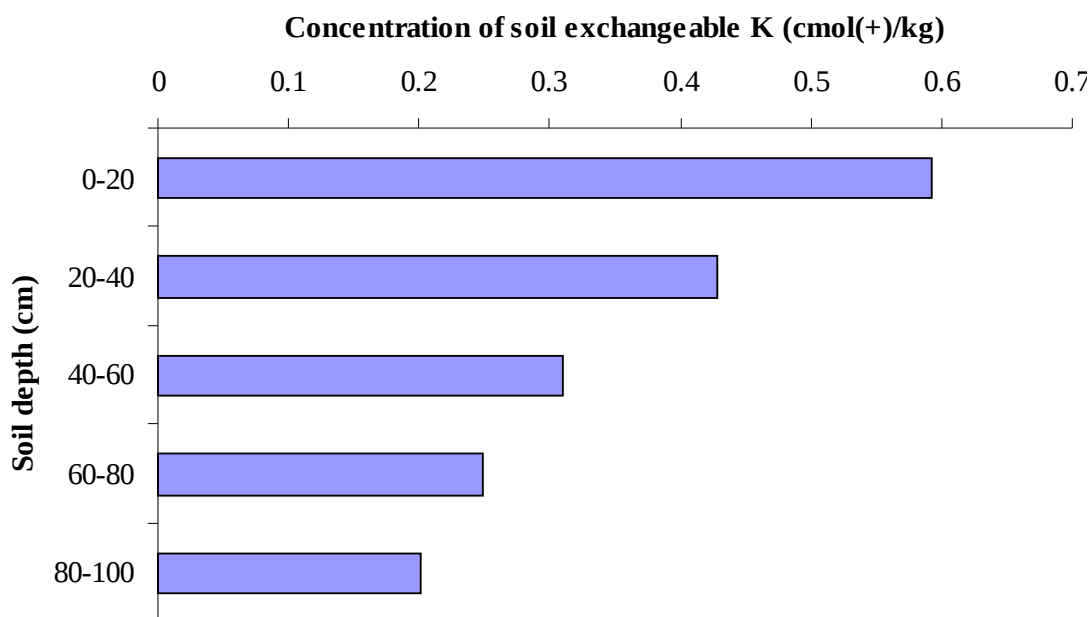
The concentrations of soil Olsen P was also highest in the surface horizons (28.8 mg kg<sup>-1</sup> of soil) with abrupt decrease to 18.6 mg kg<sup>-1</sup> of soil, at 20-40 cm depth becoming relatively constant below 60 cm depth. These findings are in agreement with studies reported in Mvomero, Morogoro where the available P in soil decreased with depth in a sequence of 0.13, 0.09, 0.06, 0.04 and 0.01 mg kg<sup>-1</sup> of soil in depth of 0-14, 14-45, 45-61, 61-106 and 106-155 cm respectively (Msanya *et al.*, 2001). Recycling of nutrients from deep soils was the most likely cause of observed increases in soil Olsen P associated with the presence of trees in the woodlots (Deans *et al.*, 1999).



**Figure 18: Soil Olsen phosphorus at different soil depths in rotational woodlots of *Acacia* species in Meatu District, Tanzania.**

Soil exchangeable K was 0.59 cmol (+) kg<sup>-1</sup> of soil at 0-20 cm and declined continuously with depth to 0.20 cmol (+) kg<sup>-1</sup> of soil at 80-100 cm. Studies reported that extractable K in a 15-year old *A. senegal* plantation was higher at the surface

(6.99 mg K (100g)<sup>-1</sup> of soil), and decreased continuously with depth to 1.73 mg K (100g)<sup>-1</sup> of soil at 50-100 cm (Deans *et al.*, 1999).



**Figure 19: Soil exchangeable potassium at different soil depth in rotational woodlots of *Acacia* species in Meatu District, Tanzania.**

**(b) Influence of fallow periods on concentrations of soil nutrient on surface soil layer (0-20 cm) under rotational woodlots**

Table 18 shows changes in concentration of soil inorganic N with increase in fallow periods. The mean for concentrations of soil inorganic N was higher in 8-year and decreased in 10-year woodlots by 26.6 mg kg<sup>-1</sup> of soil. Soil inorganic N in *A. nilotica* and *A. polyacantha* was 18.4 mg kg<sup>-1</sup> of soil lower under 10-year than 8-year woodlots. On the other hand, soil inorganic N increased by 60.4 mg kg<sup>-1</sup> of soil, in woodlots of *A. tortilis*.

The a soil inorganic N concentrations was 148.4 mg kg<sup>-1</sup> of soil, under 8-year *A. polyacantha* woodlots, which corresponded to about 400.14 kg N ha<sup>-1</sup> based on a top soil layer overall bulk density of 1.35 g cm<sup>-3</sup>. In Meatu District, these N quantities are sufficient to support four cropping seasons of maize production after the fallow period. These findings indicate that *Acacia* species in 8-year woodlots can benefit the subsequent maize crop. Similar results was reported in terms of higher maize yields produced after 5-year woodlots of *A. polyacantha* (Kimaro, 2009; Nyadzi, 2003) .In this respect, all tree species in the woodlots are effective in building up soil inorganic N in 8-year fallow period than natural fallow reported in other studies. For example, studies in Morogoro reported higher maize yields associated with *A. polyacantha* and *Gliricidia sepium* fallows, which reflected high soil fertility improvement during the fallow period (Kimaro, 2009). The fallows of these species accumulated more soil inorganic N (50 and 53 mg N kg<sup>-1</sup>), and extractable soil P (13 and 22 mg P kg<sup>-1</sup>) respectively than the natural fallow (29 mg N kg<sup>-1</sup> and 12 mg P kg<sup>-1</sup>) (Kimaro, 2009).

On the other hand, in the 10-year fallow, there was a decline in soil inorganic N in *A. nilotica* and *A. polyacantha* woodlots while *A. tortilis* showed an increase in N with fallow period. These differences were related to tree size. Larger trees tend to have higher concentration of soil nutrients than smaller trees (Belsky, 1993). The wood of *A. tortilis* is dense and as it ages it becomes denser and forms larger crowns, have a deep rooting system (Dharani, 2006). Therefore, the ability to enrich soils through nutrient cycling and nutrient pumping compared to *A. nilotica* and *A. polyacantha* (Kumar *et al.*, 1998).



**Table 18: Influence of fallow periods on soil inorganic nitrogen at 0-20 cm depth in rotational woodlot in Meatu District, Tanzania.**

Tree species	Fallow periods		Change (mg kg <sup>-1</sup> )
	8-year	10-year	
<i>A. nilotica</i>	126.3	107.8	-18.4
<i>A. polyacantha</i>	148.4	87.9	-60.4
<i>A. tortilis</i>	94.0	108.1	+14.1

Table 19 shows the change in concentrations of Olsen P with increase in fallow periods. Olsen P in the surface soil layer in 8-year fallow under woodlots was in the range between 9.6- 53.6 mg kg<sup>-1</sup> of soil and in 10-year fallows was 19.9-67.0 mg kg<sup>-1</sup> of soil. Olsen P at 0–20 cm depth increased by 27.6 mg kg<sup>-1</sup> of soil in the 8-year and by 17.2 mg kg<sup>-1</sup> of soil, in the 10-year fallow for *A. polyacantha* and *A. tortilis* woodlots, respectively. On the other hand, Olsen P was lower (-33.7 mg kg<sup>-1</sup> of soil) under 10-year compared to 8-year fallow for *A. nilotica* woodlots.

The increase in Olsen P in surface soil under 10-year fallows of *A. polyacantha* and *A. tortilis* has shown the potential of rotational woodlot for soil fertility replenishment. For the period of 8 to 10-year fallow, concentrations of Olsen P increased and were almost three times higher than in the 5-year natural fallow (12 mg P kg<sup>-1</sup> of soil) reported in Mkundi village, Tanzania (Kimaro, 2009). These findings are in agreement with studies reported in Southwestern Nigeria that extractable P at 0-15 cm soil depth increased from 20.9 kg P ha<sup>-1</sup> in a 4-year fallow of *Acacia*

*auriculiformis*, *Senna siamea*, and *Albizia lebbbeck* to 29.2 kg ha<sup>-1</sup> after 6 years of fallow (Tian *et al.*, 2001).

On the other hand, the decrease in concentrations of Olsen P in soils under 10-year woodlots of *A. nilotica* is in the range reported in a five year fallows of *A. auriculiformis*, *S. siamea*, *A. lebbbeck* and *Azadirachta indica* in Togo (Drechsel *et al.*, 1991). The decrease in Olsen P in surface soil layer after 10-years fallow in *A. nilotica* woodlots could be attributed to the following reasons. First is the effect of shade on plant nutrient uptake, which explains the increase of nutrients in soils under trees (Belsky, 2003). Although the mechanism is unknown, several studies have found that reduction in ambient radiation increase plant uptake of N, P, K, Ca, Mg, Cu and Zn (Eriksen and Whitney, 1981). If this increased uptake also reduces nutrient losses to leaching, then shade alone might explain the higher concentrations of nutrients in soils under trees. In this study *A. nilotica* had been reported to contribute low leaf and/or twig C (Table 2) consequently low shade effect leading to increased radiation, reduced uptake and presumably increased Olsen P loses through leaching.

The second reason for decrease in Olsen P in *A. nilotica* may be due to re-translocation of nutrients in the biomass. Some studies reported that *Eucalyptus tereticornis* re-translocated the highest proportion of N, P and K while *A. nilotica* re-translocated the lowest proportion of these elements (Belsky *et al.*, 2003). In addition, phosphorus had the highest rate of re-translocation compared to other nutrients, which decreased with the order: P > K > N (Belsky *et al.*, 2003). Therefore, the decrease in Olsen P observed in this study between 8 and 10-year old fallow of *A. nilotica* woodlots most likely has been re-translocated in the tree biomass and accumulate large quantities of nutrients for its fast vegetative growth (Dharani, 2006). Third

reason for the decrease in extractable soil inorganic P in soils under *A. nilotica* may presumably be associated with P storage in trees biomass (Haggar *et al.*, 1991).

**Table 19: Influence of fallow periods on soil Olsen phosphorus (mg kg<sup>-1</sup>) at 0-20 cm depth in rotational woodlots in Meatu District, Tanzania**

Tree species	Fallow Periods		Change (mg kg <sup>-1</sup> )
	8-year	10-year	
<i>A. nilotica</i>	53.6	19.9	-33.7
<i>A. polyacantha</i>	39.4	67.0	+27.6
<i>A. tortilis</i>	9.8	27.0	+17.2

Table 20 illustrates the change in concentrations of exchangeable K with increase in fallow periods under woodlots. Soil exchangeable K at the surface soil layer increased from 0.44 to 0.92 cmol (+) kg<sup>-1</sup> of soil in 8 and 10-year fallows respectively, which is an increment of 0.49 cmol (+) kg<sup>-1</sup> of soil, for two years. This was the case for fallows of all tree species, though *A. tortilis* had the highest increase of 0.87 cmol (+) kg<sup>-1</sup> of soil followed by *A. polyacantha* (0.53 cmol (+) kg<sup>-1</sup> of soil) and *A. nilotica* (0.06 cmol (+) kg<sup>-1</sup>).

**Table 20: Influence of fallow periods on soil exchangeable potassium (cmol (+) kg<sup>-1</sup> of soil) at 0-20 cm depth in rotational woodlot in Meatu District, Tanzania**

Tree species	Fallow Periods		Change (cmol kg <sup>-1</sup> )
	8-year	10-year	
<i>A. nilotica</i>	0.38	0.44	+0.06
<i>A. polyacantha</i>	0.43	0.96	+0.53
<i>A. tortilis</i>	0.51	1.37	+0.87

The increase in K in the top soil layer for *A. polyacantha* was higher (0.96 cmol (+) kg<sup>-1</sup> of soil) than those in 0-30 cm soil depth under a 7-year rotational fallow (0.65 cmol (+) kg<sup>-1</sup> of soil) at Mkundi village, Tanzania (Kimaro *et al.*, (2007).

On the other hand, soil exchangeable K of 0.44 cmol (+) kg<sup>-1</sup> under 10-year fallow reported in this study for *A. nilotica* woodlots was lower compared to those of 0.75 cmol (+) kg<sup>-1</sup> of soil for *A. nilotica* in a 7-year old rotational fallow reported by Kimaro *et al.*, (2007). This difference may be attributed to variability in climatic and soil conditions between Meatu District and Mkundi village. Meatu receives low rainfall and has a semi-arid climate and receives average rainfall of 450 mm per annum while Mkundi receives a mean annual rainfall of 800 mm (Nnko, 2003; Kimaro, 2009). Soils of Meatu District are classified as Chromic Cambisols according to FAO classification and soils at Mkundi, are classified as Regosol (FAO classification system) with kaolinite mineralogy clay (Nnko, 2003; Msanya *et al.*, 2003).

**(c) Soil pH, cation exchange capacity and bulk density on surface soil layer (0-20 cm) under rotational woodlot**

Table 21 illustrates the values of soil pH, CEC and BD at 0-20 cm soil depth in rotational woodlots. The values of soil pH under woodlots range between  $7.7 \pm 0.21$  and  $8.0 \pm 0.21$ . The pH for *A. polyacantha* woodlots ranked first ( $8.0 \pm 0.21$ ), followed by *A. tortilis* ( $7.9 \pm 0.04$ ) and *A. nilotica* ( $7.7 \pm 0.21$ ). In general, similar high soil pH values have been reported in crop fallow rotations (Kolawole *et al.*, 2005) and patches of grassland in Mwamishale in Meatu District (Kamwenda, 2006). On the other hand, soil pH values reported in this study ( $7.7 \pm 0.21$  to  $8.0 \pm 0.21$ ) are higher than those reported in cultivated soils of 7.5 before woodlots establishment in rural Shinyanga and cultivated grass and sorghum of 7.4 reported in North Sudan (Ngazi, 1997; Tahir *et al.*, 2009).

**Table 21: Mean values of soil pH, cation exchange capacity and bulk density at 0-20 cm depth under rotational woodlot in Meatu District, Tanzania**

Tree species	pH <sub>(water)</sub>		CEC (cmol (+) kg <sup>-1</sup> of soil)		Bulk density (g cm <sup>-3</sup> )	
	Mean	±SE	Mean	±SE	Mean	±SE
<i>A. nilotica</i>	7.7	0.21	23.7	2.72	1.55	0.09
<i>A. polyacantha</i>	8.0	0.21	26.4	2.74	1.35	0.07
<i>A. tortilis</i>	7.9	0.04	30.8	2.19	1.38	0.07

SE (±) is standard error of means

Woodlots of different tree species had different CEC of the soil, where *A. tortilis* ranked first ( $30.8 \pm 2.19$  cmol (+) kg<sup>-1</sup> of soil) followed by *A. polyacantha* ( $26.4 \pm 2.74$  cmol(+)<sup>-1</sup> of soil) and  $23.7 \pm 2.72$  cmol(+)<sup>-1</sup> of soil was in soils under *A. nilotica*. Generally, CEC values higher than 25 cmol (+) kg<sup>-1</sup> of soil on top soil layer is rated as good for rainfed maize production (Msanya *et al.*, 2001). However, CEC

values in woodlots under *A. nilotica* are within the moderate range required for maize production (Msanya *et al.*, 2001).

Findings in this study are contrary to CEC values reported in Morogoro (Msanya *et al.*, 2003; Kimaro *et al.*, 2007). In rotational fallow of *A. mangium*, *A. nilotica* and *A. polyacantha*, CEC approximately ranged between 8 and 12 cmol (+) kg<sup>-1</sup> of soil which was lower than CEC found in this study (Kimaro *et al.*, 2007). The increase in CEC matched those of natural Miombo fallow dominated by *Acacia* and *Hyperhenia* grass species and a 7-year *Eucalyptus* species planted fallow in Morogoro (Msanya *et al.*, 2003). The CEC values reported in this study under woodlots was three times higher (23.7 ± 2.72 to 30.8 ± 2.19 cmol (+) kg<sup>-1</sup> of soil) than those documented in other studies (Kimaro *et al.*, 2007). These disparities may be attributed to the nature of different tree species and fallow periods.

Besides, high CEC values of 55 cmol(+) kg<sup>-1</sup> of soil have been reported in soils under patches of grassland in Meatu District and in cultivated soils (40.3 cmol(+) kg<sup>-1</sup> soil) before woodlots establishment in rural Shinyanga than values of CEC reported in the present study ((Ngazi, 1997; Kamwenda, 2006). The reason for this variability is not known.

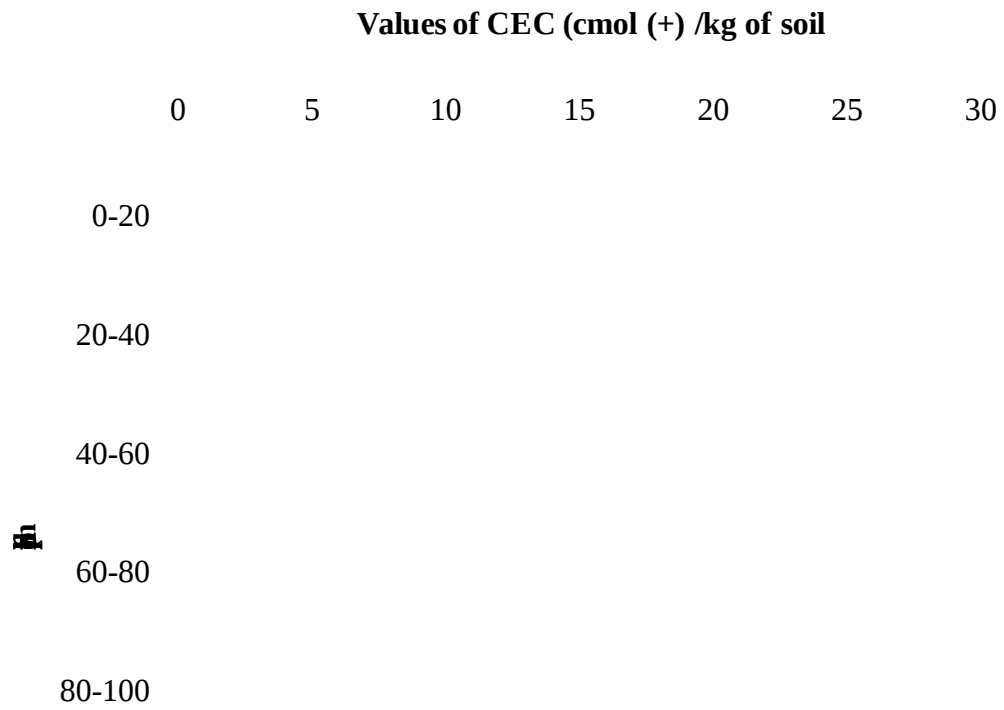
Bulk density at the surface for all woodlots averaged 1.43 ± 0.08 g cm<sup>-3</sup>. Values of BD in woodlots varied appreciably. *A. nilotica* woodlots ranked first (1.55 ± 0.09 g cm<sup>3</sup>), followed by *A. tortilis* and then *A. polyacantha*. Studies in Zimbabwe found BD levels very comparable to those reported in this study, with Miombo sites having BD of 1.3 g cm<sup>-3</sup> and the arable plots having a higher BD of 1.5 g cm<sup>-3</sup> (King and Campbell, 1994). A bulk density of 1.2 to 1.4 g cm<sup>-3</sup> is very common worldwide for

native vegetation without a thick organic horizon and agricultural conversion raises that to  $1.5 \text{ g cm}^{-3}$  (Brown and Lugo, 1990; Feller *et al.*, 2001).

On the other hand, high bulk density of  $1.5 \pm 0.09 \text{ g cm}^{-3}$  in *A. nilotica* woodlots may be attributed to compaction by grazing animals, particularly under wet conditions, which results into deterioration of soil structure hence reduced infiltration rate. Similar results have been reported however, the extent of increase in bulk density caused by grazing animals is not known (Armstrong *et al.*, 1999).

Figure 20 shows the values of CEC under woodlots at different soil depths. Changes of CEC in the soil within a profile was consistent with the highest concentration at the surface ( $25.2 \text{ cmol (+) kg}^{-1}$  of soil) and decreasing with depth upto 80 cm ( $19.4 \text{ cmol (+) kg}^{-1}$  of soil) then remain constant.

The pattern of change in values of CEC with increase in depth is in agreement with findings in other studies. For example, values of CEC in a soil profile reported at Magadu village was  $21.2 \text{ cmol (+) kg}^{-1}$  of soil in 0-13 cm depth, decreased to  $17.7 \text{ cmol (+) kg}^{-1}$  and a continuous decline to horizons > 74 cm depths ( $16.4 \text{ cmol (+) kg}^{-1}$  of soil) (Msanya *et al.*, 2001). The similarities in change of CEC with depths in the profile is most likely due to occurrence of similar vegetation (*Acacia species*, *Cassia species* and *Hyperrhenia rufa*) which increases OM on surface soil layer through litter fall. Nutrients are most likely taken up and stored in the plant biomass and soils in lower horizons remain with small CEC than the top soil layer. On the other hand, increased levels of CEC in the top soil layer than in the lower horizons under rotational woodlots reported in this study are higher compared to soils at Magadu, Morogoro.



**Figure 20: Changes of cation exchange capacity with soil depths in rotational woodlots in Meatu District, Tanzania.**

#### **4.3.3 Effects of *Ngitiri* and fallow periods on concentrations of soil nutrients**



**(a) Total nitrogen, inorganic nitrogen, Olsen phosphorus and exchangeable potassium in different soil depths under *Ngitiri***

Table 22 shows concentration of total N, inorganic N, Olsen P and exchangeable K at 0-20 cm soil depth. Overall total N in the surface soil layer in *Ngitiri* for different species was  $0.15\% \pm 0.01$ . The amount of total N in soils under *A. polyacantha* of  $0.17\% \pm 0.2$  was higher than that of  $0.15\% \pm 0.01$  of *A. nilotica* and *A. tortilis* fallows had the lowest value of  $0.13\% \pm 0.01$ .

The overall total N is within the range (0.1-0.2 %) rated as low for tropical soils (Landon, 1991; Msanya *et al.*, 2001). Besides, high total N values of 0.3 % in soils under patches of grassland were reported in Meatu District, than total N reported in the present study (Kamwenda, 2006). Soils under *Ngitiri* in the present study have pH values higher than 8.0 and such levels decrease bacterial activity and consequently nitrification of OM which is most likely cause of low total N (Landon, 1991).

On the other hand, findings in this study are contrary to reports documented in other studies. In a 6-year old plantation of *A. senegal* in Sudan at 0.3 m soil depth very low concentrations of total N of 0.027% were reported by Tahir *et al.*, (2009), lower than the overall values of total N ( $0.15 \pm 0.01$  %) in soils under *Ngitiri*. These differences may be due to difference in tree species and systems management. In addition, the values of total N at the surface soil layer under *Ngitiri* were higher than total N for pure cultivated sorghum of 0.13% in Sudan (Tahir, *et al.*, 2009).

The overall soil inorganic N was  $66.7 \pm 12.34 \text{ mg kg}^{-1}$  of soil in the *Ngitiri*. Among tree species, higher soil inorganic N was found under *A. nilotica* than under *A. polyacantha* and *A. tortilis*.

The levels of soil inorganic N on surface soil layer under *Ngitiri* are similar to those reported in other studies (Belsky *et al.*, 1993; Tahir *et al.*, 2009). For example, in low rainfall savannas of Tsavo, Kenya, higher soil N of  $1.79 \text{ kg N m}^{-3}$  under *A. tortilis* was reported compared to grassland ecosystem that had  $0.85 \text{ kg m}^{-3}$  (Belsky *et al.*, 1993). The high levels of soil inorganic N under *Ngitiri* may be attributed to direct N inputs from trees in the form of biological N-fixation, decomposition of tree residues and trapped atmospheric dust (Rao *et al.*, 1998; Kumar *et al.*, 1998). In addition, N-enrichment due to decomposition of understorey herbaceous litter could be a factor as reported by Buresh and Tian, (1998).

**Table 22: Total nitrogen, inorganic nitrogen, Olsen phosphorus and exchangeable potassium in surface soil layer (0-20 cm) under *Ngitiri* in Meatu District, Tanzania**

Tree species	TN (%)		Inorganic N ( $\text{mg kg}^{-1}$ )		Olsen P ( $\text{mg kg}^{-1}$ )		Exch.K ( $\text{cmol}(+) \text{kg}^{-1}$ )	
	Mean	$\pm$ SE	Mean	$\pm$ SE	Mean	$\pm$ SE	Mean	$\pm$ SE
<i>A. nilotica</i>	0.15	0.01	75.8	14.93	24.2	14.93	0.94	0.12
<i>A. polyacantha</i>	0.17	0.02	63.1	7.54	16.5	7.54	1.39	0.19
<i>A. tortilis</i>	0.13	0.01	61.2	14.56	28.3	14.56	0.69	0.30

TN = total nitrogen, Olsen P = available phosphorus by Olsen method, Exch. K = exchangeable potassium. SE ( $\pm$ ) is standard error of means

Olsen P in the surface soil layer averaged to  $23.0 \pm 12.34 \text{ mg kg}^{-1}$  of soil under *Ngitiri*. Highest amount of soil Olsen P of  $28.3 \pm 14.56 \text{ mg kg}^{-1}$  of soil was recorded

under *A. tortilis* than *A. nilotica* ( $24.2 \pm 14.93$  mg kg<sup>-1</sup> of soil) and *A. polyacantha* ( $16.5 \pm 7.54$  mg kg<sup>-1</sup> of soil).

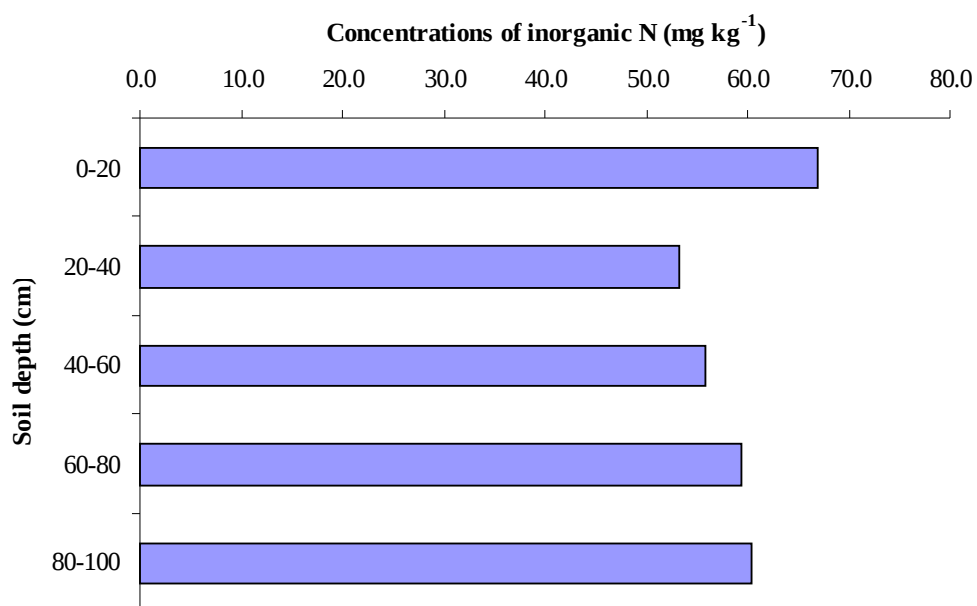
Trees can increase the availability of nutrients through increased release of nutrients from SOM and recycled organic residues. However, cycling of P from organic material is normally insufficient to meet P requirement of crops which is contrary to findings in this study (Belsky *et al.*, 1993). In *Ngitiri*, the highest levels of Olsen P under *A. tortilis*, *A. nilotica* than *A. polyacantha* are above the threshold of 10 mg P kg<sup>-1</sup> of soil sufficient to meet plant requirements (Okalebo, 1987). These levels were even higher than 9.8 mg P kg<sup>-1</sup> of soil found in naturally fallowed Miombo soils in Morogoro (Msanya *et al.*, 2003). Besides, very low available P of 4.0 mg kg<sup>-1</sup> of soil in soils was reported under patches of grassland in Meatu District compared to values in the present study (Kamwenda, 2006). This demonstrates the capacity of tree fallows in *Ngitiri* to recycle P effectively.

Many studies have reported that P availability increases with flooding (Sanchez, 1976, Tisdale *et al.*, 1993). Studies reported in Tanzania concluded that P availability increased with flooding in all soils tested (Shekifu and Semoka, 2007). This supports the fact that *A. nilotica* and *A. polyacantha* fallows commonly occur in *Ngitiri* along river banks and had Olsen P above the threshold of 10 mg kg<sup>-1</sup> of soil sufficient to meet plant requirements (Okalebo, 1987).

Exchangeable K in *Ngitiri* averaged to 1.0 cmol (+) kg<sup>-1</sup> of soil. Soils in *A. polyacantha* fallows had higher concentrations of K followed by *A. nilotica* and lastly were *A. tortilis*.

In general, soils in the surface soil layer under *Ngitiri* had high exchangeable K basing on the average of  $1.0 \pm 0.20$  cmol (+)  $\text{kg}^{-1}$  of soil which is within the range of 0.81-1.35 cmol (+)  $\text{kg}^{-1}$  for loamy soils (Msanya *et al.*, 1996; Kileo, 2000). On the other hand, *A. polyacantha* woodlands had relatively highest concentrations of  $1.39 \pm 0.20$  cmol (+)  $\text{kg}^{-1}$  of soil exchangeable K in *Ngitiri* than in patches of grassland (0.6 cmol (+)  $\text{kg}^{-1}$  of soil) reported in Meatu District (Kamwenda, 2006). Besides, values of K of 0.55 cmol (+)  $\text{kg}^{-1}$  of soil reported in cultivated soils before woodlots establishment in rural Shinyanga were lower than K values in the present study (Ngazi, 1997).

Figures 21-23 show the concentrations of soil inorganic N, Olsen P and exchangeable K with depth in 100 cm profile. The soil inorganic N in the top soil layer (0-20 cm) under *Ngitiri* was higher (67.0 mg  $\text{kg}^{-1}$  of soil) than in the lower horizons. A decline in N was observed in the sub soil though there was a slight increase in N below 40 cm.

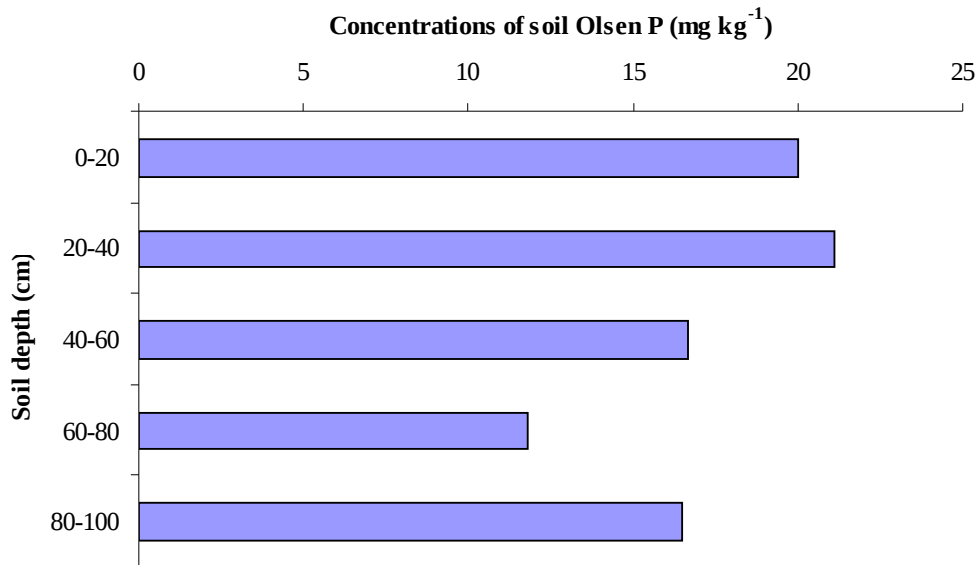


**Figure 21: Changes in soil inorganic nitrogen with soil depth in *Ngitiri* in Meatu District, Tanzania.**

Similar patterns in change of inorganic N with depth have been reported in several studies (Deans *et al.*, 2003; Walker and Desanker, 2004). For example, soil inorganic N in the top 10 cm soil layer in 10-year old fallows of *A. tortilis* and *A. nilotica* were 0.61 and 1.05 g N kg<sup>-1</sup> respectively, which exceeded those at 10-25 cm depth by 60% (Deans *et al.*, 2003). In the protected natural miombo woodlands of Chimaliro Forest Reserve and 10-20 years old agricultural fields in the surrounding village of Kasungu in Malawi, higher amounts of N in the surface soil layer than sub soil was reported (Walker and Desanker, 2004).

On the other hand, changes in soil inorganic N with depth in the profile under *Ngitiri* had similar pattern to those reported in 10-20 years old agricultural fields around Kasungu in Malawi (Walker and Desanker, 2004). Trees recycle nutrients from lower horizons and return on the surface soil layer through litter fall. There is more N on the surface soil layer because most of the litter fall accumulates on the surface and is decomposed by microbes.

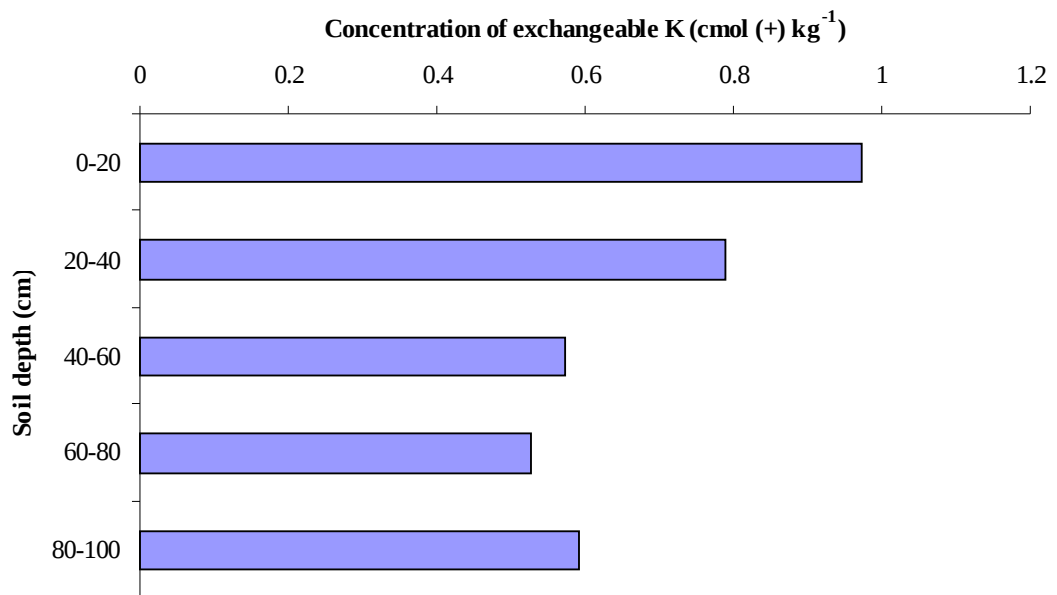
In general, the pattern of distribution of Olsen P in different soil depth was not consistent. The surface layer (0-20 cm) had slightly low Olsen P (20.0 mg kg<sup>-1</sup> of soil) compared to the 20-40 cm depth (21.1 mg kg<sup>-1</sup> of soil) which declined with depth to 80 cm increasing again to 100 cm.



**Figure 22: Changes in soil Olsen phosphorus with soil depth in Ngitiri in Meatu District, Tanzania.**

The concentrations of Olsen P (11.8-21.1 mg kg<sup>-1</sup> of soil) in *Ngitiri* are much higher than in soils which occur in valley bottoms in Morogoro (Msanya, *et al.*, 2003). For example Msanya *et al.*, (2001) reported that soils in valley bottoms had low available P, which ranged from 8.0-9.0 mg kg<sup>-1</sup> of soil. Besides, low values of 4.0 mg kg<sup>-1</sup> of soil of P were reported in soils under patches of grassland in Meatu District compared to values of P in the present study (Kamwenda, 2006). Elevated foliar and litter fall N concentrations in *Acacia* species may promote soil phosphatase production beneath trees on weathered soil, thus increasing the ability of N-rich species to acquire P (Houlton *et al.*, 2008). Although data to support this hypothesis are limited, this interaction offers an explanation for the high concentrations of P in *Acacia* species under *Ngitiri* compared to patches of grasslands. In addition, this difference may be attributed to differences in system management, locations and the nature of parent material.

Unlike Olsen P, changes of soil exchangeable K within a profile was consistent with the highest concentration of 0.97 cmol (+) kg<sup>-1</sup> of soil in the soil surface and decreased with depth up to 80 cm then increasing though not substantially.



**Figure 23: Changes of soil exchangeable potassium with soil depth under *Ngitiri* in Meatu District, Tanzania.**

The consistent pattern of distribution for soil exchangeable K in the profile is in agreement with findings from other studies. For example, Msanya *et al.*, (2003) reported higher concentrations of K in 0-14 cm (1.56 cmol (+) kg<sup>-1</sup>) than 14-45 cm soil depth (0.33 cmol (+) kg<sup>-1</sup>). However, the concentration of K in the surface soil layer in *Ngitiri* was lower compared to values of K reported in Morogoro (Msanya *et al.*, 2003). This difference may be attributed to differences in environmental conditions and locations. In addition, studies concluded at Bandia in coastal Senegal reported that concentrations of exchangeable K in the top 10 cm soil layer in a 10-year old planted *A. tortilis* and *A. nilotica* woodlots were 439 and 702 mg kg<sup>-1</sup> of soil

respectively and exceeded those reported from 10-25 cm depth by 300% (Deans *et al.*, 2003).

**(b) Influence of fallow period on concentrations of soil nutrient on surface soil layer in Ngitiri.**

Table 23 illustrates changes of soil inorganic N at 0-20 cm soil depth with increase in fallow periods. Soil inorganic N at the surface soil layer in 8-year fallow averaged to 74.0 mg kg<sup>-1</sup> of soil which was higher than the 10-year fallow (59.3 mg kg<sup>-1</sup> of soil) reported in this study for *Ngitiri*. In the top layer there was a decrease of 56.9 and 26.3 mg kg<sup>-1</sup> of soil in soil inorganic N for *A. nilotica* and *A. polyacantha* fallows respectively in two years. A gain of 39.1 mg kg<sup>-1</sup> of soil of the total inorganic N in *Ngitiri* was found in *A. tortilis* fallow.

**Table 23: Influence of fallow periods on soil inorganic nitrogen (mg kg<sup>-1</sup>) at 0-20 cm depth under *Ngitiri* in Meatu District, Tanzania**

Tree species	Fallow periods		Change (mg kg <sup>-1</sup> )
	8-year	10-year	
<i>A. nilotica</i>	104.2	47.3	-56.90
<i>A. polyacantha</i>	76.3	50.0	-26.30
<i>A. tortilis</i>	41.6	80.7	+39.12

The difference in soil inorganic N concentrations between 8 and 10-year fallow suggests that *Acacia* species are good for soil replenishment in short rotations. The decline in soil inorganic N in 10-years for *A. nilotica* and *A. polyacantha* under



*Ngitiri* could be due to senescence, which occurs as the trees age, loses some parts and reduces the amount of litter fall on surface soil layer hence low accumulation of organic matter. High N status of soil under *A. tortilis* for the 8 and 10-year old *Ngitiri* is similar to what is documented in literature for 5 and 7-year old *Acacia* species under silvopastoralism in India (Kumar *et al.*, 1998). On the other hand, increase in soil inorganic N in *A. tortilis* woodlands in two years may be attributed to litter fall accumulated on the soil surface layer and decomposed by microbial activity to release nutrients (Belsky *et al.*, 1989).

Table 24 illustrates changes of soil Olsen P in the surface soil with increase in fallow periods. Among the tree species, soil Olsen P decreased by 24.3 mg kg<sup>-1</sup> of soil in *A. nilotica* between fallows. However, Olsen P increased between the fallow periods for both *A. polyacantha* and *A. tortilis* with relatively higher increase for *A. tortilis* stands.

**Table 24: Influence of fallow periods on soil Olsen phosphorus (mg kg<sup>-1</sup> of soil) at 0-20 cm depth under *Ngitiri* in Meatu District, Tanzania**

Tree species	Fallow periods		Change (mg kg <sup>-1</sup> )
	8-year	10-year	
<i>A. nilotica</i>	36.4	12.0	-24.3
<i>A. polyacantha</i>	13.2	19.8	+6.5
<i>A. tortilis</i>	24.8	31.7	+6.9

Other studies have found little or no benefit of trees on improving extractable inorganic P in soil, some studies report a decrease in soil extractable inorganic P, presumably because of P sequestration in tree biomass (Haggar *et al.*, 1991). Studies in central Togo reported a decrease of P in the top soil layer for 5-year fallows of

planted woody species as compared to non-afforested soils (Dreschsel *et al.*, (1991). Some studies found that there was no change in extractable P at 0-15 cm soil depth in plots of 4-years planted woody fallows, though it was higher under 6-years old planted fallows (20.9-29.2 kg ha<sup>-1</sup>) compared to the natural fallow (14.1 kg ha<sup>-1</sup>) (Tian *et al.*, 2001).

Table 25 illustrates changes in soil exchangeable K in the surface soil with increase in fallow periods. Soil exchangeable K in the surface soil under a 10-years fallow was higher (1.04 cmol (+) kg<sup>-1</sup> of soil) than in an 8-years *Ngitiri*. Among tree species, soil exchangeable K in 10-year fallow was 0.95 cmol (+) kg<sup>-1</sup> of soil and 1.48 cmol (+) kg<sup>-1</sup> of soil and was higher than in the 8-years *Ngitiri* for *A. tortilis* and *A. polyacantha*, respectively. On the other hand, lower amount of K (0.69 cmol (+) kg<sup>-1</sup> of soil) was reported in *A. nilotica* fallows.

**Table 25: Influence of fallow periods on soil exchangeable potassium at 0-20 cm depth in *Ngitiri* in Meatu District, Tanzania**

Tree species	Fallow periods		Change cmol (+) kg <sup>-1</sup>
	8-year	10-year	
<i>A. nilotica</i>	1.18	0.69	-0.49
<i>A. polyacantha</i>	1.29	1.48	+0.19
<i>A. tortilis</i>	0.42	0.95	+0.53

These findings are similar to those reported by Kumar *et al.*, (1998) that exchangeable K on top soil layer decreased in a 7-year old fallow (65.42 mg K kg<sup>-1</sup>) than in a 5-year (68.43 mg K kg<sup>-1</sup>) fallow of *A. auriculiformis* in a silvopastoral system in Kerala, India. Exchangeable K is easily leached from the soil and most likely this was the cause of the low proportion of soil K that is returned through litter fall and higher retention in biomass (Toky and Singh, 1995). On the other hand, other

studies reported increase in exchangeable K with increase in fallow period in a tree less control plots, being higher (53.13 mg K kg<sup>-1</sup>) in a 7-year old fallow than in a 5-year old fallow (36.66 mg K kg<sup>-1</sup>) (Kumar *et al.*, 1998).

**(c) Soil pH, cation exchange capacity, and bulk density of the surface soil layer under *Ngitiri* in Meatu District, Tanzania**

Table 26 shows soil pH, CEC and BD at 0-20 cm depth under *Ngitiri*. Soil pH in the top soil layer (0-20 cm) under *Ngitiri* averaged to 8.0 ± 0.16 and pH was higher compared to those of 4.9 - 5.2 reported by Nyadzi *et al.*, (2003) in Tabora under woodlots of *Acacia* species. The soil pH was relatively similar (8.1 ± 0.04) for both *A. polyacantha* and *A. tortilis* under the *Ngitiri*. Soil pH under *A. nilotica* was comparatively low to the other trees species. Soil pH was modestly higher in tree species under *Ngitiri* and no distinct differences with respect to species variation in soil pH. These findings are contrary to what is documented in other studies for a 7-year old *A. auriculiformis* fallow in silvopastoral system which had low soil pH values of 4.7 but relatively higher than in a tree less (control) plots which had soil pH of 4.6 (Kumar *et al.*, 1998).

**Table 26: Soil pH, cation exchange capacity and bulk density at 0-20 cm depth in *Ngitiri* under different tree species in Meatu District, Tanzania**

Tree species	pH (water)		CEC (cmol(+) kg <sup>-1</sup> )		BD (g cm <sup>-3</sup> )	
	Mean	±SE	Mean	±SE	Mean	±SE
<i>A. nilotica</i>	8.0	0.16	40.8	1.45	1.23	0.08
<i>A. polyacantha</i>	8.0	0.04	35.3	2.04	1.32	0.05
<i>A. tortilis</i>	8.1	0.03	26.8	0.54	1.43	0.05

SE (±) is standard error of means

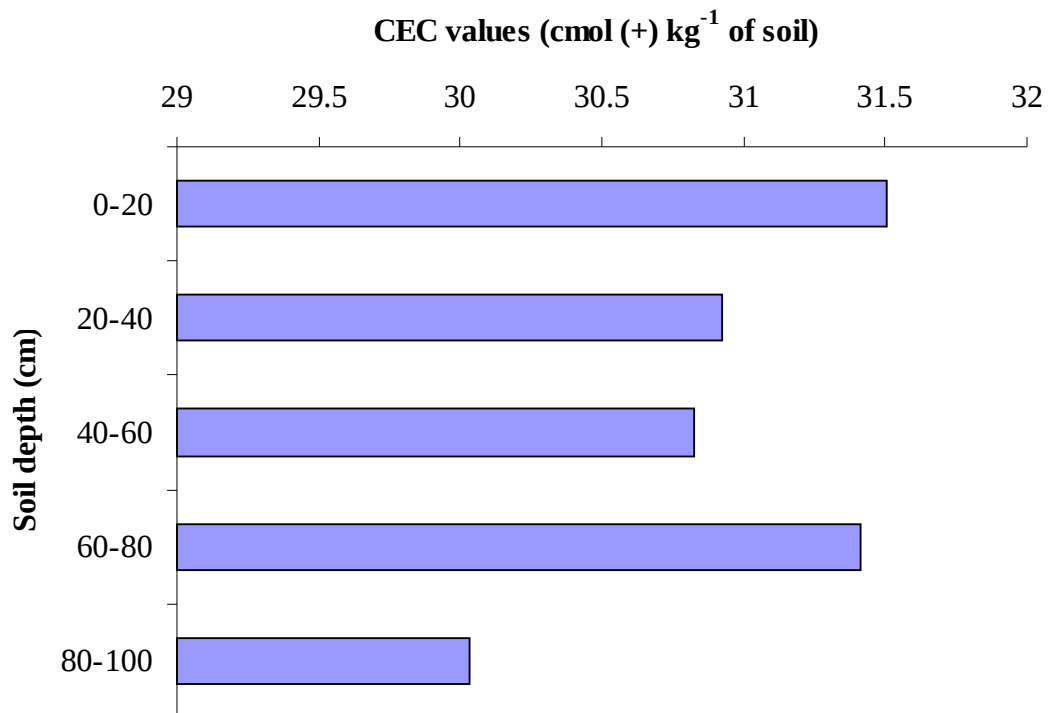
The CEC of the top soil under *Ngitiri* averaged  $34.3 \pm 1.34$  cmol (+) kg<sup>-1</sup> of soil. *Ngitiri* of different tree species had different CEC where *A. nilotica* ranked first followed by *A. polyacantha* and *A. tortilis*. These findings are similar to studies reported in Morogoro for soils occurring in valleys where nutrient retention capacity was high (20-30 cmol (+) kg<sup>-1</sup>) (Msanya *et al.*, 2001). However, very high CEC values of 83.5 cmol (+) kg<sup>-1</sup> of soil were reported in soils under patches of grassland in Meatu District compared to CEC values reported in the present study (Kamwenda, 2006) .

Bulk density of the surface soil under *Ngitiri* averaged  $1.33 \pm 0.06$  g cm<sup>-3</sup>. Soils under *Ngitiri* of different tree species had different soil bulk densities with *A. tortilis* having the highest BD of  $1.43 \pm 0.05$  g cm<sup>-3</sup> followed by *A. polyacantha* and the last was *A. nilotica*.

Salako *et al.*, (2001) reported BD levels relatively comparable to those found in this study, with planted wood and natural fallows having BD between 1.17 and 1.23 g cm<sup>-3</sup> in Southwestern Nigeria. A bulk density of 1.2–1.4 g cm<sup>-3</sup> is very common worldwide for native vegetation without thick organic horizon and agricultural conversion raises the BD to 1.5 g cm<sup>-3</sup> (Brown and Lugo, 1990). The increased bulk density in soils under *A. tortilis* under *Ngitiri* may be due to soil compaction by grazing animals.

Figure 24 show the values of CEC under *Ngitiri* at different soil depths. Changes in CEC within a profile was consistent with the highest CEC values in the soil surface (31.5 cmol (+) kg<sup>-1</sup> of soil) and decreasing with depth up to 60 cm (30.8 cmol (+) kg<sup>-1</sup> of soil) then increasing though not substantially.

The pattern of change in quantities of CEC with increase in depth is in agreement with findings from other studies. For example, studies in Morogoro reported higher CEC values in a soil profile at Bigwa being 30.9 cmol (+) kg<sup>-1</sup> of soil, in 0-20 cm depth, decreased to 9.9 cmol (+) kg<sup>-1</sup> of soil and a slight increase to horizons > 75 cm depths (11.1 cmol (+) kg<sup>-1</sup> of soil) (Msanya *et al.*, 2001). The similarities in change of CEC with depth in the profile is most likely due to occurrence of similar vegetation which increases OM on surface soil layer through litter fall. On the other hand, CEC values in the top soil layer to lower horizons under *Ngitiri* were higher compared to soils at Bigwa. This difference may be attributed to the differences in environment conditions and locations.



**Figure 24: Changes of cation exchange capacity with soil depth under *Ngitiri* in Meatu District, Tanzania.**

## CHAPTER FIVE

### 5.0 CONCLUSIONS AND RECOMMENDATIONS

#### 5.1 Conclusions

##### (i) Above and below-ground C storage and Allometric models

The present study has revealed that rotational woodlots have higher potential than *Ngitiri* for storage of above and below-ground carbon. Although there is a substantial amount of above and below-ground C stocks/storage in *Acacia* fallows under both systems in Meatu District, and their continued management and conservation has potential to mitigate carbon emissions. Estimates of above and below-ground C in this study are preliminary and an initial assessment of such potential in rotational woodlots and *Ngitiri* in Meatu District. Efforts to continue assessing other woodlots and *Ngitiri* in Meatu District to improve these estimates are necessary.

On the other hand, the study has established that *Ngitiri* is very potential in above-ground C sequestration than rotational woodlots since it has captured higher quantities of C from the atmosphere in tree components between 8 and 10-year fallow periods. Higher accumulation of above-ground C in two years under *A. tortilis* woodlots and *A. polyacantha* fallows under *Ngitiri* suggest that these local tree species adapted in Meatu District are suitable for enhancement of C sequestration.

The developed allometric models in this study show that diameter at breast height (DBH) is the only predictor variable in predicting above-ground C of all tree components of *Acacia* species studied and total above-ground C in *A. tortilis* and *A. polyacantha*. The inclusion of H does not improve the performance of the models with exception of prediction of total above-ground C for *A. nilotica*. Therefore, allometric

models developed from this study can be used in predicting above-ground C for estimation of C stocks in different tree components of *Acacia* species.

**(ii) Soil organic carbon**

*Ngitiri* plots had larger quantities of total SOC stocks in 100 cm soil profile and it captured higher SOC than woodlots between 8 and 10-year fallow periods. This suggests that *Ngitiri* is a potential sink of SOC storage/stocks and sequestration than rotational woodlots. On the other hand, total SOC estimates were higher in *A. tortilis* fallows than in other tree species under woodlots. In *Ngitiri* it was higher in soils under *A. nilotica* fallows than other *Acacia* species and *A. polyacantha* takes the second lead for C storage in soil for both systems. It is concluded that *Acacia* species are potentially capable of SOC storage in both systems and they have environment benefits which have not been practically demonstrated to farmers in Meatu District.

**(iii) Soil fertility improvement**

The quantities of total N, inorganic N, available P (Olsen) and exchangeable K in *Acacia* fallows under rotational woodlots and *Ngitiri* are sufficient to support more than one cropping season of maize production after 8 and 10-year fallow periods. Besides, all tree species in the rotational woodlots are effective in building up soil inorganic N in 8-year fallow period than natural fallows.

Enhanced soil fertility was found under trees in rotational woodlots and *Ngitiri* compared to patches of grassland, natural fallow, and pure cropping. This means that nutrients are efficiently recycled in trees consequently more input in the surface soil layer. Although, both systems had good performance in replenishing soil fertility, it is concluded that, rotational woodlots have higher potential in soil fertility improvement than the *Ngitiri*.

All *Acacia* species in woodlots and *Ngitiri* are potentially capable of soil fertility improvement although fast growing trees like *A. nilotica* remove large quantities of nutrients from the soil at the end of rotation. Soils under *A. polyacantha* in rotational woodlots were the most fertile. *A. nilotica* have a potential for use as soil ameliorating trees in *Ngitiri* and *A. tortilis* can be used in both systems for soil amelioration.

The present study has established that CEC and pH values in soils under *Acacia* fallows in both systems are higher than in natural fallows and cultivated soils. Low BD under *Ngitiri* soils was similar to those reported in miombo woodlands, suggesting that the system can restore soil fertility as in the native vegetation.

In general, fallow periods have effect on change in nutrients in the surface soil layer in both systems. Although *Acacia* fallows in rotational woodlots are depleted of soil inorganic N in two years but accumulated more soil Olsen P and exchangeable K than under *Ngitiri* this suggests that planted *Acacia* species are superior to those naturally regenerated.

## 5.2 Recommendations

From the study findings, the following are pertinent recommendations:

**(i) Further studies are recommended in lines of:**

- (a) In order to have actual branch C estimates under *Ngitiri*, a long-term controlled experiment is recommended.
- (b) Estimates from allometric models developed from widely distributed species could be useful in predicting C across broad geographic regions. A comparison of species-specific models from different regions that test for similarities in equation coefficients might be a useful area of research.



- (c) More efforts in assessing SOC sequestration in woodlots and different types of *Ngitiri* are recommended.
- (d) Long-term studies to characterize changes in soil properties such as decline in Olsen P and inorganic N in 10-year *A. nilotica* woodlots are recommended.
- (e) Studies on effect of shade on soil nutrient uptake and re-translocation in biomass of *Acacia* woodlots are recommended.

**(ii) Management strategies**

These are recommendations to be used as strategies for management of rotational woodlots and *Ngitiri* in Meatu District in order to reduce CO<sub>2</sub> emissions and improve soil fertility. It is recommended that:

- (a) Rotational woodlot should be used for above and below-ground C storage/stocks in *Acacia* fallows.
- (b) In short-term fallows, *Ngitiri* conservation is suitable for above-ground C sequestration in *Acacia* rather than establishment of woodlots
- (c) In long-term fallows rotational woodlots is appropriate for storage of SOC in the top soil while *Ngitiri* is suitable for C storage in sub soil
- (d) Rotational woodlots should be used for soil fertility improvement in *Acacia* fallows
- (e) *A. nilotica* and *A. polyacantha* in woodlots be planted for soil fertility improvement in short-term rotations.
- (f) *A. tortilis* in woodlots should be planted in long-term rotations and retained in *Ngitiri* for soil fertility improvement.

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**APPENDICES****Appendix 1: Data collection form for trees (destructive sampling)**

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<b>S/N</b>	<b>Species</b>	<b>DBH</b> <b>(cm)</b>	<b>Height</b> <b>(cm)</b>	<b>Total field</b> <b>green weight</b> <b>(AGB) (kg)</b>	<b>Sample green</b> <b>weight</b> <b>(AGB) (g)</b>	<b>Sample</b> <b>dry weight</b> <b>(AGB) (g)</b>
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**Appendix 2: Field data collection form for quantification of  
above-ground biomass**

<b>Plot No.</b>	<b>Species</b>	<b>Systems</b>	<b>Fallow periods (years)</b>	<b>DBH (cm)</b>	<b>Height (cm)</b>	<b>No.Trees &lt; 5 cm DBH</b>	<b>Remarks</b>



**Appendix 3: Data collection form for soil sampling**

Plot No.	Species	Systems	Fallow periods (years)	Data labels for depth levels					Remarks
				1	2	3	4	5	

**Key:**

**Depth levels for profile soil sampling**

**1 = 0-20 cm**

**2 = 20-40 cm**

**3 = 40-60 cm**

**4 = 60-80 cm**

**5 = 80-100 cm**

**Appendix 4: Sample data used to derive and validate models for  
*Acacia nilotica***

S/N	dbh (cm)	Height (m)	Stem Biomass (kg tree <sup>-1</sup> )	Br Biomass (kg tree <sup>-1</sup> )	L/Twig
					Biomass (kg tree <sup>-1</sup> )
1	20	10	90.56	133.62	15.63
2	18.2	11.5	44.96	67.88	8.09
3	13	9.8	23.28	29.66	4.75
4	22	7.8	81.49	123.87	12.80
5	17.5	7	19.10	72.11	10.36
6	28	6.8	71.59	209.64	18.78
7	9.5	3.9	12.22	9.43	1.97
8	8.7	3.5	5.96	5.39	1.07
9	26.5	7.2	56.47	158.16	14.40
10	14.4	4.8	13.52	14.87	0.76
11	23	6.9	94.15	61.45	12.71
12	21.3	5.9	11.55	15.17	4.37
13	16.5	6	23.73	48.40	5.58
14	19.5	6.8	41.85	67.58	9.87
15	12	6.5	13.09	98.36	1.82
16	24.8	6.4	78.74	131.22	12.34
17	25.6	8.6	117.75	148.18	19.93
18	29.2	6.5	57.52	149.98	21.04
19	12	6.5	11.99	19.53	3.59
20	15.5	6.9	37.15	34.89	5.05
21	10	6	7.45	5.11	1.75
22	27	8	69.74	147.25	25.56
23	5.1	3.4	4.27	2.72	1.78
24	11.7	6.5	22.95	13.42	2.07
25	6	4.5	2.50	1.98	0.85

26	7.7	4.5	6.52	2.02	3.82
27	7.5	4.4	3.83	2.13	2.12

**Appendix 5: Sample data used to derive and validate models for  
A.polyacantha**

S/N	DBH (cm)	Height (m)	Stem Biomass (kg tree <sup>-1</sup> )	Br Biomass (kg tree <sup>-1</sup> )	L/Twig Biomass (kg tree <sup>-1</sup> )
28	25.2	13.3	124.73	44.92	11.67
29	28.5	12.6	122.58	167.55	26.75
30	29	14.9	163.13	150.72	23.15
31	31.5	15.9	264.92	159.75	18.82
32	21.4	13.4	84.43	34.36	5.94
33	19.2	11	85.31	94.23	11.93
34	29	14.8	214.82	126.36	18.76
35	10	4.4	6.26	12.71	3.38
36	31.6	12.5	206.34	90.30	12.03
37	27.2	12.8	142.80	57.32	10.85
38	26	12.7	113.24	113.31	35.75
39	30	12.6	179.65	153.49	29.54
40	33	13.8	208.94	119.63	8.31
41	32.5	9.5	105.60	115.17	26.35
42	19.5	7.9	45.28	38.52	8.91
43	17.5	7.8	28.07	11.16	2.19
44	14	8	13.40	27.16	6.66
45	11	7.5	20.88	14.50	2.51
46	16	11	20.88	47.13	7.67
47	6	5.6	2.26	1.51	1.36
48	5	5.9	2.54	1.65	0.44
49	20	13.3	86.71	37.53	8.08
50	22	12	89.99	57.55	7.64
51	23	9.3	85.62	50.05	14.24
52	18	9.1	50.91	22.91	3.72
53	34	12	219.74	270.94	24.19
54	15.2	7	27.98	19.06	5.67
55	9.3	7	6.60	10.11	2.65

56	13	6.8	10.29	19.75	4.33
57	7	4.8	3.31	2.55	2.34
58	8.2	7.3	5.26	7.66	1.61
59	12.5	7	12.11	24.88	7.65

### Appendix 6: Sample data used to derive and validate models for

#### *Acacia tortilis*

S/N	DBH (cm)	Height (m)	Stem		L/Twig
			Biomass (kg tree <sup>-1</sup> )	Br Biomass (kg tree <sup>-1</sup> )	Biomass (kg tree <sup>-1</sup> )
60	16.5	10.2	60.9	50.1	15.53
61	17.5	8	51.9	41.6	10.34
62	20.5	8.1	54.2	138.0	28.54
63	22	9.2	80.0	66.9	27.90
64	27.2	8.4	142.1	126.5	71.78
65	25.5	9.7	102.7	201.8	56.95
66	20	7.6	60.4	65.6	23.79
67	14.5	5.7	25.6	28.2	13.29
68	18.5	7.6	58.3	55.1	24.82
69	23.5	6.7	82.2	112.6	31.58
70	28.7	8.4	100.2	139.3	64.27
71	19.4	9.3	59.7	60.0	174.90
72	21	6.7	67.1	87.8	23.33
73	26.1	7.2	112.7	158.9	58.93
74	21.7	8.6	41.4	110.4	34.40
75	25	8.2	109.5	204.6	41.19
76	24.4	8.7	83.7	132.1	49.63
77	16	6	22.7	37.0	16.59
78	11.3	5	18.7	16.1	11.77
79	13	6.4	21.4	9.5	5.63
80	15.5	6.5	38.9	41.6	32.81
81	10	5.3	14.1	17.1	10.98
82	12	4.7	20.0	29.0	16.01
83	8	4	7.7	10.0	6.40
84	9.8	5	14.2	11.1	7.80
85	10.2	4.8	10.7	8.5	8.54
86	6.3	4.4	6.5	4.4	3.28
87	6.5	5.3	3.7	2.8	1.42
88	5.5	3.3	2.4	1.4	1.42
89	11	5.4	9.7	12.0	8.67

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90	5	5.6	2.7	6.1	3.19
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### Appendix 7: Data for Profile samples for soil texture and CN

ratio

SN	SYSTEM	Years	Fallow types	Soil depth (cm)	% clay	% silt	% sand	C:N
1	Ngitiri	10	<i>A.nilotica</i>	0-20 P-samples	32	45	23	14.9
2	Ngitiri	10	<i>A.nilotica</i>	20-40 P-samples	40	43	17	11.1
3	Ngitiri	10	<i>A.nilotica</i>	40-60 P-samples	47	35	18	9.8
4	Ngitiri	10	<i>A.nilotica</i>	60-80 P-samples	46	35	18	11.4
5	Ngitiri	10	<i>A.nilotica</i>	80-100 P-samples	43	31	26	9.8
6	Ngitiri	10	<i>A.polyacantha</i>	0-20 P-samples	30	33	36	11.3
7	Ngitiri	10	<i>A.polyacantha</i>	20-40 P-samples	35	31	34	18.1
8	Ngitiri	10	<i>A.polyacantha</i>	40-60 P-samples	34	29	36	11.4
9	Ngitiri	10	<i>A.polyacantha</i>	60-80 P-samples	34	28	38	10.2
10	Ngitiri	10	<i>A.polyacantha</i>	80-100 P-samples	32	29	38	11.0
11	Ngitiri	10	<i>A.tortilis</i>	0-20 Profile samples	24	20	56	8.4
12	Ngitiri	10	<i>A.tortilis</i>	20-40 Profile samples	27	29	44	6.1
13	Ngitiri	10	<i>A.tortilis</i>	40-60 Profile samples	23	29	48	6.0
14	Ngitiri	10	<i>A.tortilis</i>	60-80 Profile samples	24	28	48	5.4
15	Ngitiri	10	<i>A.tortilis</i>	80-100 Profile samples	18	26	56	7.1
16	Ngitiri	8	<i>A.nilotica</i>	0-20 Profile samples	27	21	52	7.1
17	Ngitiri	8	<i>A.nilotica</i>	20-40 Profile samples	33	31	36	10.5
18	Ngitiri	8	<i>A.nilotica</i>	40-60 Profile samples	49	23	28	13.1
19	Ngitiri	8	<i>A.nilotica</i>	60-80 Profile samples	52	33	15	12.1
20	Ngitiri	8	<i>A.nilotica</i>	80-100 Profile samples	50	36	14	7.5
21	Ngitiri	8	<i>A.polyacantha</i>	0-20 Profile samples	38	26	36	16.5
22	Ngitiri	8	<i>A.polyacantha</i>	20-40 Profile samples	35	21	44	7.4
23	Ngitiri	8	<i>A.polyacantha</i>	40-60 Profile samples	36	23	40	10.1
24	Ngitiri	8	<i>A.polyacantha</i>	60-80 Profile samples	35	25	40	10.5
25	Ngitiri	8	<i>A.polyacantha</i>	80-100 Profile samples	40	24	36	11.4
26	Ngitiri	8	<i>A.tortilis</i>	0-20 Profile samples	10	22	68	4.4
27	Ngitiri	8	<i>A.tortilis</i>	20-40 Profile samples	20	21	59	6.6
28	Ngitiri	8	<i>A.tortilis</i>	40-60 Profile samples	30	23	47	6.3
29	Ngitiri	8	<i>A.tortilis</i>	60-80 Profile samples	22	30	48	5.4
30	Ngitiri	8	<i>A.tortilis</i>	80-100 Profile samples	21	29	50	9.5
31	R woodlots	10	<i>A.nilotica</i>	0-20 Profile samples	21	21	58	13.5
32	R woodlots	10	<i>A.nilotica</i>	20-40 Profile samples	21	19	60	6.2
33	R woodlots	10	<i>A.nilotica</i>	40-60 Profile samples	24	22	54	6.1
34	R woodlots	10	<i>A.nilotica</i>	60-80 Profile samples	15	21	64	8.6
35	R woodlots	10	<i>A.nilotica</i>	80-100 Profile samples	17	23	60	8.6
36	R woodlots	10	<i>A.polyacantha</i>	0-20 Profile samples	9	25	66	9.0
37	R woodlots	10	<i>A.polyacantha</i>	20-40 Profile samples	10	19	71	3.1
38	R woodlots	10	<i>A.polyacantha</i>	40-60 Profile samples	9	18	72	4.5
39	R woodlots	10	<i>A.polyacantha</i>	60-80 Profile samples	1	18	81	3.1
40	R woodlots	10	<i>A.polyacantha</i>	80-100 Profile samples	9	17	74	1.0
41	R woodlots	10	<i>A.tortilis</i>	0-20 Profile samples	21	27	52	10.1
42	R woodlots	10	<i>A.tortilis</i>	20-40 Profile samples	29	25	46	6.3
43	R woodlots	10	<i>A.tortilis</i>	40-60 Profile samples	23	20	57	8.2
44	R woodlots	10	<i>A.tortilis</i>	60-80 Profile samples	25	22	53	8.8
45	R woodlots	10	<i>A.tortilis</i>	80-100 Profile samples	29	30	41	4.4
46	R woodlots	8	<i>A.nilotica</i>	0-20 Profile samples	26	30	44	6.1
47	R woodlots	8	<i>A.nilotica</i>	20-40 Profile samples	30	28	42	6.3
48	R woodlots	8	<i>A.nilotica</i>	40-60 Profile samples	20	34	46	5.1

SN	SYSTEM	Years	Fallow types	Soil depth (cm)	% clay	% silt	% sand	C:N
49	R woodlots	8	<i>A.nilotica</i>	60-80 Profile samples	20	28	52	6.5
50	R woodlots	8	<i>A.nilotica</i>	80-100 Profile samples	20	27	53	10.7
51	R woodlots	8	<i>A.polyacantha</i>	0-20 Profile samples	11	21	68	6.3
52	R woodlots	8	<i>A.polyacantha</i>	20-40 Profile samples	11	23	66	11.4
53	R woodlots	8	<i>A.polyacantha</i>	40-60 Profile samples	11	23	66	6.1
54	R woodlots	8	<i>A.polyacantha</i>	60-80 Profile samples	14	23	63	8.9
55	R woodlots	8	<i>A.polyacantha</i>	80-100 Profile samples	13	21	66	8.2
56	R woodlots	8	<i>A.tortilis</i>	0-20 Profile samples	25	27	48	5.7
57	R woodlots	8	<i>A.tortilis</i>	20-40 Profile samples	19	28	53	11.6
58	R woodlots	8	<i>A.tortilis</i>	40-60 Profile samples	27	31	42	5.6
59	R woodlots	8	<i>A.tortilis</i>	60-80 Profile samples	29	29	42	4.3
60	R woodlots	8	<i>A.tortilis</i>	80-100 Profile samples	27	32	41	4.0
61	Ngitiri	10	<i>A.nilotica</i>	0-20 Profile samples	39	38	24	10.2
62	Ngitiri	10	<i>A.nilotica</i>	20-40 Profile samples	46	35	18	9.3
63	Ngitiri	10	<i>A.nilotica</i>	40-60 Profile samples	46	35	18	23.8
64	Ngitiri	10	<i>A.nilotica</i>	60-80 Profile samples	44	33	22	9.5
65	Ngitiri	10	<i>A.nilotica</i>	80-100 Profile samples	46	33	20	10.7
66	Ngitiri	10	<i>A.polyacantha</i>	0-20 Profile samples	24	31	44	15.0
67	Ngitiri	10	<i>A.polyacantha</i>	20-40 Profile samples	44	33	22	9.0
68	Ngitiri	10	<i>A.polyacantha</i>	40-60 Profile samples	46	31	22	10.5
69	Ngitiri	10	<i>A.polyacantha</i>	60-80 Profile samples	46	31	22	13.0
70	Ngitiri	10	<i>A.polyacantha</i>	80-100 Profile samples	46	31	22	13.0
71	Ngitiri	10	<i>A.tortilis</i>	0-20 Profile samples	20	24	56	9.3
72	Ngitiri	10	<i>A.tortilis</i>	20-40 Profile samples	24	24	52	6.6
73	Ngitiri	10	<i>A.tortilis</i>	40-60 Profile samples	26	30	44	5.7
74	Ngitiri	10	<i>A.tortilis</i>	60-80 Profile samples	18	32	50	1.6
75	Ngitiri	10	<i>A.tortilis</i>	80-100 Profile samples	14	28	58	1.8
76	Ngitiri	8	<i>A.nilotica</i>	0-20 Profile samples	36	40	24	14.3
77	Ngitiri	8	<i>A.nilotica</i>	20-40 Profile samples	38	36	26	10.1
78	Ngitiri	8	<i>A.nilotica</i>	40-60 Profile samples	40	36	24	11.4
79	Ngitiri	8	<i>A.nilotica</i>	60-80 Profile samples	42	38	20	10.7
80	Ngitiri	8	<i>A.nilotica</i>	80-100 Profile samples	40	38	22	13.0
81	Ngitiri	8	<i>A.polyacantha</i>	0-20 Profile samples	22	22	56	8.1
82	Ngitiri	8	<i>A.polyacantha</i>	20-40 Profile samples	30	22	48	85.7
83	Ngitiri	8	<i>A.polyacantha</i>	40-60 Profile samples	28	20	52	7.1
84	Ngitiri	8	<i>A.polyacantha</i>	60-80 Profile samples	26	22	52	8.6
85	Ngitiri	8	<i>A.polyacantha</i>	80-100 Profile samples	27	19	54	6.3
86	Ngitiri	8	<i>A.tortilis</i>	0-20 Profile samples	14	22	64	8.6
87	Ngitiri	8	<i>A.tortilis</i>	20-40 Profile samples	22	22	56	6.0
88	Ngitiri	8	<i>A.tortilis</i>	40-60 Profile samples	31	21	48	10.0
89	Ngitiri	8	<i>A.tortilis</i>	60-80 Profile samples	19	31	50	4.3
90	Ngitiri	8	<i>A.tortilis</i>	80-100 Profile samples	22	30	48	7.1
91	R woodlots	10	<i>A.nilotica</i>	0-20 Profile samples	13	21	66	15.6
92	R woodlots	10	<i>A.nilotica</i>	20-40 Profile samples	16	23	61	16.7
93	R woodlots	10	<i>A.nilotica</i>	40-60 Profile samples	20	23	57	8.9
94	R woodlots	10	<i>A.nilotica</i>	60-80 Profile samples	24	25	51	3.2
95	R woodlots	10	<i>A.nilotica</i>	80-100 Profile samples	16	21	63	7.1
96	R woodlots	10	<i>A.polyacantha</i>	0-20 Profile samples	11	25	64	12.9
97	R woodlots	10	<i>A.polyacantha</i>	20-40 Profile samples	11	25	64	12.6
98	R woodlots	10	<i>A.polyacantha</i>	40-60 Profile samples	5	20	75	3.6
99	R woodlots	10	<i>A.polyacantha</i>	60-80 Profile samples	1	24	75	4.4
100	R woodlots	10	<i>A.polyacantha</i>	80-100 Profile samples	17	28	55	11.7
101	R woodlots	10	<i>A.tortilis</i>	0-20 Profile samples	19	30	51	12.1

SN	SYSTEM	Years	Fallow types	Soil depth (cm)	% clay	% silt	% sand	C:N
102	R woodlots	10	<i>A.tortilis</i>	20-40 Profile samples	33	23	44	8.9
103	R woodlots	10	<i>A.tortilis</i>	40-60 Profile samples	29	32	39	6.0
104	R woodlots	10	<i>A.tortilis</i>	60-80 Profile samples	31	31	38	5.6
105	R woodlots	10	<i>A.tortilis</i>	80-100 Profile samples	25	36	39	2.9
106	R woodlots	8	<i>A.nilotica</i>	0-20 Profile samples	1	21	78	6.8
107	R woodlots	8	<i>A.nilotica</i>	20-40 Profile samples	19	19	62	5.7
108	R woodlots	8	<i>A.nilotica</i>	40-60 Profile samples	5	19	76	2.5
109	R woodlots	8	<i>A.nilotica</i>	60-80 Profile samples	7	19	74	2.0
110	R woodlots	8	<i>A.nilotica</i>	80-100 Profile samples	5	17	78	1.4
111	R woodlots	8	<i>A.polyacantha</i>	0-20 Profile samples	9	17	74	5.6
112	R woodlots	8	<i>A.polyacantha</i>	20-40 Profile samples	10	19	71	6.0
113	R woodlots	8	<i>A.polyacantha</i>	40-60 Profile samples	16	21	63	10.7
114	R woodlots	8	<i>A.polyacantha</i>	60-80 Profile samples	20	23	57	8.2
115	R woodlots	8	<i>A.polyacantha</i>	80-100 Profile samples	9	21	70	3.9
116	R woodlots	8	<i>A.tortilis</i>	0-20 Profile samples	15	27	58	4.2
117	R woodlots	8	<i>A.tortilis</i>	20-40 Profile samples	27	27	46	5.4
118	R woodlots	8	<i>A.tortilis</i>	40-60 Profile samples	27	26	47	4.6
119	R woodlots	8	<i>A.tortilis</i>	60-80 Profile samples	29	27	44	5.2
120	R woodlots	8	<i>A.tortilis</i>	80-100 Profile samples	23	32	45	2.9
121	Ngitiri	10	<i>A.nilotica</i>	0-20 Profile samples	23	29	48	8.9
122	Ngitiri	10	<i>A.nilotica</i>	20-40 Profile samples	34	33	32	8.3
123	Ngitiri	10	<i>A.nilotica</i>	40-60 Profile samples	6	25	68	7.1
124	Ngitiri	10	<i>A.nilotica</i>	60-80 Profile samples	40	35	24	11.2
125	Ngitiri	10	<i>A.nilotica</i>	80-100 Profile samples	36	38	26	45.5
126	Ngitiri	10	<i>A.polyacantha</i>	0-20 Profile samples	21	27	52	12.8
127	Ngitiri	10	<i>A.polyacantha</i>	20-40 Profile samples	28	35	36	17.3
128	Ngitiri	10	<i>A.polyacantha</i>	40-60 Profile samples	38	37	24	11.2
129	Ngitiri	10	<i>A.polyacantha</i>	60-80 Profile samples	34	27	38	11.1
130	Ngitiri	10	<i>A.polyacantha</i>	80-100 Profile samples	34	28	38	12.5
131	Ngitiri	10	<i>A.tortilis</i>	0-20 Profile samples	26	30	44	8.8
132	Ngitiri	10	<i>A.tortilis</i>	20-40 Profile samples	26	30	44	3.6
133	Ngitiri	10	<i>A.tortilis</i>	40-60 Profile samples	22	34	44	2.2
134	Ngitiri	10	<i>A.tortilis</i>	60-80 Profile samples	21	31	48	7.1
135	Ngitiri	10	<i>A.tortilis</i>	80-100 Profile samples	14	26	60	17.9
136	Ngitiri	8	<i>A.nilotica</i>	0-20 Profile samples	38	38	24	10.0
137	Ngitiri	8	<i>A.nilotica</i>	20-40 Profile samples	40	38	22	14.3
138	Ngitiri	8	<i>A.nilotica</i>	40-60 Profile samples	40	36	24	11.9
139	Ngitiri	8	<i>A.nilotica</i>	60-80 Profile samples	28	34	38	7.8
140	Ngitiri	8	<i>A.nilotica</i>	80-100 Profile samples	24	30	46	2.7
141	Ngitiri	8	<i>A.polyacantha</i>	0-20 Profile samples	18	24	58	9.1
142	Ngitiri	8	<i>A.polyacantha</i>	20-40 Profile samples	23	21	56	6.2
143	Ngitiri	8	<i>A.polyacantha</i>	40-60 Profile samples	24	24	52	3.6
144	Ngitiri	8	<i>A.polyacantha</i>	60-80 Profile samples	26	21	53	4.8
145	Ngitiri	8	<i>A.polyacantha</i>	80-100 Profile samples	10	24	66	7.1
146	Ngitiri	8	<i>A.tortilis</i>	0-20 Profile samples	23	23	54	5.6
147	Ngitiri	8	<i>A.tortilis</i>	20-40 Profile samples	19	21	60	11.4
148	Ngitiri	8	<i>A.tortilis</i>	40-60 Profile samples	26	24	50	7.1
149	Ngitiri	8	<i>A.tortilis</i>	60-80 Profile samples	24	28	48	17.9
150	Ngitiri	8	<i>A.tortilis</i>	80-100 Profile samples	22	24	54	3.6
151	R woodlots	10	<i>A.nilotica</i>	0-20 Profile samples	13	19	68	8.0
152	R woodlots	10	<i>A.nilotica</i>	20-40 Profile samples	21	21	58	12.2
153	R woodlots	10	<i>A.nilotica</i>	40-60 Profile samples	3	23	74	7.8
154	R woodlots	10	<i>A.nilotica</i>	60-80 Profile samples	20	23	57	6.3



SN	SYSTEM	Years	Fallow types	Soil depth (cm)	% clay	% silt	% sand	C:N
155	R woodlots	10	<i>A.nilotica</i>	80-100 Profile samples	6	19	75	3.9
156	R woodlots	10	<i>A.polyacantha</i>	0-20 Profile samples	11	26	63	6.2
157	R woodlots	10	<i>A.polyacantha</i>	20-40 Profile samples	11	21	68	7.9
158	R woodlots	10	<i>A.polyacantha</i>	40-60 Profile samples	9	30	61	0.8
159	R woodlots	10	<i>A.polyacantha</i>	60-80 Profile samples	1	22	78	5.5
160	R woodlots	10	<i>A.polyacantha</i>	80-100 Profile samples	1	19	80	4.8
161	R woodlots	10	<i>A.polyacantha</i>	0-20 Side samples	13	23	64	4.8
162	R woodlots	10	<i>A.polyacantha</i>	20-40 Side samples	11	26	63	13.6
163	R woodlots	10	<i>A.tortilis</i>	0-20 Profile samples	19	28	53	18.9
164	R woodlots	10	<i>A.tortilis</i>	20-40 Profile samples	33	30	37	10.5
165	R woodlots	10	<i>A.tortilis</i>	40-60 Profile samples	31	34	35	11.4
166	R woodlots	10	<i>A.tortilis</i>	60-80 Profile samples	27	38	35	6.6
167	R woodlots	10	<i>A.tortilis</i>	80-100 Profile samples	29	35	36	5.1
168	R woodlots	8	<i>A.nilotica</i>	0-20 Profile samples	1	21	78	4.1
169	R woodlots	8	<i>A.nilotica</i>	20-40 Profile samples	9	19	72	2.9
170	R woodlots	8	<i>A.nilotica</i>	40-60 Profile samples	1	19	80	1.0
171	R woodlots	8	<i>A.nilotica</i>	60-80 Profile samples	1	17	82	2.0
172	R woodlots	8	<i>A.nilotica</i>	80-100 Profile samples	1	17	82	2.9
173	R woodlots	8	<i>A.polyacantha</i>	0-20 Profile samples	27	29	44	33.3
174	R woodlots	8	<i>A.polyacantha</i>	20-40 Profile samples	22	27	51	11.3
175	R woodlots	8	<i>A.polyacantha</i>	40-60 Profile samples	22	23	55	19.6
176	R woodlots	8	<i>A.polyacantha</i>	60-80 Profile samples	18	21	61	3.9
177	R woodlots	8	<i>A.polyacantha</i>	80-100 Profile samples	14	19	67	8.6
178	R woodlots	8	<i>A.tortilis</i>	0-20 Profile samples	17	25	58	4.9
179	R woodlots	8	<i>A.tortilis</i>	20-40 Profile samples	21	25	54	3.7
180	R woodlots	8	<i>A.tortilis</i>	40-60 Profile samples	11	26	63	2.4
181	R woodlots	8	<i>A.tortilis</i>	60-80 Profile samples	3	26	71	3.4
182	R woodlots	8	<i>A.tortilis</i>	80-100 Profile samples	1	26	73	2.9