EFFECTS OF EUCALYPTUS PLANTATION ON SOIL PHYSICO-CHEMICAL PROPERTIES IN THIRIRIKA SUB-CATCHMENT, KIAMBU COUNTY, KENYA.

BY

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A Thesis submitted in partial fulfillment of the requirement for the award of the degree of Masters of Science (Integrated Watershed Management) in the School of Pure and Applied Sciences of Kenyatta University.

FEBRUARY, 2016
DECLARATION

This thesis is my original work and has not been presented for a degree or any other award in any University.

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This work is dedicated to my mum Auntie Abena and my lovely siblings Rosemond Sarah Cobbinah and Ebenezer Cobbinah (Kobina Peprah). I love you all very much and you are very close to my heart.
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ABSTRACT

Trees are very important in Thiririka sub-catchment of Kiambu County in Kenya for reasons such as income generation, soil and water conservation, biodiversity conservation, charcoal production, erosion control, among many others. *Eucalyptus* spp. (*E. grandis, E. saligna* and *E. globulus*) remain part of the dominant tree species planted in the Thiririka sub-catchment. Although these species are planted in various spatial patterns in the sub-catchment to meet the demand for fuel wood, building construction, timber, electricity poles, water conservation, charcoal production and erosion control, and cushion farmers when the markets for their agricultural produce fail or are low, reports such as drying up of water courses, affecting the soil physico-chemical properties, tendency to deplete soil nutrients and fertility, suppression of other vegetation, reduction of forest biodiversity and reducing crop yield in agro-forestry systems have been made. Although a number of reports have been made in other countries concerning the negative impact of *Eucalyptus* spp. plantation on edaphic characteristics of soils, few studies have been done in Kenya on the implications of *Eucalyptus* spp. on the soil physico-chemical properties. This study was therefore, carried out to assess the effects of *Eucalyptus* spp. plantations on selected soil physical and chemical properties in the Thiririka sub-catchment. Two experimental plots (monoculture *Eucalyptus* spp. plantation and native forest of mixed vegetation) of 100 m x 100 m (1 ha) each were used for the study. Each experimental plot was sub-divided into five sub-plots of 20 m x 20 m for soil and litter sampling. All soil samples were collected at a depth of 0-20 cm using screw soil auger. Soil analyses were done using standard methods. Statistical analysis of the data collected was done using SPSS 17.0 statistical software and Microsoft Excel 2010. The results from the *Eucalyptus* spp. plantation were compared to those from the native forest within the same catchment and conclusions regarding the soil fertility level were drawn based on internationally acceptable standards. The results obtained in the study indicated that *Eucalyptus* spp. plantation significantly affects the soil moisture (26.6 %). Soil bulk density under *Eucalyptus* spp. plantation (1.16 g cm$^{-3}$) was within acceptable range. Also, the results showed that cultivation of *Eucalyptus* spp. significantly lowered the soil pH (4.8), leading to a significant decline in soil total nitrogen (0.09 %) and soil total organic carbon (0.83 %) concentrations. Decomposition of the litter of *Eucalyptus* spp. also caused increase in concentration of soil exchangeable acidity (0.32 c mol Kg$^{-1}$), soil exchangeable sodium (0.52 c mol Kg$^{-1}$), Fe concentration (95.28 mg kg$^{-1}$), immobilization of soil available phosphorus (concentration of P was 23.2 mg kg$^{-1}$), rendering it unavailable for plant use. However, in the study, no significant differences were found between the *Eucalyptus* spp. plantation and the control native forest in terms of soil exchangeable Mg, Ca and K, cation exchange capacity and effective cation exchange capacity although, concentrations of the exchangeable Mg, Ca and K and effective cation exchange capacity were low, which possibly contributed to the increased soil acidity, exchangeable acidity and Mn and Fe concentrations observed in the soils under the *Eucalyptus* sp. plantation. Furthermore, the *Eucalyptus* spp. plant litter fall concentrations of total N (1.05 %) and total P (0.15 %) were lower compared with the native forest, where concentrations of total N and total P were 2.11 and 0.17 %, respectively. The study demonstrated that sole cultivation of *Eucalyptus* spp. had the tendency to lower soil fertility and so it is advisable to interplant *Eucalyptus* sp. with other leguminous species, in addition to good agronomic practices such as nitrogenous and phosphate fertilizer application to replenish loss of the essential soil nutrients such as N and P associated with *Eucalyptus* sp. planting and also to ensure sustainability of *Eucalyptus* sp. cultivation on the soil resources.
TABLE OF CONTENTS

DECLARATION .................................................................................................................. ii

DEDICATION ..................................................................................................................... iii

ACKNOWLEDGEMENTS .................................................................................................. iv

ABSTRACT ......................................................................................................................... vi

TABLE OF CONTENTS ....................................................................................................... vii

LIST OF FIGURES ........................................................................................................... xiii

LIST OF TABLES .............................................................................................................. xiv

LIST OF PLATES ............................................................................................................... xv

LIST OF SI UNITS ............................................................................................................ xvi

ACRONYMS AND ABBREVIATIONS .............................................................................. xvii

CHAPTER ONE ................................................................................................................ 1

INTRODUCTION .............................................................................................................. 1

1.1 Background to the Study ......................................................................................... 1

1.2 Statement of the Problem ....................................................................................... 3

1.3 Justification for the Study ....................................................................................... 4

1.4 Research Questions ................................................................................................. 5

1.5 Research Hypotheses .............................................................................................. 5

1.6 Objectives of the Study ........................................................................................... 5

1.6.1 General Objectives ............................................................................................. 5
1.6.2 Specific Objectives........................................................................................................ 5

1.7 Significance and Anticipated Outcomes of the Study....................................................... 6

1.8 Scope and Limitations of the Study .................................................................................. 6

1.9 Conceptual Framework ..................................................................................................... 7

1.10 Operational Definition of Terms .................................................................................... 9

1.10.1 Allelopathy ................................................................................................................ 9

1.10.2 Carbon to Nitrogen (C:N) Ratio of Plant Litter ........................................................ 10

1.10.3 Immobilization of Soil Nutrients ............................................................................. 10

1.10.4 Litter Fall .................................................................................................................... 10

1.10.5 Sub-catchment .......................................................................................................... 11

1.10.6 Transpiration Rates .................................................................................................. 11

CHAPTER TWO .................................................................................................................. 12

LITERATURE REVIEW ...................................................................................................... 12

2.1 Effects of Eucalyptus spp. Plantation on Soil Physical Properties ............................... 12

2.1.1 Soil Bulk Density ....................................................................................................... 12

2.1.2 Soil Moisture ............................................................................................................. 12

2.1.3 Soil Texture ............................................................................................................... 13

2.2 Effects of Eucalyptus spp. Plantation on Soil Chemical Properties ......................... 13

2.2.1 Soil pH ...................................................................................................................... 13

2.2.2 Soil Exchangeable Acidity ....................................................................................... 15
2.2.3 Soil Organic Carbon and Soil Organic Matter ......................................................... 15

2.2.4 Soil Total Nitrogen and Soil Available Phosphorus .................................................. 17

2.2.5 Soil Exchangeable Cations and Cation Exchange Capacity (CEC) ................................. 18

2.2.6 Soil Micro-Nutrients .................................................................................................. 19

2.2.7 Plant Nutrients in Eucalyptus spp. Plantation Litter Fall ............................................. 20

CHAPTER THREE ........................................................................................................ 23

MATERIALS AND METHODS .................................................................................. 23

3.1 Study Area Characteristics ......................................................................................... 23

3.1.1 Topographic Features ............................................................................................. 23

3.1.2 Administrative and Political Units ........................................................................... 24

3.1.3 Climate ..................................................................................................................... 25

3.1.3.1 Rainfall ............................................................................................................... 25

3.1.3.2 Temperature ....................................................................................................... 25

3.1.4 Soils ......................................................................................................................... 26

3.1.5 Socio-Economic Activities ..................................................................................... 27

3.1.6 Environment, Water and Sanitation .................................................................... 27

3.2 Field Experimental Design ....................................................................................... 27

3.3 Sampling Procedure, Mapping and Sample Preparation ............................................. 29

3.4 Laboratory Analyses .................................................................................................. 30

3.4.1 Soil Moisture .......................................................................................................... 30
### 3.4.2 Soil Dry Bulk Density ................................................................. 31
### 3.4.3 Soil Texture (Particle Size Distribution) ........................................ 31
### 3.4.4 Soil pH ...................................................................................... 32
### 3.4.5 Soil Total Organic Carbon .......................................................... 32
### 3.4.6 Soil Total Nitrogen ...................................................................... 33
### 3.4.7 Soil Available Phosphorus .......................................................... 34
### 3.4.8 Soil Exchangeable Bases .............................................................. 34
### 3.4.9 Exchangeable Acidity .................................................................. 35
### 3.4.10 Determination of Available Soil Micro-Nutrients ......................... 35
### 3.4.11 Plant Litter Analyses ................................................................. 35
### 3.5 Data Analyses and Processing ......................................................... 36

### CHAPTER FOUR .................................................................................. 37

### RESULTS AND DISCUSSION .............................................................. 37

4.1 Effects of *Eucalyptus* spp. Plantation and Native Forest on Soil Physical Properties ... 37

4.1.1 Soil Texture (Particle Size Distribution) ........................................... 37

4.1.2 Soil Moisture .................................................................................. 37

4.1.3 Soil Bulk Density ............................................................................ 38

4.2 Effects of *Eucalyptus* spp. Plantation and Native Forest on Soil Chemical Properties . 39

4.2.1 Soil pH .......................................................................................... 39

4.2.2 Soil Available Phosphorus .............................................................. 40
4.2.3 Soil Total Nitrogen ................................................................. 41
4.2.4 Soil Total Organic Carbon .......................................................... 43
4.3 Effects of EP and NF on Soil Exchangeable Cations, CEC, Exchangeable Acidity .... 45
4.3.1 Soil Exchangeable Cations .............................................................. 45
4.3.2 Soil Cation Exchange Capacity ......................................................... 46
4.3.3 Soil Exchangeable Acidity .............................................................. 46
4.3.4 Soil Effective Cation Exchange Capacity .............................................. 47
4.4 Effects of Eucalyptus spp. Plantation and Native Forest on Soil Micro-Nutrients .... 47
4.5 Plant Nutrients in Eucalyptus spp. Plantation and Native Forest Litter Fall ............ 49
4.5.1 Total Potassium, Calcium and Magnesium in EP and NF Plant Litter .......... 49
4.5.2 Plant Litter Total Nitrogen, Organic Carbon and Total Phosphorus in EP and NF .... 51
4.5.2.1 Plant Litter Total N Concentration .................................................. 51
4.5.2.2 Plant Litter Total Phosphorus Concentration ...................................... 52
4.5.2.3 Plant Litter Total Organic Carbon Concentration ................................ 52
4.5.3 Total Cu$^{2+}$, Total Fe$^{2+}$, Total Zn$^{2+}$ and Total Mn$^{2+}$ in EP and NF Plant Litter ... 54
4.5.3.1 Plant Litter Total Cu$^{2+}$ Concentration ....................................... 54
4.5.3.2 Plant Litter Total Zn$^{2+}$ Concentration ........................................ 54
4.5.3.3 Plant Litter Total Mn$^{2+}$ and Total Fe$^{2+}$ Concentrations ..................... 55
4.6 Testing for Hypothesis i, ii and iii .................................................................. 56

CHAPTER FIVE ......................................................................................... 59
SUMMARY OF FINDINGS, CONCLUSION AND RECOMMENDATIONS .................. 59

5.1 Summary of Key Findings ................................................................. 59

5.2 Conclusion ......................................................................................... 60

5.3 Recommendations ............................................................................. 61

5.4 Areas for Further Research ............................................................... 62

REFERENCES ....................................................................................... 63

APPENDICES ....................................................................................... 73
LIST OF FIGURES

Figure 1.1: Linkages of conceptual framework for the study……………………………………..9

Figure 3.1: Map of the study area with sampling points…………………………………………24

Figure 3.2: Monthly Rainfall for Thiririka sub-catchment for the year 2012.........................25

Figure 3.3: Mean monthly Temperatures for Thiririka Sub-catchment for the year 2012. ....... 26

Figure 4.1: Total K, Total Ca and Total Mg concentrations in EP and NF Plant Litter.........51

Figure 4.2: Total Cupper, Iron, Zinc and Manganese in EP and NF Plant Litter.................. 56

Figure 5.1: Soil textural triangle showing the percentages of sand, silt and clay................. 76
LIST OF TABLES

Table 2.1: pH Ranges and their Interpretation Guide. ................................................................. 14
Table 2.2: Summary of Key Empirical Studies on *Eucalyptus* spp. and Research Gaps. .......... 22
Table 4.1: Soil Physical Properties of *Eucalyptus* spp. Plantation and Native Forest soils. ...... 39
Table 4.2: Soil pH, available P, total N and total organic carbon of EP and NF Soils.............. 45
Table 4.3: Soil exchangeable cations, exchangeable acidity, CEC in EP and NF soils. .......... 47
Table 4.4: Soil available micro-nutrient concentrations in EP and NF soils. ............................ 49
Table 4.5: Total nitrogen, total organic carbon and total phosphorus in EP and NF plant litter. . 53
Table 4.6: Correlations between some soil parameters for EP soils............................................. 58
Table 5.1: Sample Size, Means, Standard Deviations of Soil Physico-chemical Parameters ..... 73
Table 5.2: Sample Size, Means, Standard Deviations of Plant Litter Parameters ....................... 75
LIST OF PLATES

Plate 3.1: *Eucalyptus* spp. plantation in Thiririka sub-catchment ........................................ 28
Plate 3.2: Native forest plantation in Thiririka sub-catchment. .................................................. 28
Plate 3.3: Soil sampling under *Eucalyptus* spp. plantation using screw auger. ......................... 30
Plate 4.1: *Cynodon dactylon* grass growing on the fringes of EP in Thiririka sub-catchment. ..... 43
Plate 4.2: *Acacia mearnsii* growing on the fringes of EP in Thiririka sub-catchment............... 43
LIST OF SI UNITS

C mol kg$^{-1}$ ………………Centimol charge per Kilogram

g cm$^{-3}$ ………………………gram per cubic centimetres

Mg kg$^{-1}$ …………………Milligram per Kilogram

Ppm……………………….Part per Million
ACRONYMS AND ABBREVIATIONS

CEC..........................Cation Exchange Capacity

DAAD.........................German Academic Exchange Service

ECEC..........................Effective Cation Exchange Capacity

EP............................Eucalyptus spp. plantation

Ex............................Exchangeable

FAO.........................Food and Agriculture Organization

NF............................Native Forest

pH.........................Hydrogen Ion Concentration

SOM..........................Soil Organic Matter

TOC..........................Total Organic Carbon

TN..........................Total Nitrogen
CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Many concerns have been reported about the negative ecological effects of *Eucalyptus* species from many countries the world over. These concerns include issues of high transpiration rates, soil fertility depletion, disruption of biodiversity conservation and their allelopathic effects that inhibit undergrowth regeneration (Baragali *et al*., 1993; Heilman and Norby, 1997; Calder *et al*., 1997; Jagger and Pender, 2000; Aweto and Moleele, 2005; Zewdie, 2008; Alemie, 2009; Cao *et al*., 2010; Demessie *et al*., 2012; Tererai, 2012; Ravina, 2012; Tererai *et al*., 2014; Cortez *et al*., 2014).

Lane *et al*. (2004) in China found that the expansion of *Eucalyptus* spp. plantation lowers water tables and reduces water availability for irrigation on lands previously used for arable crops or occupied by indigenous trees and grass due to soil hydrophobicity (water repellency) and its deep and dense root network. Wen *et al*. (2009) and Zhu *et al*. (2009) indicated that in China, afforestation of exotic *Eucalyptus* spp. plantation is reported to adversely affect the soil physical and chemical properties and plant community biodiversity. In Argentina, a lot of controversy has arisen about the nutrient cycling capacity, ecological and economic implications of *Eucalyptus* spp. in terms of sustainable forestry (Goya *et al*., 2008).

Within Africa, previous authors have reported that *Eucalyptus* spp. plantations (EP) have devastating effects on the soil physico-chemical properties, depleting soil organic matter content and negatively impacts soil hydrology (Aweto and Moleele, 2005; Kindu *et al*., 2006a, b; Kenya Forest Services, 2009; Oballa *et al*., 2010; FAO, 2011; Tererai, 2012; Tererai *et al*., 2014). For
instance, El-Amin et al. (2001) reported that in Sudan, *Eucalyptus* spp. caused crop yield reduction due to nutrient depletion and production of toxic exudates (allelochemicals). A study in Ethiopia, 1993 compared the nutrient status in plantations of *Eucalyptus globulus*, cypress and cedar (Teketay, 2003). The study showed that soils under *Eucalyptus globulus* plantations had lower nutrient content compared to those in cedar and cypress forests.

Alemie (2009) who conducted a study on *Eucalyptus* sp. in Koga watershed in Ethiopia, attributed the drought status of previously functional nearby water stores in the watershed to the deep and dense roots network of the *Eucalyptus* spp., which have high potential to suck water in addition to increased soil hydrophobicity induced by decomposition of their litter and poor undergrowth, which reduced infiltration and water table in the watershed. He further added that increasing plantations of *Eucalyptus* spp. would create competition between agricultural food crops and trees for land area, major resources (water and soil nutrients) and light.

*Eucalyptus* spp. was introduced in Kenya in 1902 by the British colonial government to provide fuel wood for the Kenya-Uganda railway (Oballa et al., 2010) but it has been reported that *Eucalyptus* spp. grown as a short rotation crop for high biomass production, led to rapid soil nutrient depletion (Kenya Forestry Service, 2009; Oballa et al., 2010). Previous studies have also found increased concentrations of micro-nutrients, especially Fe and Mn in soils under *Eucalyptus* spp. compared to those under plantations such as tea of similar age (Oballa and Langat, 2002; Kenya Forestry Service, 2009). Furthermore, Aweto and Moleele (2005) reported that *Eucalyptus* spp. were not efficient in cycling macro-nutrients such as nitrogen and phosphorus, as litter from the species have high carbon to nitrogen (C:N) ratio (Castro-Díez et al., 2011) and hence low rates of mineralization (Bernhard-Reversat and Schwartz, 1997), which results in low rates of nutrient release. The species also have allelopathic effect on other plants as
a result of the allelo-chemicals that are released during the decomposition process, which inhibit the growth of other plant species underneath them (El-Amin et al., 2001; Mfahaya et al., 2009; Oballa et al., 2010; Zhang et al., 2010; FAO, 2011; Ruwanza et al., 2014). These allelopathic chemicals or allelochemicals can also persist in the soil, affecting both neighboring plants as well as those planted in succession (Ferguson et al., 2013).

Owing to the perceived negative ecological impacts of *Eucalyptus* spp. on soil and water resources, interest in the plant has waned and the population of *Eucalyptus* spp. in state forests, farmlands, stream banks and catchment areas in Kenya have reduced drastically (Oballa et al., 2010; FAO, 2011). Consequently, farmers have been advised not to establish plantations of *Eucalyptus* spp. within 15 m of the riverine vegetation and 6 m from any neighbouring farm (Mfahaya et al., 2009).

The effects of *Eucalyptus* spp. plantations on soil properties and depletion of the soil essential nutrients still remain unclear (Bernhard-Reversat, 1999; El-Amin et al., 2001) and conventional scientific reports are scanty (Oballa et al., 2010). Therefore, additional documentation on the specific effects of *Eucalyptus* spp. plantations in relation to soil physical (soil moisture and soil bulk density) and chemical properties (pH; organic carbon; available phosphorus; total nitrogen; exchangeable bases; exchangeable acidity; cation exchange capacity; and soil micro-nutrients (Fe, Zn, Cu and Mn)) as well as contribution of the litter fall to soil nutrients enrichment in Kenya is required.

1.2 Statement of the Problem

*Eucalyptus* spp. (*E. grandis, E. saligna* and *E. globulus*) remain part of the dominant tree species planted in the Thiririka sub-catchment in Kiambu County of Kenya. Although these species are
planted in various spatial patterns in the sub-catchment to meet the demand for fuel wood, building construction, timber, electricity poles, water conservation, charcoal production and erosion control, and cushion farmers when the markets for their agricultural produce fail or are low (Oballa et al., 2010), reports such as drying up of water courses, affecting the soil physico-chemical properties, tendency to deplete soil nutrients and fertility, suppression of other vegetation, reduction of forest biodiversity and reducing crop yield in agro-forestry systems have been made. To safeguard and maintain the sustainability of the soil and water in the Thiririka Sub-catchment, it is imperative that effects of *Eucalyptus* spp. plantation on the soil physico-chemical properties be evaluated and ascertained as the study will help establish whether these species have devastating effects on soil resources or not.

### 1.3 Justification for the Study

Although a number of reports have been made in other countries concerning the negative impact of *Eucalyptus* spp. plantation on edaphic characteristics of soils, few studies have been done in Kenya on the implications of *Eucalyptus* spp., which have been used for industrial and agro-forestry purposes, on the soil physico-chemical properties (Oballa et al., 2010). Additionally, Bernhard-Reversat (1999) reported that ecological implications of exotic trees like *Eucalyptus* spp., are often questioned but their effects on the soil ecology has not been adequately studied. In view of the above reports, this study was aimed to investigate the effects of *Eucalyptus* spp. plantation on selected soil physical and chemical properties in the Thiririka sub-catchment in Kiambu County, Kenya, with the view to helping land management planners to make efficient land use decisions in the study area and to better inform farmers’ decisions to undertake *Eucalyptus* spp. plantation in the sub-catchment.
1.4 **Research Questions**

The study sought to answer the following research questions:

i. Do *Eucalyptus* spp. plantations negatively affect soil physical properties?

ii. Do *Eucalyptus* spp. plantations negatively affect soil chemical properties?

iii. What are the amounts of nutrients (C, N, P, K, Ca, Mg, Fe, Zn, Cu and Mn) in litter fall from *Eucalyptus* spp. plantation?

1.5 **Research Hypotheses**

i. No significant differences exist between *Eucalyptus* spp. plantations and native forest in their effects on soil physical properties

ii. No significant differences exist between *Eucalyptus* spp. plantations and native forest in their effects on soil chemical properties.

iii. No significant differences exist between *Eucalyptus* spp. plantations and native forest litter fall in their nutrient amounts.

1.6 **Objectives of the Study**

1.6.1 **General Objectives**

The general objective of the study was to evaluate the effects of *Eucalyptus* spp. plantation and native forest on selected soil physical and chemical properties.

1.6.2 **Specific Objectives**

The study addresses the following specific objectives:

i. To evaluate the effects of *Eucalyptus* spp. plantation and native forest on soil physical properties (soil texture; soil moisture; and soil bulk density).
To evaluate the effects of *Eucalyptus* spp. plantation and native forest on soil chemical properties (pH; organic carbon; available phosphorus; total nitrogen; exchangeable bases; exchangeable acidity; cation exchange capacity; and soil micro-nutrients (Fe, Zn, Cu and Mn)).

To determine amount of nutrients (C, N, P, K, Ca, Mg, Fe, Zn, Cu and Mn) in litter fall from *Eucalyptus* spp. plantation and native forest.

### 1.7 Significance and Anticipated Outcomes of the Study

Land management planners can use this information in their decisions on land use in the study area and to understand the particular choices made by farmers concerning *Eucalyptus* spp. plantation in the Thiririka sub-catchment.

The results from this study will help National Environmental Management Authority (NEMA), Kenya Forestry Services (KFS), community leaders, extension officers, farmers, opinion leaders, NGOs and stakeholders to understand, redesign and improve as well as take steps to minimize negative impacts of *Eucalyptus* spp. plantations.

The outcome of this research would be beneficial to local, district, County and National governments as it will generate a baseline data for further studies and research, and policy dialogues. The findings will also facilitate monitoring and evaluation of *Eucalyptus* spp. plantations regarding their effects on the soil properties in Thiririka sub-catchment in Kiambu County, Kenya.

### 1.8 Scope and Limitations of the Study

The study primarily focused on the Thiririka watershed located in Kiambu County of Kenya. Major limitation of this study is that it did not undertake measurement of all soil aspects of the
Eucalyptus spp. vegetation and many other varieties of tree species, owing to logistical constraints. Measurements were also done during one season in March and April, 2015, although collecting data over a longer period of time could have provided much more data for a more concrete prediction of the effect of Eucalyptus spp. plantations on soil physical and chemical properties.

1.9 Conceptual Framework

This study adapts and modifies the conceptual framework used by Tererai (2012) to study the effects of invasive trees in riparian zones using insights from Eucalyptus spp. invasions in South Africa. The framework had been modified to include soil physical, chemical parameters, soil organic matter and litter fall contribution of Eucalyptus spp. to soil nutrients. Implications of the effects, mitigation strategies for policy action and sustainable management of Eucalyptus spp. cultivation and the beneficial impacts for such mitigation strategies have also been added.

Environmental effects of Eucalyptus spp. plantations have been studied and reported by previous authors such as Arriagada et al. (2009), Tererai (2012), Demessie et al. (2012), Albaugh et al. (2013), Tererai et al. (2014) and Cortez et al. (2014). These studies however, did not indicate the effects of the Eucalyptus spp. plantations on the soil physico-chemical properties such as soil moisture; soil bulk density; soil organic matter content; soil exchangeable cations such as Ca, Mg, K and Na; soil exchangeable acidity; soil micro-nutrients such as Mn, Fe, Zn, and Cu. Cultivation of exotic Eucalyptus spp. plantation may lead to lower litter production and poor nutrient release resulting in soil productivity decline in the long term (Demessie et al., 2012). Eucalyptus spp. plantation, through its litter decomposition can improve or deplete the soil biological, physical and chemical properties (El-Amin et al., 2001).
Additionally, analysis of litter fall nutrients such as C, N, P, K, Ca, Mg, Fe, Zn, Cu and Mn contribution of *Eucalyptus* spp. to soil fertility improvement had been have been studied to a minimal extent. Litter fall is a major pathway for the return of organic matter and other essential nutrients to the soil (Vitousek *et al.*, 1995) from plant components through the decomposition process (Demessie *et al.*, 2012). Oballa *et al.* (2010) reported increased concentrations of soil micro-nutrients (Fe and Mn) under short rotation *Eucalyptus* spp. plantations in Kenya. This study, however, failed to provide analysis of the *Eucalyptus* spp. plantation on soil available Cu and Zn.

Therefore, it is important to understand the quantitative linkage and magnitude at which *Eucalyptus* spp. plantation affects the selected soil physico-chemical properties in Thiririka sub-catchment to help farmers take appropriate measures in addressing any implications that arise from this tree plantation.

The implications of the effects include soil degradation, hydrological impacts and reduced plant biodiversity due to allelopathic effects of *Eucalyptus* spp. plantations. Mitigation strategies that can be employed to reduce these impacts include increased research work on *Eucalyptus* spp. plantations and policy interventions on planting of *Eucalyptus* spp. on farms. These strategies will lead to improved management of *Eucalyptus* spp. plantations, reduced soil degradation, sustainable agro-forestry systems, improved plant biodiversity and in the nutshell enhances sustainable watershed. These linkages are explained further in the figure 1.1.
Figure 1.1: Linkages of conceptual framework for the study showing the effects of *Eucalyptus* spp. plantations on soil physico-chemical properties.

Source: Adapted and modified after Tererai, 2012.

1.10 Operational Definition of Terms

1.10.1 Allelopathy

Allelopathy refers to the beneficial or harmful effects of one plant on another plant, both crop and weed species, from the release of bio-chemicals, known as allelochemicals, from plant parts by leaching, root exudation, volatilization, residue decomposition, and other processes in both natural and agricultural systems (Ferguson *et al*., 2013). Allelochemicals with negative
allelopathic effects are, for instance, an important part of plant defense against herbivory (i.e., animals eating plants as their primary food) (Stamp, 2003). Plants such as Tectona grandis, Eucalyptus sp., neem tree, among others are known to exhibit allelopathic effects.

1.10.2 Carbon to Nitrogen (C:N) Ratio of Plant Litter

Carbon to nitrogen ratio (C: N) is the weight of carbon divided by the weight of nitrogen in a composting material (Wortman et al., 2006). Carbon to nitrogen ratio is an important factor that influences the rate of decomposition of organic material to form humus. High C:N ratio leads to immobilization of soil nitrogen, as soil available N gets bound in microbial processing of the low nitrogen litter (Briones and Ineson, 1996). Eucalyptus spp. are reported to produce large quantities of litter material which has high C:N ratios, high lignin and phenolic content (Castro-Díez et al., 2011).

1.10.3 Immobilization of Soil Nutrients

Immobilization is a term used to refer to conversion of soil nutrient from the inorganic form to organic form, which are unavailable for plant use. It is the opposite of mineralization, which is the release of organically bound nutrients in an inorganic form usable to organisms and/or plants. Immobilization of soil nutrients occurs when pH of the soil is strongly acidic and when the plant litter material has slower decomposition rates and high C:N ratio.

1.10.4 Litter Fall

Litter fall, plant litter, leaf litter, tree litter, soil litter, or duff, is dead plant material, such as leaves, bark, needles, and twigs, which has fallen to the ground. Litter fall may be very useful in predicting regional nutrient cycling and soil fertility.
1.10.5 Sub-catchment

A catchment is defined as the land area that contributes runoff to a given drainage or river system. A sub-catchment is smaller drainage or river system which contributes runoff to a larger one. The sub-catchment used in this study is Thiririka sub-catchment which measures 192 km$^2$ in size and located in Kiambu County, Kenya.

1.10.6 Transpiration Rates

Transpiration is the process of water movement through a plant and its evaporation from aerial parts, such as from leaves but also from stems and flowers. Leaf surfaces are dotted with pores called stomata, and in most plants they are more numerous on the undersides of the foliage. Evapo-transpiration is therefore, defined as the total process of water loss or movement from both the soil and plants. *Eucalyptus* spp. is one that has received many criticisms in literature in that it may cause a change in the local climate. This is because of their very high evapo-transpiration rate, which may lead to a lower water table. This high rate of soil water loss consequently leads to depletion of the soil moisture content, which is claimed to adversely affect local rainfall levels, resulting in possible desertification of the area (FAO, 2011).
CHAPTER TWO
LITERATURE REVIEW

2.1 Effects of *Eucalyptus* spp. Plantation on Soil Physical Properties

2.1.1 Soil Bulk Density

FAO (2011) found increased soil bulk density from 0.58 mg m\(^{-3}\) to 0.70 mg m\(^{-3}\) for *Eucalyptus* spp. plantations in Australia. Ravina (2012) found higher soil bulk density at 1.24 g cm\(^{-3}\) under *Eucalyptus* spp. plantation compared to native forest of 0.66 g cm\(^{-3}\) within 0~20 cm depth of soils in Brazil. Aweto and Moleele (2005) also found that *Eucalyptus* spp. plantations increased soil bulk density more than the native forest of *Acacia* spp. in Botswana. Increased soil bulk density is associated with reduced soil infiltration, increased surface run off, with consequent reduction in soil moisture.

2.1.2 Soil Moisture

Cao *et al.* (2010) reported low soil moisture contents, ranging from 20.2 to 30.5 % in the top soil (0-10 cm depth) of four areas under *Eucalyptus* spp. plantations in China. A study in India on the hydrological impacts of *Eucalyptus* spp. plantation indicated that in some regions, *Eucalyptus* spp. plantation exhibited greater water use than recorded rainfall over the same time period implying short to medium term soil moisture reductions (Calder *et al.*, 1997). According to Calder *et al.* (1997), a phenomenon known as “soil water mining” was occurring, whereby, the trees’ extensive root systems were able to tap into deeper soil layers that other species were unable to reach. They concluded that, the implication of this is a disturbance in the water table and potential draining of underground aquifers, reducing groundwater recharge.
Alemie (2009) further reported soil moisture reduction under *Eucalyptus* spp. plantations in Koga watershed in Ethiopia with the reductions being highest at distances closer to the *Eucalyptus* spp. Tererai *et al.* (2014) also reported that invaded sites of *Eucalyptus camaldulensis* showed significantly reduced soil moisture levels than their counterpart of un-invaded sites in winter and spring seasons of riparian soils of the Berg River catchment in Western Cape Province, South Africa.

### 2.1.3 Soil Texture

Aweto and Moleele (2005) found that between 0 and 20 cm soil depth, the mean proportion of clay was significantly higher under *Eucalyptus* spp. plantation soils compared to an *Acacia* forest plantation in Botswana. They further argued that higher clay content of soil means higher cation exchange capacity of the *Eucalyptus* spp. plantation. Balamurugan *et al.* (2000) also reported increase in clay and decrease in sand content under *Eucalyptus* spp. plantation.

Moreover, Alem *et al.* (2010) found in Ethiopia that the percentage of clay particles in soil collected from *Eucalyptus grandis* plantation was significantly higher than that of the adjacent native sub-montane Rain Forest. Khanmirzaei *et al.* (2011) further reported in Iran that clay and coarse silt contents were significantly greater under *Eucalyptus* spp. plantations, whereas sand fraction was less.

### 2.2 Effects of *Eucalyptus* spp. Plantation on Soil Chemical Properties

#### 2.2.1 Soil pH

Rhoades and Binkley (1996) found a reduction in soil pH from 5.9 to 5.0 after eight years of *Eucalyptus saligna* establishment. Cao *et al.* (2010) also found reduced soil pH between 0 to 10
cm soil depths of four areas, which ranged from 4.2 to 4.5, under *Eucalyptus* spp. plantations in China. Similarly, Alemie (2009) found reduced soil pH and strongly acidic values ranging between 3.5 to 4.0 under *Eucalyptus* spp. plantations in Koga watershed in Ethiopia.

Aweto and Moleele (2005) argued that *Eucalyptus* sp. immobilizes soil exchangeable bases, especially calcium leading to low soil pH. Bailey *et al.* (2005) adds that acidification usually leads to depletion of the soil base cations (e.g., K⁺, Mg²⁺, Ca²⁺). This depletion arises from replacement of the basic cations by Al³⁺ and H⁺ ions at the exchange site.

According to Castro-Díez *et al.* (2011), low soil pH limits the growth and activities of decomposer soil microorganisms as soil biological activities are reduced in acidic soils. Berendse (1998) indicated that at soil pH of below 5.5, soil trace nutrients like Manganese (Mn) and Aluminium (Al) availability increase to levels that become toxic for most plant growth. Further, soil nutrients such as phosphorus and nitrogen tend to form insoluble compounds with Al and Fe in acidic soils, become adsorbed and therefore, made inaccessible for plant uptake. Table 4.2 provides the soil pH ranges and their interpretation guide of soil acidity.

**Table 2.1: pH Ranges and their Interpretation Guide. Source: Horneck *et al.* (2011)**

<table>
<thead>
<tr>
<th>pH</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5.1</td>
<td>Strongly Acidic</td>
</tr>
<tr>
<td>5.2-6.0</td>
<td>Moderately Acidic</td>
</tr>
<tr>
<td>6.1-6.5</td>
<td>Slightly Acidic</td>
</tr>
<tr>
<td>6.6-7.3</td>
<td>Neutral</td>
</tr>
<tr>
<td>7.4-8.4</td>
<td>Moderately Alkaline</td>
</tr>
<tr>
<td>&gt;8.5</td>
<td>Strongly Alkaline</td>
</tr>
</tbody>
</table>
2.2.2 Soil Exchangeable Acidity (Al$^{3+}$ and H$^+$)

Soils that have reduced pH and are strongly acidic have been found to contain higher exchangeable acidity. Oyedele et al. (2009) indicated that hydrolysis of Al$^{3+}$ ions contribute to development of soil acidity. Frimpong et al. (2014) indicated that when the soil pH drops below 5.5, aluminum and manganese toxicities may occur. In this regard, increasing soil exchangeable acidity (H$^+$ + Al$^{3+}$) concentration would lead to lower the soil pH. Soils with higher exchangeable acidity have been reported to cause immobilization of soil essential nutrients such as P, N, Ca, Mg, and K under Eucalyptus spp. plantations (Aweto and Moleele, 2005).

2.2.3 Soil Organic Carbon and Soil Organic Matter

Benefits of improved organic matter in the soil include improved water and nutrient holding capabilities; better soil structure which enhances root growth and increases aeration; a more hospitable environment for soil organisms; and a reserve of plant nutrients. Lal (2005) pointed out that the soil carbon content depends on complex interactions among climate, soils, tree species and management, and the chemical composition of the litter, as determined by the dominant tree species. Substantial changes in soil organic matter (SOM) have been reported after substitution of the natural vegetation by short-rotation Eucalyptus spp. plantations in Brazil (Lima et al., 2008).

Sharmsher et al. (2002) found that 83 % in the surface soil and 94 % in the sub-soil of soil samples in Pakistan were low (< 1 %) in organic matter under Eucalyptus spp. plantation soils. Reports by Jan et al. (1996) also indicated significant organic matter changes in Eucalyptus spp. plantation soils relative to Shorea robusta natural forest soil in Uttar Pradesh, Pakistan. Similar findings have been reported by Bernhard-Reversat (1998) who found that the organic carbon
concentration in the 0–10 cm depth of native *Acacia seyal* woodland in Keur Maktar, Senegal was twice that in a corresponding layer of soil under *Eucalyptus* spp. plantation.

Baber *et al.* (2006) conducted a study on the effect of *Eucalyptus camaldulensis* on soil properties and soil fertility in Khan District in Pakistan. They found that the organic matter content in the surface soil at 0-15 cm depth ranged from 0.38 to 1.10 %. By comparing the results with the established criteria for soil fertility, the soil samples were low in organic matter. Organic matter contents are considered low if it is less than 4 %, medium if it is between 4 % and 8 %, and high if it is above 8 % (University of Connecticut, Cooperative Extension System, 2003).

According to Cortez *et al.* (2014), the results for soil total organic carbon (TOC) indicated that organic C decreased in the first year of the conversion of native forest to *Eucalyptus* spp. plantations in Brazil. Chen *et al.* (2013) indicated that during deforestation of native vegetation and establishment of *Eucalyptus* spp. plantation, soil macro-aggregates are disrupted and exposed to microbial breakdown, with the consequence of organic matter being lost from soil. Zhang *et al.* (2012) add that lower organic matter inputs are provided to the soil since young *Eucalyptus* spp. stands may provide a low amount of inputs of plant residues to the soil.

However, Leite *et al.* (2010) found in Brazil that contents of soil organic matter were considerably higher in *Eucalyptus* spp. soils than in pasture areas, which they attributed to the greater amount of residues produced by the *Eucalyptus* spp. plantation (leaves, branches, bark and especially roots) that remained in the soil. Hou (2006) also argued that *Eucalyptus* spp. have a high growth rate and C fixation potential; therefore, part of the assimilated C is transported to the soil through litter fall and rhizodeposits, and hence the potential of increasing soil organic C
content with time (Lima et al., 2006). Therefore, it is likely that the changes in soil chemical properties, particularly in SOM, differ after several *Eucalyptus* spp. plantation rotations, varying with the soil type and dominant climate conditions (Leite et al., 2010).

### 2.2.4 Soil Total Nitrogen and Soil Available Phosphorus

FAO (2011) made a comparison of 1 to 8 years old *Eucalyptus* spp. plantations and natural mixed broad leaved forest in the central Himalayas. The study found soil total N and available P decreased as a result of reforestation with *Eucalyptus* spp. plantation. A study by Leite et al. (2010) pointed out that large nutrient amounts are exported when *Eucalyptus* spp. plantation are harvested, causing a reduction in the soil nutrients content such as total N and available P.

Jagger and Pender (2000) pointed out that when considering which tree species should be chosen for afforestation or agro-forestry, the depletion of soil nutrients is one of the most commonly cited criticisms associated with the *Eucalyptus* spp. In contrast to other trees commonly used, such as *Leucaena* and *Acacia*, *Eucalyptus* spp. do not fix nitrogen from the atmosphere as the leguminous species do. They, therefore, concluded that fast growing non-leguminous *Eucalyptus* spp. are not recommended for intercropping with annual crops.

Tererai et al. (2014) found that soil total N decreased with an increase in *Eucalyptus camaldulensis* cover compared to the site not covered by the *Eucalyptus* spp. in South Africa. This was attributed to the high biomass and higher nutrient consumption rates of the *Eucalyptus* spp. Alemie (2009) also found that concentration of soil TN decreased under plantations of *Eucalyptus* spp. in Ethiopia.
Nitrogen concentration in soils is reflected in part by the rate of decomposition of the plant material (Demessie et al., 2012). Previous authors have reported that *Eucalyptus* spp. produce litter with low nutrient concentrations, which decomposes slowly to release low concentrations of nutrients (Aweto and Moleele, 2005; Baber et al., 2006; Cao et al., 2010; Demessie et al. 2012).

Aweto and Moleele (2005) indicated that soil available phosphorus was relatively low in soil under *Eucalyptus* spp. plantation (< 5µg g$^{-1}$) at 0–20 cm depth of the soil, which was attributed to the long-term immobilization in the plantation standing biomass. In Australia, Polglase et al. (1992) found that the concentration of soil available phosphorus in the topsoil (0–5 cm depth) under *Eucalyptus* spp. plantation declined from an initial concentration of 34 to 2.3 µg g$^{-1}$ after 16 years. Alemie (2009) further reported that soil available phosphorus concentration in *Eucalyptus* spp. plantation within 0–20 cm depth of soil was in the very low range (< 5 mg kg$^{-1}$) in Ethiopia.

2.2.5 Soil Exchangeable Cations (Na$^+$, Ca$^{2+}$, Mg$^{2+}$ and K$^+$) and Cation Exchange Capacity (CEC)

Aweto and Moleele (2005) indicated that decline in pH in plantation soil would lead to a lowering of soil base saturation, as these exchangeable bases (Ca$^{2+}$, Mg$^{2+}$, and K$^+$) are immobilized, resulting in soil exchangeable bases depletion over time.

Leite et al. (2010) found that soil exchangeable K, Ca, and Mg declined in the *Eucalyptus* spp. plantation soils compared to the native forest soils in Brazil. Tererai et al. (2014) in their study in South Africa found that soil exchangeable cations such as Ca and Mg were generally higher in
un-invaded sites and declined along the invasion gradient of *Eucalyptus camaldulensis* (lightly, moderately and heavily invaded) in all seasons.

Aweto and Moleele (2005), in their study in Gaborone, South Eastern Botswana, found lower exchangeable nutrient cation content, especially calcium, magnesium and potassium of both 0–10 and 10–20 cm depths of soil under *Eucalyptus* spp. plantation. Bernhard-Reversat (1988) observed that the calcium, magnesium and potassium concentrations were considerably lower in the 0–20 cm depth of soil under 8 year *Eucalyptus* spp. plantation in Senegal than in soil under native semi-arid Sudano-sahelian savanna. Jaiyebo (1998) indicated a reduced concentration of soil exchangeable bases under plantations of *Eucalyptus* spp. in northern Nigeria.

Alem *et al.* (2010) observed higher soil exchangeable Na concentration in *Eucalyptus grandis* compared to that in native forest in Ethiopia. Adetunji (1996) indicated that soils with exchangeable Na of 1 c mol kg\(^{-1}\) should be regarded as potentially sodic. When Na is present in the soil in significant quantities, particularly in proportion to the other cations present, it can have an adverse on crops and physical conditions of the soil (Adetunji, 1996; Bashour and Sayegh, 2007).

### 2.2.6 Soil Trace Elements/Micro-Nutrients (*Zn\(^{2+}\), Fe\(^{2+}\), Mn\(^{2+}\) and Cu\(^{2+}\))

Soil micro-nutrients availability often correlate well with soil pH and organic matter levels (Horneck *et al.*, 2011). According to Horneck *et al.* (2011), availability of most micro-nutrients decreased as pH increased. They further reported that micro-nutrient deficiencies rarely occur when the soil pH is below 6.5 and that micro-nutrient deficiencies generally occur only when soil pH is 8.0 or above.
Baber et al. (2006) found in Khan District in Pakistan that soils under *Eucalyptus camaldulensis* plantation contained reduced levels of soil micro-nutrients such as Zn$^{2+}$, Fe$^{2+}$, Mn$^{2+}$ and Cu$^{2+}$ but this was because the soil pH range was in the basic range of 8 to 8.5. Soil available Fe$^{2+}$, and especially Mn$^{2+}$, followed the same pattern. Khanmirzaei et al. (2011) carried out a study on four *Eucalyptus* spp. plantation plots in Iran. The study found significant increases in soil available micro-nutrients especially Fe and Mn contents at 0 – 20cm soil depth. In the study, Fe increased from 1.85 to 3.60 mg kg$^{-1}$ and Mn from 2.10 to 11.28 mg kg$^{-1}$.

Generally, Montagnini (2000) indicated that soil major nutrient availability decreases and micro-nutrients increase in plantation of fast-growing tree species with high nutrient uptake, high immobilization of nutrients in the plant biomass and with decreased mineralization.

### 2.2.7 Plant Nutrients in *Eucalyptus* spp. Plantation Litter Fall

Lemma et al. (2007) reported that as an insulating layer, litter protects the soil from extreme changes in moisture and temperature, intercepts thorough-fall, and improves infiltration. According to Demessie et al. (2012), the quantity and quality of litter production and the decomposition process play an important role in soil fertility management in terms of nutrient cycling, carbon budgeting and formation of soil organic matter under plantations, where part or all of the biomass accumulated during the production period is hauled out of the site after harvest. Under such circumstances, it will be likely that continuous cropping with short rotation crops will result in nutrients depletion and deterioration of physical and biochemical activity of the soil (Parrotta 1999; Fisher and Binkley, 2000; Wang et al., 2007).

*Eucalyptus* spp. are associated with large quantities of litter with high C:N ratios, high lignin and phenolic content (Castro-Díez et al., 2011). This results in lower net N mineralization, as soil
available N gets bound in microbial processing of the low N-litter (Briones and Ineson, 1996; Bernhard-Reversat and Schwartz, 1997). For instance, Dalla Tea and Marcó (1996) reported fourteen year old *Eucalyptus* spp. plantations in Argentina to have 25 Mg ha\(^{-1}\) of litter with a low concentration of nitrogen (8 kg mg\(^{-1}\)) and phosphorus (0.25 kg mg\(^{-1}\)).

The recalcitrant litter and consequently low decomposition rates of *Eucalyptus* spp. litter (Tererai *et al.*, 2014) also explains the reduced levels of soil total N, P and K concentrations usually found under *Eucalyptus* spp. plantation soils. Many invasive alien plants tend to speed up litter decomposition and increase nutrient pools for plant uptake (Ehrenfeld, 2003), in particular N content (Lake and Leishman, 2004; Follstad Shah *et al.*, 2009). However, *Eucalyptus* spp. plantation have been reported to produce nutrient-poor litter, with slow decomposition rate, thus resulting in little or no effect on soil-nutrient pools (Castro-Díez *et al.*, 2011), especially those mostly in monocultures (Forrester *et al.*, 2006).

According to Wang *et al.* (2007) and Pandey *et al.* (2007), when natural forests are replaced by monoculture plantations, the forest species diversity decreases, the total litter fall gets reduced and eventually the pattern of nutrient release through decomposition changes. Scarcity of humus formation and a high annual disappearance of organic matter in the forest floors under *Eucalyptus* spp. plantations have been reported (Goya *et al.*, 2008). Most of the studies that have reported elevated C and N in soils are for N-fixing species growing on nutrient-poor soils (Yelenik *et al.*, 2004; Gaertner *et al.*, 2011). For cases of *Eucalyptus* spp. plantation, elevated soil nutrients have mostly and usually been reported in vegetation assemblages when they are mixed with leguminous species like that of *Acacia* species (Bauhus *et al.*, 2000; Laclau *et al.*, 2005; Forrester *et al.*, 2006; Gaertner *et al.*, 2011).
Table 2.2: Summary of Key Empirical Studies on *Eucalyptus* spp. and Research Gaps.

<table>
<thead>
<tr>
<th>No.</th>
<th>Author/Year</th>
<th>Summary of findings</th>
<th>Gaps identified</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Leite <em>et al.</em> (2010)</td>
<td>The study considered alterations of soil chemical properties by <em>Eucalyptus</em> spp. plantations in five regions in the Rio Doce-Valley, Brazil. It was found that management practices applied in <em>Eucalyptus</em> spp. plantation caused significant alterations in some soil chemical properties. The readily available and long-term nutrient contents were reduced (except soil available phosphorus).</td>
<td>This study failed to indicate the effects of <em>Eucalyptus</em> spp. plantations on the soil physical parameters.</td>
</tr>
<tr>
<td>2</td>
<td>Arriagada <em>et al.</em> (2009)</td>
<td>This study considered the effect of <em>Arbuscular mycorrhizal</em> fungal inoculation on <em>Eucalyptus</em> spp. seedlings and some soil enzyme activities under application of sewage sludge amendment. The study concluded that sewage sludge from municipal wastewater improved soil fertility due to high content of organic and inorganic plant nutrients. Also, the application of sewage sludge to <em>Eucalyptus</em> spp. seedlings inoculated with AM fungi also showed results very variable in the plant biomass production and the enzymes activities.</td>
<td>In this study, the effects of <em>Eucalyptus</em> spp. plantation on the soil chemical and physical properties were not indicated.</td>
</tr>
<tr>
<td>3</td>
<td>Cortez <em>et al.</em> (2014)</td>
<td>This study took into consideration soil microbial properties in <em>Eucalyptus</em> spp. plantations of different ages. The study established that <em>Eucalyptus</em> spp. plantation had significant impacts on the soil microbial biomass C, N, respiration, and C use efficiency.</td>
<td>The study presented limited effects of the <em>Eucalyptus</em> spp. plantation on the soil chemical properties. Also, the effects of the plantation on the soil physical parameters were missing in the study.</td>
</tr>
<tr>
<td>4</td>
<td>Albaugh <em>et al.</em> (2013)</td>
<td>This study considered quantification of water use of <em>Eucalyptus</em> spp. in South Africa. It was concluded that average daily transpiration rates of <em>Eucalyptus</em> spp. in South Africa range from 2 to 7 mm; these varied with season-associated climatic variables, soil water availability, stand age, and site growth potential.</td>
<td>The study therefore failed to indicate the effects of the <em>Eucalyptus</em> spp. plantation on the soil physical and chemical properties.</td>
</tr>
</tbody>
</table>
CHAPTER THREE
MATERIALS AND METHODS

3.1 Study Area Characteristics

Geographically, Thiririka catchment is 192 km$^2$ in Kiambu County, Kenya, under Tana and Athi River Drainage system. The catchment borders Thika District to the North and East and Kiambu East to the South and West. The catchment has a population of about 114,180 people, representing a density of approximately 593.5 individuals/km$^2$ (Gatundu Agricultural Office, 2013; Rwabura Irrigation Project Report, 2013). There are several rivers and streams that traverse the catchment. These include Ndarugu, Rauabura, Kahuga and many others. All these flow from the Aberdare ranges to West and towards the southeast joining River Athi. Altitude ranges from 1520 m down to 2280 m above sea level (Rwabura Irrigation Project Report, 2013). The catchment soils correspond entirely with typical Humic Nitisols and Andosols (Gatundu Agricultural Office, 2013). The map of the catchment with the various sampling points is shown in Figure 3.1.

3.1.1 Topographic Features

The Thiririka sub-catchment is generally hilly to the North, West, and the Central and Southern parts, gentle plains to the East and South East, and there are several valley bottoms scattered all over centripetal drainage system draining into the Athi Basin (Rwabura Irrigation Project Report, 2013). The altitude ranges from 1600 meters above sea level at the lower zones to about 2200 meters above sea level in the West and North Western Parts (Rwabura Irrigation Project Report, 2013).
3.1.2 Administrative and Political Units

The Thiririka sub-catchment covers part of the Gatundu South District, within three divisions namely Ng’enda in the South, Kiganjo in the West and Ndarugu in the North. These are further divided into twelve locations and forty seven sub-locations.

Figure 3.1: Map of the study area of the Thiririka sub-catchment showing sampling points.
3.1.3 Climate

3.1.3.1 Rainfall

The Thiririka sub-catchment experiences an annual average rainfall ranging between 800 and 2000 mm which vary along the agro-ecological zones (Kenya Meteorological Department, 2012). The sub-catchment receives a mean annual rainfall of 1160 mm with two distinct peaks in March to May and October to December (bi-modal pattern). The maximum and minimum rainfall received is 257 mm and 33.4 mm in April and July respectively (Kenya Meteorological Department, 2012), as shown in Figure 3.2.

Figure 3.2: Monthly Rainfall for Thiririka sub-catchment for the year 2012 (data obtained from Kenya Meteorological Department, 2012).

3.1.3.2 Temperature

The temperature in the Thiririka sub-catchment varies from humid to semi-humid characteristics. The mean annual temperature in the humid zone varies between 14 °C to 18 °C, while in the sub-humid to semi-humid zones the mean annual temperatures vary between 18 °C and 22 °C. The
annual maximum temperatures range from 25.2 °C to 30.4 °C in the months of August and March respectively, while the minimum temperatures range from 9.8 °C and 15.4 °C in the months of February and April respectively (Kenya Meteorological Department, 2012), as shown in Figure 3.3.

![Figure 3.3: Mean monthly Minimum and Maximum Temperatures for Thiririka Subcatchment for the year 2012 (data obtained from Kenya Meteorological Department, 2012).](image)

### 3.1.4 Soils

The study area lies in the tertiary volcanic rocks region of Central Kenya. Its geology can be classified as Kerichwa valley tuffs along the river valleys and the middle and upper Kerichwa valley tuffs found on the higher grounds (Gatundu Agricultural Office, 2013). The soils found in the upper parts of the Thiririka sub-catchment are classified as humic nitisols, while those found in the lower parts of the sub-catchment are classified as rhodic nitisols. These soils have great agricultural potential (Rwabura Irrigation Project Report, 2013).
3.1.5 Socio-Economic Activities

The main economic activities in the sub-catchment are subsistence and commercial farming. Commercial farming mainly involves the growing of macadamia nuts, coffee, tea, and other food crops. Subsistence farming involves the growing of maize, beans, potatoes, arrow roots, bananas, sugar cane, sweet potatoes, cassava, yams, kales, and vegetables. Most typical type of farming practiced in the sub-catchment is mixed cropping. Livestock rearing is another important activity in the Thiririka sub-catchment and includes cattle, goats, and sheep. Donkeys are an important form of transport, particularly for firewood, water and other goods for the market (Mensah et al., 2015).

3.1.6 Environment, Water and Sanitation

The Thiririka sub-catchment’s water resources comprise both surface and groundwater. There are several rivers and streams including the Ndarugu, Ruabura, Thiririka and Kahuga. These rivers flow from the Aberdare Ranges to the West towards the South East joining the River Tana forming part of the Athi and Tana catchment system. Boreholes supply water to communities where there are no springs and rivers. The major source of water supply to the catchment is the Thiririka River (Mensah et al., 2015).

3.2 Field Experimental Design

Two experimental plots of 100 m x 100 m (1 ha) were used for the study. Each experimental plot was sub-divided into five sub-plots of 20 m x 20 m, which served as replications. The sub-plots were sampled for soil and litter. The experimental plots were Eucalyptus spp. plantation (EP) and native forest (NF). The monoculture Eucalyptus spp. plantation plot served as the treatment
(Plate 3.1) and consisted of species such as *Eucalyptus grandis*, *Eucalyptus saligna*, and *Eucalyptus globulus*. The neighbouring native forest of mixed vegetation served as the control plot (Plate 3.2) and consisted of undergrowth and many different plant species such as *Cynodon dactylon*, *Podocarpus* spp., *Acacia mearnsii*, *Croton macrostachyus*, and many other legume species growing together.

Plate 3.1: *Eucalyptus* spp. plantation in Thiririka sub-catchment (09/01/2015).

Plate 3.2: Native forest plantation in Thiririka sub-catchment (20/04/2015).
3.3 Sampling Procedure, Mapping and Sample Preparation

Soil samples were collected randomly at the depth of 0 – 20 cm using the screw auger (Plate 3.3) at 25 sampling points within the sub-plots (20 m x 20 m). Five composite samples were taken at each of the EP and NF plots. A hand held GARMIN GPS-60 device was used to map coordinates of the various sampling points. These collected soil samples were placed in polythene bags and transported to the Kenyatta University Chemistry laboratory for analysis.

Soil samples were air-dried at 65 ºC for 48 hours in shallow wooden trays in a well-ventilated place protected from rain and contamination. All soil samples were ground and made to pass through a 2-mm sieve after all the gravel, live and dead organic residues have been removed. A representative sample of approximately 500 g was retained by cone and quartering. This representative sample was then handed in for the selected soil physico-chemical analysis.

Litter sampling was done by hand randomly within the entire sub-plots of 20 m x 20 m. The litter collected consisted of dead branches, roots, twigs and leaves found under the forest and were bulked together. The plant litter collected at each plot was dried separately at 70 ºC for 48 hours. This was weighed and ground with Retsch SR 2000 laboratory grinding mill. The litter samples from the two study sites (EP and NF) were then analyzed at the laboratory to determine their nutrient composition.
3.4 Laboratory Analyses

3.4.1 Soil Moisture

Soil moisture was determined by the Gravimetric method as provided by Kolay (2000). A metal Can with a lid was weighed accurately with a Scout™ Pro 2000 g Balance ($W_1$). About 100 g of soil was placed in the Can and weigh accurately along with the lid ($W_2$). The Can covered with the lid and the soil was oven-dried for 48 hours. The Can was then removed from the oven covered tightly with the lid and placed in a desiccator to cool for about 30 minutes. After cooling, the Can was weighed accurately with the oven-dry soil in it and the weight recorded ($W_3$). Percent moisture content on oven-dry basis was then calculated using the formula in equation 1 below:

\[
\text{Percentage Soil Moisture} = \frac{\text{Wt. of moist soil} - \text{Wt. of oven dried soil}}{\text{Wt. of oven dried soil}} \times 100 \quad \text{Equation 1}
\]
3.4.2 Soil Dry Bulk Density

The soil bulk density was determined 24 hours after rainfall using the Core method prescribed for undisturbed soils (Kolay, 2000). 1 to 2 cm of soil surface was removed and a core sampler driven into the soil. The soil from around the core sampler was evacuated and the soil beneath was cut off. Both ends of the core sampler were trimmed and flushed with a straight edge knife. The core sample was oven dried to a constant weight using the WTC Binder Oven at 105 °C for 24 hours. The soil bulk density was calculated using the formula in equation 2 below:

\[
\text{Bulk Density (g cm}^{-3}\text{)} = \frac{\text{Wt. of soil core (oven-dry basis) (g)}}{\text{Vol. of soil core (cm}^3\text{)}}
\]

3.4.3 Soil Texture (Particle Size Distribution)

Soil texture analysis was done using the Bouyoucos hydrometer method (Hinga et al., 1980; Klute, 1986). Oven-dry soil sample weighing 50 g was put in a plastic shaking bottle and 50 ml Calgon (dispersion agent) added. A blank sample (without soil sample) was also prepared (represented reading for blank sample, Rb). The mixture was placed on a mechanical shaker and shaken for 3 hours. The suspension was transferred into the sedimentation measuring cylinder, and top up to the 1000 ml mark. The mixture was stirred well using a metal plunger to bring the particles into suspension. By the use of a soil hydrometer, a reading was taken after 40 seconds (represented the first reading, R1). After two hours, the hydrometer was used to take the second reading (R2). The second reading gave the clay content. The calculations were done as follow (equations 3, 4, and 5):

\[
\% \text{ Clay} = \frac{R2-Rb}{50} \times 100
\]

The first reading gives the Silt + Clay
That is % (Silt + Clay) = R1/50 *100………………………………………………Equation 4
Therefore, % Silt = this reading minus % clay
% sand = 100 - % (Silt + Clay)…………………………………………………………Equation 5
After getting the percentage sand, silt and clay, the soil textural triangle was used to classify the soil. Figure 5.1

3.4.4 Soil pH

The pH of the soils was determined using ST 10 OHAUS pH meter. All pH measurements were performed using a 1:2.5 (w/v) soil: water ratio by weighing 20 g of 2 mm air-dried soil into a 100 ml glass beaker and adding 50 ml distilled water. The soil was mixed with the distilled water and stirred intermittently using a stirrer for 30 minutes before pH was determined (Anderson and Ingram, 1993).

3.4.5 Soil Total Organic Carbon (TOC)

Soil total organic carbon was determined by the colorimetric method described by Schulte and Hoskins (2009). Oven-dry soil sample weighing 1 g was scooped into a 50 ml Erlenmeyer flask. The organic carbon in the soil sample was oxidised by 0.5 M Na$_2$Cr$_2$O$_7$•2H$_2$O and 5 M H$_2$SO$_4$. 10 ml of dichromate-sulphuric acid digestion solution was pipetted. A reagent blank without soil was also prepared in the same way. This was heated at 150 °C for 30 minutes to ensure complete oxidation. Barium chloride was added to cool the digest. After mixing thoroughly, the digests were allowed to stand overnight. 10 ml of the clear supernatant was transferred into a colorimeter tube. The soil organic carbon concentration was read on the Specord 200 Plus Ultra Violet Spectrophotometer at 600 nm. The per cent organic matter (OM) in the soil was then estimated using the equation 6:
\[
\% \text{ OM} = \frac{\% \text{ total C} \times 1.72}{0.58}
\]

Where \( C \) = organic carbon concentration

### 3.4.6 Soil Total Nitrogen (TN)

Soil TN was determined by the Kjeldahl method as provided by Bashour and Sayegh (2007). Air-dried soil sample weighing 1 g was weighed into 500 ml Kjeldahl flask. Five millilitres distilled water was added to wet the soil thoroughly. A scoop of digestion accelerator mixture (sulphuric-salicylic acid mixture) was added to each tube. Five millilitres of conc. \( \text{H}_2\text{SO}_4 \) was added and the mixture was digested by heating on rack in a fume cupboard gently at first until vigorous effervescence subsided. Heating was continued for 1 hour after digest was clear with no charred organic matter remaining. The digest was cooled and 20 ml distilled water added and the soil was allowed to settle. The supernatant solution was decanted into 100 ml volumetric flask. The process was repeated washing the sand particles and quantitatively transferring supernatant to the flask and made to the 100 ml mark. Five millilitres of 40 % \( \text{NaOH} \) and 100 ml of distilled water were added. The mixture was distilled, collecting the distillate into 5 ml of the boric acid (\( \text{H}_3\text{BO}_3 \)) solution -indicator mixture. The distillate was titrated with 0.01 M \( \text{H}_2\text{SO}_4 \) from green to pinkish end point and the titre value recorded. The soil TN was calculated using the formula in equation 7:

**Calculation**

\[
\text{Kjeldahl N (\%) = } (T - B) \times M \times \frac{2.8}{S}
\]

\( T \) = ml of standard acid with sample titration

\( B \) = ml of standard acid with blank titration
M = molarity of sulphuric acid

S = weight of soil sample in g

3.4.7 Soil Available Phosphorus

Soil available phosphorus was determined by the Mehlich double acid method (Maghanga et al., 2012). An oven–dried soil sample weighing 2.5 g was put into a 100 ml shaking bottle and 20 ml of the extracting solution (a mixture of 0.1 M HCl and 0.025 M H₂SO₄) added. The mixture was shaken for 5 minutes and filtered through a Whatman No. 40 filter paper. A 5 ml of the extract was transferred to a 25 ml flask and diluted to the mark. 5 millilitres of L-Ascorbic Acid was added to each sample and waited for the blue colour formation. After 5 minutes the concentration of P in the filtrate was determined at 830 nm wavelength using Specord 200 Plus Ultra Violet Spectrophotometer.

3.4.8 Soil Exchangeable Bases (Ca²⁺, Mg²⁺, Na⁺, and K⁺)

An air-dried 2 mm sieved soil sample weighing 5 g was put into an extraction bottle and 50 ml of 1.0 M NH₄OAc solution at pH 7.0 was added. The bottle with its content was placed in a shaking machine and shaken for one hour. At the end of the shaking, the suspension was centrifuged at 3000 rpm for 5 minutes. The supernatant solution was filtered through No. 40 Whatman filter paper. Twenty five millilitres aliquots of the extract were used for the determination of Ca, Mg, Na, and K (Rhoades, 1982). Calcium and magnesium were determined on the 210 VGP Atomic Absorption Spectrophotometer and potassium and sodium by Sherwood 410 Flame Photometer. The Cation Exchange Capacity (CEC) was calculated by summing all the exchangeable cations together as shown in equation 8:
CEC = Exch. K$^+$ + Exch. Ca$^{2+}$ + Exch. Mg$^{2+}$ + Exch. Na$^+$ .................................Equation 8

Where, CEC = Cation Exchange Capacity

Exch. = Exchangeable

### 3.4.9 Exchangeable Acidity

Soil exchangeable acidity was determined by the titration method (Robertson et al., 1999). Ten grams of 2 mm sieve soil was weighed into a 100 ml plastic extraction bottle and 50 ml of 1.0 M KCl solution was added. It was shaken for 30 minutes and the suspension was filtered into an empty clean bottle. Twenty five millilitre aliquots of the filtrate were pipetted into a 100 ml conical flask. Two to three drops of phenolphthalein indicator was added and titrated to a permanent pink end point using 0.01 M NaOH. The titre for NaOH was recorded. This represented exchangeable acidity (both H$^+$ and Al$^{3+}$). The Effective Cation Exchange Capacity (ECEC) was estimated by summation of exchangeable bases and exchangeable acidity.

### 3.4.10 Determination of Available Soil Micro-Nutrients (Zn$^{2+}$, Mn$^{2+}$, Fe$^{2+}$ and Cu$^{2+}$)

The oven-dry soil samples were extracted in a 1:10 ratio (w/v) with 0.1 M HCl. For Mn$^{2+}$, the oven-dry soil was extracted in a 1:5 ratio (w/v) with the Double acid method using a mixture of 0.1 M HCl and 0.025 M H$_2$SO$_4$. The elements (Zn$^{2+}$, Mn$^{2+}$, Fe$^{2+}$ and Cu$^{2+}$) were determined with the 210 VGP Atomic Absorption Spectrophotometer (Adetunji, 1996; Maghanga et al., 2012).

### 3.4.11 Plant Litter Analyses

Approximately 0.1 gram of oven dried (70 °C) ground leaf biomass was weighed into a labelled, dry and clean digestion tube. Five millilitres of concentrated H$_2$SO$_4$ was added to each tube and digested at 330 °C for 2 hours at the same time adding drops of H$_2$O$_2$ until the solution became
colourless. The digest was allowed to cool and 25 ml of distilled water was added and mixed well to dissolve more sediments. The mixture was filtered and topped up to the 100 ml mark with distilled water. From the digest Total N, P, K, Ca, Mg, Cu, Zn, Mn and Fe were determined (Okalebo et al., 2002). Potassium was determined on the Sherwood 410 Flame Photometer. The concentrations of calcium, magnesium, copper, zinc, iron and manganese were read on the 210 VGP Atomic Absorption Spectrophotometer. Total phosphorus was measured at 830 nm wavelength using Specord 200 Plus Ultra Violet Spectrophotometer by the Ascorbic acid indicator method and total nitrogen using Boric acid indicator by titrimetric method. Total carbon was determined using potassium dichromate by the colorimetric method.

3.5 Data Analyses and Processing

Data obtained from the laboratory analyses were subjected to statistical analysis to determine the mean values, standard deviation and the standard error of the means using SPSS 17.0 Statistical Software and Microsoft Excel 2010. Independent T-tests were used to compare the mean differences for all the tested parameters between soil samples of Eucalyptus spp. plantation and native forest. In this statistical analysis, the confidence level was set at 95 % such that if the \( P \) value is < 0.05, the test is significant and if \( P \) value is > 0.05, then there is no significant different between the variables compared.

Tables and bar charts were used to display and explain the soil physico-chemical properties of Eucalyptus spp. plantation compared to the native forest in the Thiririka sub-catchment. Correlation analyses were also used to compare strengths of relationships among some of the measured variables using SPSS 17.0 Statistical Software.
CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Effects of *Eucalyptus* spp. Plantation and Native Forest on Soil Physical Properties

The results on the soil physical properties pertaining to soil particle distribution, percentage gravimetric soil moisture content and soil bulk density under *Eucalyptus* spp. and control native forest are presented in Table 4.1.

4.1.1 Soil Texture (Particle Size Distribution)

The particle size analysis data showed that the soil under EP was clayey with sand, clay and silt contents of 13 %, 75.2 % and 12 % respectively, whiles the soils under the NF were found to be sandy clay loam with sand, clay and silt contents of 47.6 %, 27 % and 28 % respectively (Table 4.1). The soil particle size distribution found in this study was similar to those reported by Aweto and Moleele (2005). Balamurugan *et al.* (2000) and Alem *et al.* (2010) also made similar observations of soils under *Eucalyptus* spp. plantation.

4.1.2 Soil Moisture

The gravimetric soil moisture content recorded was 26.26 % and 58.04 % in the EP and NF soils respectively (Table 4.1). The soil moisture content in the EP soil was significantly lower (t (8) = -7.38, P < 0.05) than that in the NF soil. Demessie *et al.* (2012) made similar findings and attributed the lower moisture content in soils under *Eucalyptus* spp. plantation to the fact that the species is a broad-leaved plant, which needs to transpire greater amounts of water to produce a unit mass of dry matter.
This study also showed empty patches under the EP compared to a dense, continuous layer of undergrowth including *Cynodon dactylon*, *Podocarpus* sp., found under the NF. The absence of undergrowth in the EP is indicative of a reduced biodiversity. In agreement with Aweto and Moleele (2005), the sparse undergrowth and the light canopy of the EP trees can lead to a higher rate of soil water evaporation, contributing further to the reduction in soil moisture content in the EP soil relative to those under the NF vegetation, where the undergrowth could lower soil temperature and reduce evaporation to enhance soil water infiltration. These observations also agree with Cao *et al.* (2010) who found low soil moisture contents, ranging from 20.2 to 30.5% in the top soil (0–10 cm) under *Eucalyptus* spp. plantations aged from 3 to 13 years in China.

### 4.1.3 Soil Bulk Density

The soil bulk densities recorded in the EP and NF soils were 1.16 and 1.06 g cm\(^{-3}\) respectively (Table 4.1). The bulk density of the EP soil was significantly higher (t (8) = 20.39, P < 0.05) than that for NF soil. Soil bulk density is used as a measure of soil compaction and health (Field Ecology Guide, 1998). Higher soil bulk density means less amount of water held in the soil at field capacity and at lower soil bulk densities, soils are less compacted and are able to retain water (Kakaire *et al.*, 2015).

Ravina (2012) found a higher soil bulk density of 1.24 g cm\(^{-3}\) under *Eucalyptus* spp. plantation compared to 0.66 g cm\(^{-3}\) in native forest in a Brazilian soil (0-15 cm). Kolay (2000) indicated that bulk density of productive natural soils generally ranges from 1.1 to 1.5 g cm\(^{-3}\). Since the soil bulk densities found in both the EP and NF soils were within this range, the findings from the study did not confirm those of Aweto and Moleele (2005), who concluded that *Eucalyptus* spp. plantations increased soil bulk density more than the native forest in Botswana.
Table 4.1: Soil Physical Properties of *Eucalyptus* spp. Plantation (EP) and Native Forest (NF) soils (Mean ± SE).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Sand (%)</th>
<th>Clay (%)</th>
<th>Silt (%)</th>
<th>Textural class</th>
<th>Soil Moisture (%)</th>
<th>Bulk Density (g cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Eucalyptus</em></td>
<td>13 ± 0.5</td>
<td>75.2 ± 1.0</td>
<td>12 ± 1.1</td>
<td>Clay</td>
<td>26.26 ± 3.2</td>
<td>1.16 ± 0.0</td>
</tr>
<tr>
<td>Native Forest</td>
<td>47.6 ± 1.5</td>
<td>27 ± 0.5</td>
<td>28 ± 1.3</td>
<td>Sandy Clay loam</td>
<td>58.04 ± 2.8</td>
<td>1.06 ± 0.0</td>
</tr>
</tbody>
</table>

*P*-value 0.00* 0.00*

**Key**
SE = Standard error mean
*Figures followed by * means significant difference exists between the measured parameters for EP and NF at P < 0.05.

4.2 Effects of *Eucalyptus* spp. Plantation and Native Forest on Soil Chemical Properties

The results on the soil chemical properties pertaining to soil pH, total nitrogen, total organic carbon concentrations and available phosphorus of *Eucalyptus* spp. and control native forest soils are presented in Table 4.2.

4.2.1 Soil pH

The pH of the soils was 4.8 and 5.5 for EP and NF, respectively (Table 4.2). The pH of the soils under the EP (strongly acidic) was significantly lower (*t* (8) = -4.69, *P* = 0.002) than that found in the NF soil (medium acidic). The low pH of the EP is consistent with the low exchangeable bases such as Ca, Mg, and K found in the EP litter fall. Mensah (2015) reported that the bases released by litter decay can check acidification. The correlation analysis (Table 4.6) shows a positive relationship (*r* = 0.41, 0.40 and 0.43, respectively) between soil pH and exchangeable Ca, Mg, and K. This means that as soil exchangeable bases decreases, the soil pH is also reduced and vice versa. Aweto and Moleele (2005) argued that *Eucalyptus* spp. immobilize soil
exchangeable bases, especially calcium leading to low soil pH. Inferring from Honeck et al. (2011) that most nutrient elements occur in available forms at a soil pH range of 5.5 to 6.5, the NF soil was likely to be more fertile with a greater availability of plant nutrients compared to the EP soil.

These findings also agree with those of Aweto and Moleele (2005), who found that soil pH was significantly lower in soil under *Eucalyptus camaldulensis* in both the 0–10 and 10–20 cm soil depths in Botswana, compared to native Acacia forest. Similarly, Sanginga and Swift (1992) reported that soil pH was lower under the plantation of *Eucalyptus grandis* than in the native savanna woodland in Zimbabwe. Jaiyebo (1998) concluded that the soil acidity under *Eucalyptus* spp. was likely to increase with time.

### 4.2.2 Soil Available Phosphorus (P)

The mean concentration of soil available P recorded were 23.2 and 52 mg kg\(^{-1}\) for EP and NF, respectively (Table 4.2). The concentration of available P in the EP soil was significantly lower \((t (8) = -6.707, P < 0.05)\) compared to that in the NF soil. The available P in the EP soil falls below the medium sufficiency range of 26–54 mg kg\(^{-1}\) suggested by Carrow et al. (2004). The relatively lower available P registered for the EP soil may be due to the low pH value which might have resulted in higher amount of soil available P fixed/adsorbed. Aweto and Moleele (2005) reported that *Eucalyptus* spp. have a higher capacity of immobilizing phosphorus, and make them inaccessible for plant use. Berendse (1998) adds that at soil pH of below 5.5, soil trace nutrients like Aluminium (Al) availability increases to levels that are unsuitable for most plant growth and soil soluble phosphorus (P) tends to form insoluble compounds with Al and Fe in acidic soils, which are inaccessible to native plants.
These findings are in agreement with those of Polglase et al. (1992), who found that the concentration of inorganic phosphorus in the 0–5 cm depth of soil under Eucalyptus spp. plantation declined from an initial concentration of 34 to 2.3 µg g\(^{-1}\) when the plantation attained the age of 16 years in Australia. Aweto and Moleele (2005) also found that available phosphorus was low (below 5 µg g\(^{-1}\)) in soil under Eucalyptus spp. plantation in both the 0–10 and 10–20 cm depths of soil in Botswana. Furthermore, Alemie (2009) reported that available phosphorus concentration in Eucalyptus spp. plantation within 0–20 cm depth of soil was in the very low range (< 5 mg kg\(^{-1}\)) in Ethiopia.

4.2.3 Soil Total Nitrogen (TN)

The mean concentration of soil TN was recorded as 0.09 and 0.24 % for EP and NF, respectively (Table 4.2). The TN concentration found in the EP soil was significantly lower (t (8) = -21.65, P < 0.05) compared to that in the NF. Alemie (2009) found that concentration of soil TN decreased under plantations of Eucalyptus spp. in Ethiopia. Nitrogen concentration in soils is reflected in part by the rate of decomposition of the plant material (Cao et al., 2010). Previous authors have reported that Eucalyptus spp. produce litter with low nutrient concentrations, which decomposes slowly to release low concentrations of nutrients (Aweto and Moleele, 2005; Baber et al., 2006; Cao et al., 2010; Demessie et al., 2012), and coupled with the prevailing low soil pH, N mineralization from the EP litter would have been considerably slow. Additionally, Tererai et al. (2014) attributed the low total available N under Eucalyptus spp. plantations in South Africa to the high soil nutrient uptake rates of the plant. Thus, as observed in this study, the lower TN concentration found in the EP soils compared to those of the NF was not unexpected.
Monoculture *Eucalyptus* spp. plantations have been found to alter the forest species diversity due to its allelopathic effects (Pandey *et al.*, 2007; Wang *et al.*, 2007). The sparse undergrowth observed under the EP was indicative of reduced biodiversity. As regards the EP, the few plant species found growing were usually located on the fringes of the EP some 2 or 3 m away from the plantation. These were mostly *Cynodon dactylon* grass (Plate 4.1) and *Acacia mearnsii* (popularly called “wattle” tree) (Plate 4.2). On the contrary, the NF was associated with undergrowth consisting of many different plant species including *Cynodon dactylon, Podocarpus* sp., *Acacia mearnsii, Croton macrostachyus*, and many other legume species. This observation indicates greater biodiversity and hence a greater variety of litter fall, which would possibly result in balanced ecosystem functioning due to more soil organic matter accumulation and probably a faster rate of decomposition to form humus. These observations confirm report by FAO (1993) that the biodiversity of a natural forest is often greater than that of *Eucalyptus* spp. plantations as the species composition of natural ecosystems are very diverse, whilst that of *Eucalyptus* spp. plantations is limited. Forrester *et al.* (2006) also demonstrated that mixing *Acacia mearnsii* with *Eucalyptus globulus* increased the quantity and rates of N and P cycled through aboveground litter fall when compared with *Eucalyptus globulus* monocultures. Other researchers have also found higher quantities of N and P cycled through litter fall in mixtures of N-fixing trees and non-N-fixing than non-leguminous monoculture *Eucalyptus* spp. plantations alone (Binkley and Ryan, 1998; Parrotta, 1999).
Plate 4.1: *Cynodon dactylon* grass growing on the fringes of *Eucalyptus* spp. Plantation in Thiririka sub-catchment.

Plate 4.2: *Acacia mearnsii* (“Wattle” tree) growing on the fringes of *Eucalyptus* spp. plantation in Thiririka sub-catchment.

4.2.4 Soil Total Organic Carbon (TOC)

The concentration of soil TOC recorded in the EP and NF were 0.83 and 2.23 %, respectively (Table 4.2). The TOC in soils of the EP was significantly lower (t (8) = -38.86, P < 0.05) than in the soils of NF. These values translate to soil organic matter concentrations of 2.467 and 6.613 % for EP and NF, respectively. Organic matter contents are considered low if it is less than 4 %,
medium if it is between 4 % and 8 %, and high if it is above 8% (University of Connecticut, Cooperative Extension System, 2003). The relatively lower TOC in EP soil is possibly due to the differences in the rates of plant litter decomposition under the EP and NF vegetation (Demessie et al., 2012). Sharmsher et al. (2002) found that 83 % of the soil samples under Eucalyptus spp. plantation areas were found low (< 1%) in organic matter. Jan et al. (1996) also made observation of reduced organic matter concentrations in Eucalyptus spp. soils relative to Shorea robusta native forest soil in Uttar Pradesh, Pakistan.

Similar results have also been found by Bernhard-Reversat (1998) in Keur Maktar, Senegal, where the amount of organic carbon in the 0–10 cm depth of native Acacia seyal woodland was twice the concentration in corresponding layer of Eucalyptus spp. plantation. Again, in the Sudan Savanna zone of Cameroon, total carbon in the topsoil of Eucalyptus spp. plantation fallow declined while that of Acasia polyacantha plantation fallow increased significantly over a period of seven years (Brady and Weil, 1996). Furthermore, the organic carbon levels under 5 year and 10 year plantations of Eucalyptus spp. plantation, near Pointe Noire, Congo, were below the level in a savanna control plot, suggesting that there was no substantial build-up of organic carbon in soil under the Eucalyptus spp. plantation during the first 10 years following plantation establishment (Brady and Weil, 1996).
Table 4.2: Soil pH, available P, total N and total organic carbon of EP and NF Soils

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Soil Available P (mg kg⁻¹)</th>
<th>Soil pH</th>
<th>Total N (%)</th>
<th>Total organic carbon (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalyptus</td>
<td>23.2</td>
<td>4.8</td>
<td>0.09</td>
<td>0.83</td>
</tr>
<tr>
<td>Natural Forest</td>
<td>52.0</td>
<td>5.5</td>
<td>0.24</td>
<td>2.23</td>
</tr>
</tbody>
</table>

P-value

|                | 0.001* | 0.002* | 0.00* | 0.00* |

Figures followed by * means significant difference exists between the measured parameters for EP and NF at P < 0.05

4.3 Effects of Eucalyptus spp. Plantation and Native Forest on Soil Exchangeable Cations, Cation Exchange Capacity (CEC), Exchangeable Acidity (Al³⁺ + H⁺), and Effective Cation Exchange Capacity (ECEC)

4.3.1 Soil Exchangeable Cations (Ca²⁺, Mg²⁺, K⁺ and Na⁺)

Table 4.3 shows the concentrations of exchangeable cations and the CEC found in the EP and NF soils studied. Among the exchangeable cations, the concentration of exchangeable calcium was highest with values 5.34 and 7.29 c mol kg⁻¹ for soils under EP and NF, respectively. However, these were not significantly different from each other. Similarly, no significant differences were found among the concentrations of Mg, Na and K in the EP and NF soils. This observation could not be explained as the EP soil was strongly acidic compared to the NF soil.

Bailey et al. (2005) reported that acidification usually leads to depletion of the soil base cations (e.g., K⁺, Mg²⁺, Ca²⁺) due to replacement of the basic cations by Al³⁺ and H⁺ ions at the exchange site. Aweto and Moleele (2005) also indicated that low soil pH leads to low soil base saturation.
Contrary to observations made in this study, Aweto and Moleele (2005) found lower exchangeable nutrient cation (calcium, magnesium and potassium) of both 0–10 and 10–20 cm depths in soil under *Eucalyptus* spp. plantation, explaining that the *Eucalyptus* sp. immobilizes soil nutrients in their standing biomass faster than they recycle such nutrients back to the topsoil, which resulted in soil exchangeable bases depletion over time. Bernhard-Reversat (1988) and Jaiyebo (1998) indicated a reduced concentration of exchangeable bases under plantations of *Eucalyptus* spp. in Senegal and northern Nigeria, respectively.

4.3.2 Soil Cation Exchange Capacity (CEC)

Although the Cation exchange capacity (CEC) recorded in the EP (7.58) soil was lower than in the NF soil (9.99 c mol kg\(^{-1}\)) (Table 4.3), the figures were found to be statistically similar. This was not unexpected as the concentrations of the exchangeable actions were similar in both soils. The cation exchange capacities in both soils were greater than 4 c mol kg\(^{-1}\) but lower than 10 c mol kg\(^{-1}\). These values reflect the highly weathered nature of the soils on which the plantations were developed. Thus, the litter from the vegetation would have significantly contributed to the CEC recorded in the soils.

4.3.3 Soil Exchangeable Acidity (Al\(^{3+}\) + H\(^{+}\))

The concentrations of soil exchangeable acidity in the EP and NF were 0.32 and 0.16 c mol kg\(^{-1}\), respectively (Table 4.3). The higher exchangeable acidity (P < 0.05) found in the EP soil is attributed to the low soil pH. Oyedele *et al.* (2009) explained that hydrolysis of Al\(^{3+}\) ions contribute to the development of soil acidity; therefore, increasing soil exchangeable acidity (H\(^{+}\) and Al\(^{3+}\)) concentration would have lowered soil pH in the EP soils. The correlation analysis (Table 4.6) shows a strong negative relationship (r = -0.87) between soil the pH and soil
exchangeable acidity. In this regard, Frimpong et al. (2014) reported that when the soil pH drops below 5.5, aluminum and manganese toxicities may occur.

### 4.3.4 Soil Effective Cation Exchange Capacity (ECEC)

In terms of effective cation exchange capacity (ECEC), EP recorded 7.904 c mol Kg\(^{-1}\) and 10.154 c mol Kg\(^{-1}\) for NF (Table 4.3). There was no significant difference \((t (8) = -772, \ P = 0.491)\) between the EP and NF.

#### Table 4.3: Concentration of soil exchangeable cations, exchangeable acidity, CEC and ECEC in EP and NF soils.

<table>
<thead>
<tr>
<th>Exchangeable Cations</th>
<th>Eucalyptus spp. (c mol Kg(^{-1}))</th>
<th>Native forest (c mol Kg(^{-1}))</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium</td>
<td>0.52</td>
<td>0.44</td>
<td>0.66</td>
</tr>
<tr>
<td>Calcium</td>
<td>5.34</td>
<td>7.29</td>
<td>0.46</td>
</tr>
<tr>
<td>Potassium</td>
<td>0.82</td>
<td>1.29</td>
<td>0.46</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.91</td>
<td>0.97</td>
<td>0.83</td>
</tr>
<tr>
<td>CEC</td>
<td>7.58</td>
<td>9.99</td>
<td>0.46</td>
</tr>
<tr>
<td>Acidity (H(^+) + Al(^{3+}))</td>
<td>0.32</td>
<td>0.16</td>
<td>0.001*</td>
</tr>
<tr>
<td>ECEC</td>
<td>7.90</td>
<td>10.15</td>
<td>0.49</td>
</tr>
</tbody>
</table>

*Figures followed by * means significant difference exists between the measured parameters for EP and NF at \(P < 0.05\)

### 4.4 Effects of *Eucalyptus* spp. Plantation and Native Forest on Soil Available Micro-Nutrients (Mn\(^{2+}\), Cu\(^{2+}\), Zn\(^{2+}\) and Fe\(^{2+}\))

The mean soil available micro-nutrient concentration in EP and NF soils are presented in Table 4.4. The mean concentration of soil Mn\(^{2+}\) recorded were 3.33 and 1.76 mg kg\(^{-1}\) for EP and NF, respectively. The soil Mn concentration registered for EP was significantly higher (3.33 mg kg\(^{-1}\), \(P < 0.05\)) compared to that in the NF soil (1.76 mg kg\(^{-1}\)). The higher Mn recorded for the EP is
attributable to the strongly acidic nature and reduced pH of the EP soil. Manganese toxicity is more common in acidic soils. Inferring from the correlation analysis (Table 4.6), there was a moderate negative relationship \((r = -0.42)\) between the soil pH and available Mn. This means that reducing soil pH increases concentration of soil available Mn and vice versa.

Frimpong et al. (2014) reported that when the pH of soils drop below 5.5, plant growth is reduced due to metal toxicities such as aluminum and manganese toxicities. Horneck et al. (2011) also indicated that availability of most micro-nutrients such as Mn and Fe decreases as pH increases and vice versa. They added that soil test Mn values between 1 and 5 mg kg\(^{-1}\) are usually sufficient. The soil Mn found in both soils was within this range.

The mean concentration of Zn\(^{2+}\) found in the EP and NF soils were 11.91 and 19.0 mg kg\(^{-1}\), respectively. In agreement with those of Tererai et al. (2014), the concentration of Zn under the EP was significantly lower \((P < 0.05)\) than that in NF soils.

In terms of Fe\(^{2+}\), EP soils registered mean concentration at 95.28 and 62.78 mg kg\(^{-1}\) for NF soils. For Cu\(^{2+}\), EP recorded mean concentration of 1.08 mg Kg\(^{-1}\) and 1.434 mg kg\(^{-1}\) for NF. Soil available Cu\(^{2+}\) and Fe\(^{2+}\) concentrations found in both soils were however not found to be statistically significant. Similar to these findings, Tererai et al. (2014), reported that soil available Cu was lower in the heavily invaded site with *Eucalyptus* spp. compared to the un-invaded site in the Berg watershed in South Africa but found no significant difference between the two sites.
Table 4.4: Soil available micro-nutrient concentrations in EP and NF soils (Mean ± SE).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Manganese (mg Kg(^{-1}))</th>
<th>Copper (mg Kg(^{-1}))</th>
<th>Iron (mg Kg(^{-1}))</th>
<th>Zinc (mg Kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eucalyptus</td>
<td>3.33 ± 0.0</td>
<td>1.08 ± 0.2</td>
<td>95.28 ± 24.0</td>
<td>11.91 ± 1.9</td>
</tr>
<tr>
<td>Native Forest</td>
<td>1.76 ± 0.0</td>
<td>1.43 ± 0.1</td>
<td>62.78 ± 4.2</td>
<td>19.00 ± 1.1</td>
</tr>
</tbody>
</table>

| P-value        | 0.00*                      | 0.23                    | 0.25                  | 0.01*                |

Key
SE = Standard error mean
Figures followed by * means significant difference exists between the measured parameters for EP and NF at P < 0.05

4.5 Plant Nutrients in *Eucalyptus* spp. Plantation and Native Forest Litter Fall

The results on the amount of plant nutrients: total potassium, total calcium, total magnesium, total nitrogen, total organic carbon, total phosphorus, and micro-nutrients (manganese, iron, copper and zinc) in EP and NF litter fall are presented and discussed in the following sections.

4.5.1 Total Potassium, Total Calcium and Total Magnesium Concentrations in EP and NF Plant Litter

Figure 4.1 shows concentrations of total potassium (K), total calcium (Ca) and total magnesium (Mg) in plant leaf litter fall from EP and NF.

The concentrations of total K in plant leaf litter recorded were 0.03 and 0.30 % for EP and NF, respectively. The total K in EP leaf litter was significantly lower (t (8) = -93.69, P < 0.05) than that in the NF leaf litter. Concentrations of total Ca were 0.31 and 0.83 % for EP and NF, respectively. The concentration of total Ca in the EP leaf litter was significantly lower (t (8) = -165.387, P < 0.05) than that in NF leaf litter. Also, concentration of total Mg was registered as
0.03 % for EP and 0.14 % for NF. The total plant litter Mg from the EP was significantly lower 
(t (8.00) = -187.03, P < 0.05) than that from the NF.

The lower concentrations of total K, Ca and Mg observed in the EP leaf litter can be attributed to 
higher immobilization rate of the *Eucalyptus* spp. leaf litter. As observed by Aweto and Moleele 
(2005), *Eucalyptus* spp. immobilize soil nutrients in their standing biomass faster than they 
recycle such nutrients back to the topsoil. Thus, the lower concentrations of plant total K, Ca, 
and Mg could have also resulted in low level of the soil base saturation (K, Ca, and Mg) 
observed in the soil from the EP site.

Bray and Graham (2004) further add that litter fall constitutes a pathway for both energy and 
nutrient transfer between plants and soils in forest land. Thus, the low soil pH observed for the 
EP soil could also account for the low concentrations of plant litter total K, Ca, and Mg, as acidic 
soils inhibit the rate of organic matter decomposition to release such nutrients (Castro-Díez et al., 
2011).

The monoculture nature of the EP altered the plant biodiversity and undergrowth. In this way, 
the EP litter fall decreased in nutrient recycling and release, which could have resulted in lower 
concentrations of total Ca, Mg, and K in EP plant litter. The NF on the other hand, consisted of 
mixed species with improved biodiversity, faster decomposition to release nutrients, which 
accounted for higher concentrations of total Ca, Mg, and K in its litter. Wang *et al.* (2007) and 
Pandey *et al.* (2007) reported that when natural forests are replaced by monoculture plantations, 
forest species diversity decreases and eventually alter the pattern of nutrient release through 
decomposition.
4.5.2 Total Nitrogen, Total Organic Carbon and Total Phosphorus Concentrations in EP and NF Plant Litter

4.5.2.1 Plant Litter Total N Concentration

The mean concentrations of total N in plant litter were recorded as 1.05 and 2.11 % for EP and NF, respectively (Table 4.5). Total N in plant litter for EP was significantly lower (t (8) = -171.14, P < 0.05) than that in the NF plant litter fall. The lower concentration of total N in EP plant litter could be attributed to microbial immobilization of N due to lower mineralization rate from the high C/N ratio EP litter. Castro-Díez et al. (2011) reported that Eucalyptus spp. produce litter that has high C/N ratios, which results in lower net N mineralization.

The monoculture nature and sparse undergrowth observed under the EP is indicative of reduced plant biodiversity due to its allelopathic effects. The NF consisted of undergrowth with different plant species, including many leguminous species. These observations indicate improved and
greater biodiversity under the NF, which contributed to higher total N in its plant litter fall. Binkley and Ryan (1998), Parrotta (1999), Forrester et al. (2006) and Alem et al. (2010) indicated that higher quantities of N and P are cycled through litter fall in mixtures of N-fixing trees and non-N-fixing than non-leguminous monoculture Eucalyptus spp. plantations alone. Briones and Ineson (1996) add that leaves of Eucalyptus spp. mixed with other species decompose in a relatively faster rate to release and make total N more available as compared to Eucalyptus spp. leaves only.

4.5.2.2 Plant Litter Total Phosphorus Concentration

The concentrations of total P in plant litter fall were 0.15 and 0.17 % for EP and NF, respectively (Table 4.5). Concentration of total P in EP litter fall was significantly lower ($t (8) = -4.53$, $P < 0.05$) than that in NF litter fall. This is could be attributed to P immobilization in the leaf litter of Eucalyptus spp. plantation. Also, low litter nutrient problems are a major feature of monoculture fast-growing Eucalyptus spp. that immobilize nutrients in their biomass faster than they recycle them back to the soil (Aweto and Moleele, 2005).

4.5.2.3 Plant Litter Total Organic Carbon Concentration

The mean concentration of plant total organic carbon (TOC) was recorded as 52.12 and 48.18 % for EP and NF, respectively (Table 4.5). The TOC concentration in the EP litter fall was significantly higher ($t (8) = 3.584$, $P = 0.007$) than that in NF litter fall. Demessie et al. (2012) made similar observations and attributed the lower concentration of plant litter in the native forest to losses due to recycling of nutrients to other parts of the plant during leaf senescence. Leite et al. (2010) also found relatively greater concentration of total organic carbon in plant litter from Eucalyptus spp. than in the native pasture plantation in Brazil, which they attributed to the greater amount of residues produced by the Eucalyptus spp. forest (leaves, branches, bark
and especially roots). These findings are also in agreement with those of Marcela et al. (2009), who found that *Eucalyptus grandis* leaf litter had higher content of total organic carbon than the comparing native forest.

Aweto and Moleele (2005) argued that *Eucalyptus* spp. plantation does not result in a substantial destabilization of litter supply to the soil and the subsequent process of decomposition of plant litter to form organic matter. They added that this is to be expected as both ecosystems, the native forest and the *Eucalyptus* spp. plantation, are dominated by trees. Young (1989) pointed out that where the vegetation species are trees, they provide both woody and herbaceous residues, and thus a high range in quality and quantity both of above–ground litter and root residues, and hence greater amount of organic matter provided by the plant litter. This phenomenon of EP producing higher quantities of plant litter explains why they have been encouraged in reclaiming degraded lands because of its ameliorative advantage (Jagger and Pender, 2000; Mishra et al. 2003; Aweto and Moleele, 2005; Morgan, 2005).

**Table 4.5: Concentrations of total nitrogen, total organic carbon and total phosphorus in EP and NF plant litter (Mean ± SE).**

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Total Nitrogen (%)</th>
<th>Total Organic Carbon (%)</th>
<th>Total Phosphorus (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EP</td>
<td>1.05 ± 0.0</td>
<td>52.12 ± 1.0</td>
<td>0.15 ± 0.0</td>
</tr>
<tr>
<td>NF</td>
<td>2.11 ± 0.0</td>
<td>48.18 ± 0.4</td>
<td>0.17 ± 0.0</td>
</tr>
</tbody>
</table>

*P*-value

- **Total Nitrogen (P-value):** 0.00*  
- **Total Organic Carbon (P-value):** 0.007*  
- **Total Phosphorus (P-value):** 0.002*

**Key**
- EP = *Eucalyptus* spp. plantation
- NF = Native forest
- SE = Standard error mean
4.5.3 Total Cu\(^{2+}\), Total Fe\(^{2+}\), Total Zn\(^{2+}\) and Total Mn\(^{2+}\) Concentrations in EP and NF

**Plant Litter**

**4.5.3.1 Plant Litter Total Cu\(^{2+}\) Concentration**

The mean concentration of total Cu in plant litter fall was lowest among the trace-elements measured and was recorded as 4.36 and 16.16 \% for EP and NF respectively (Figure 4.2). Total Cu in litter fall from EP was significantly lower (t (8) = -2318.88, \(P < 0.05\)) than that in the NF plant litter. This could be attributed to the fact that *Eucalyptus* spp. plant litter has a lower capacity of accumulating Cu in the plant litter, due to higher immobilization rate of nutrients in the plant biomass (Hou *et al*., 2010). The higher level of total Cu registered by NF could also indicate that the NF plant litter accumulates greater concentration of Cu from the soil and limit their bioavailability (Hogarh *et al*., 2015). Furthermore, the lowest leaf litter Cu concentration recorded among the other trace-elements could partly be due to low mobility of the element in plants (Maiti *et al*., 2004).

**4.5.3.2 Plant Litter Total Zn\(^{2+}\) Concentration**

The mean concentrations of total Zn in plant litter were 12.24 and 75.90 \% for EP and NF, respectively (Figure 4.2). Total Zn in litter fall from EP was significantly lower (t (8) = -631.57, \(P < 0.05\)) than that in the NF litter fall. This could be attributed to the fact that *Eucalyptus* spp. plant litter has a lower capacity of accumulating Zn in its plant litter, due to higher immobilization rate of nutrients in the plant biomass (Hou *et al*., 2010). The higher Zn recorded under the NF also could be attributed to the fact that the plant litter immobilizes Zn contaminant in the soil and limit their bioavailability (Hogarh *et al*., 2015) for plant uptake.
4.5.3.3 Plant Litter Total Mn$^{2+}$ and Total Fe$^{2+}$ Concentrations

The mean concentrations of total Fe in litter fall were registered as 40.28 and 144.60 % for EP and NF, respectively (Figure 4.2). Total Fe in plant litter from the EP was significantly lower ($t (8) = -337.75, P < 0.05$) than that in NF litter fall. The mean concentrations of total Mn in plant litter were 448.40 and 571.73 % for EP and NF, respectively. Total Mn in litter from the EP was significantly lower ($t (8) = -304.02, P < 0.05$) than that in NF litter fall. The lower plant litter concentration of total Fe and Mn could be due to the monoculture nature of the *Eucalyptus* spp. plantation that has lower capacity of accumulating the trace-elements (Fe and Mn) in the leaf litter (Hou *et al*., 2010).

The higher concentration of the trace-elements (Fe and Mn) in the NF plant litter could be attributed to the mixed species nature observed under the forest. Maiti *et al*. (2004) indicated that under mixed forest of *Acacia mangium, Acacia auriculiformis* and *Gmelina aborea*, average plant total Fe accumulation was highest within the range of 110 to 292 mg kg$^{-1}$ than the counterpart single species forest.
Figure 4.2: Total Cupper (Cu), Total Iron (Fe), Total Zinc (Zn) and Total Manganese (Mn) concentrations in EP and NF Plant Litter.

4.6 Testing for Hypothesis i, ii and iii

4.6.1 Hypothesis that no significant differences exist between EP and NF in their effects on soil physical properties (soil moisture and soil bulk density)

This hypothesis was tested using the student’s t-test by establishing the differences between individual means of EP and NF soils for soil moisture and soil bulk density at 95% confidence interval. The results showed that there was a significant difference ($P < 0.05$) between EP and NF for soil moisture and soil bulk density (Table 4.1). Therefore, the hypothesis that no significant differences exist between *Eucalyptus* spp. plantations and native forest in their effects on soil physical properties (soil moisture and soil bulk density) is rejected.
4.6.2 Hypothesis that no significant differences exist between EP and NF in their effects on soil chemical properties (pH; total organic carbon; available phosphorus; total nitrogen; exchangeable bases; exchangeable acidity; cation exchange capacity; and soil micro-nutrients (Fe, Zn, Cu and Mn)).

The results of the student’s t-test showed that there was a significant difference \((P < 0.05)\) between the means of EP and NF for soil pH, soil available phosphorus, total nitrogen, and total organic carbon (Table 4.2). These parameters were significantly lower in the EP soil than for the NF soils. In addition, soil exchangeable acidity varied significantly \((P < 0.05)\) between EP and NF (Table 4.3). In terms of soil exchangeable bases (Ca, Mg, K, and Na), there were no significant variations \((P > 0.05)\) between EP and NF (Table 4.3). For soil micro-nutrients (Fe, Zn, Cu and Mn), Mn and Zn differed significantly \((P < 0.05)\) between EP and NF, whilst Cu and Fe did not vary significantly \((P > 0.05)\) between the two treatments (Table 4.4). The null hypothesis that no significant differences exist between EP and NF in their effects on soil chemical properties is rejected for soil pH, soil available phosphorus, total nitrogen, total organic carbon, soil exchangeable acidity, soil available Mn and Zn, and accepted for soil exchangeable bases (Ca, Mg, K, and Na).

4.6.3 Hypothesis that no significant differences exist between EP and NF litter fall in their nutrient (C, N, P, K, Ca, Mg, Fe, Zn, Cu and Mn) amounts.

The results of the student’s t-test showed that total potassium, total calcium, and total magnesium of plant litter fall varied significantly \((P < 0.05)\) between EP and NF (Figure 4.1). Plant total N and total P for EP litter were significantly lower \((P < 0.05)\) than that of NF (Table 4.5). On the other hand, plant litter TOC of the EP was significantly higher \((P < 0.05)\) than that of NF (Table 4.5). The mean concentration of plant litter total Copper, Iron, Zinc, and Manganese, were all
significantly lower ($P < 0.05$) in EP than that of NF (Figure 4.1). The null hypothesis that no significant differences exist between EP and NF litter fall in their nutrient amount is therefore rejected for all parameters.

**Table 4.6: Correlations Between Some Soil Parameters for EP soils**

<table>
<thead>
<tr>
<th>Soil Parameters</th>
<th>Pearson Correlation ($r$)</th>
<th>Relationship Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil pH and available Mn</td>
<td>-0.42</td>
<td>Moderate negative relationship</td>
</tr>
<tr>
<td>Soil pH and available Fe</td>
<td>0.33</td>
<td>Moderate positive relationship</td>
</tr>
<tr>
<td>Soil pH and available Cu</td>
<td>0.38</td>
<td>Moderate positive relationship</td>
</tr>
<tr>
<td>Soil pH and available Zn</td>
<td>0.42</td>
<td>Moderate positive relationship</td>
</tr>
<tr>
<td>Soil pH and available P</td>
<td>-0.47</td>
<td>Moderate negative relationship</td>
</tr>
<tr>
<td>Soil pH and ExAcidity</td>
<td>-0.87</td>
<td>Strong negative relationship</td>
</tr>
<tr>
<td>Soil ExAcidity and ExCa</td>
<td>-0.26</td>
<td>Weak negative relationship</td>
</tr>
<tr>
<td>Soil ExAcidity and ExMg</td>
<td>-0.25</td>
<td>Weak negative relationship</td>
</tr>
<tr>
<td>Soil ExAcidity and ExK</td>
<td>-0.31</td>
<td>Moderate negative relationship</td>
</tr>
<tr>
<td>Soil pH and ExCa</td>
<td>0.41</td>
<td>Moderate positive relationship</td>
</tr>
<tr>
<td>Soil pH and ExMg</td>
<td>0.40</td>
<td>Moderate positive relationship</td>
</tr>
<tr>
<td>Soil pH and ExK</td>
<td>0.43</td>
<td>Moderate positive relationship</td>
</tr>
<tr>
<td>Soil pH and TN</td>
<td>0.95</td>
<td>Strong positive relationship</td>
</tr>
<tr>
<td>Soil pH and TOC</td>
<td>0.55</td>
<td>Strong positive relationship</td>
</tr>
<tr>
<td>Soil TN and TOC</td>
<td>0.78</td>
<td>Strong positive relationship</td>
</tr>
</tbody>
</table>
CHAPTER FIVE
SUMMARY OF FINDINGS, CONCLUSION AND RECOMMENDATIONS

5.1 Summary of Key Findings

Based on soil and plant litter samples collected from the field and laboratory analyses the following findings were made:

The particle size analysis of the soils showed that the area under Eucalyptus spp. plantation was predominantly clayey whilst soils under the native forest (control) were predominantly sandy clay loam. The percentage soil moisture of the Eucalyptus spp. plantation was lower (P < 0.05) with mean value of 26.26 % compared with that of the control native forest of value 58.04 %. The soil bulk density under the Eucalyptus spp. plantation (1.16 g cm\(^{-3}\)) was significantly higher (P < 0.05) compared to that of the control plot of native forest (1.06 g cm\(^{-3}\)). The soil bulk density under the Eucalyptus spp. plantation, however, fell within the acceptable bulk density range of 1.1 to 1.5 g cm\(^{-3}\) for productive soils as indicated by Kolay (2000).

The pH level of the Eucalyptus spp. plantation (4.8) was significantly lower (P < 0.05) compared with the control native forest (5.5). The total N found for the Eucalyptus spp. (0.09 %) was significantly lower (P < 0.05) compared to that of the control native forest (0.24 %). The mean soil TOC was recorded as 0.832 and 2.23 % for soils under Eucalyptus spp. plantation and native forest respectively. The level of TOC in soils of the Eucalyptus spp. plantation was found to be significantly lower (P < 0.05) than that of the soils of the control native forest.

Lower exchangeable cations (Ca, Mg, and K) concentration was recorded under the Eucalyptus spp. plantation compared with the control native forest. However, no significant differences (P > 0.05) were found between Eucalyptus spp. plantation and native forest. Accumulation of soil
available P under *Eucalyptus* spp. was significantly lower (23.2, P < 0.05) compared to that in the NF soil (52 mg kg⁻¹).

In terms of soil micro-nutrients, soil Mn concentration registered for EP was significantly higher (3.33 mg kg⁻¹, P < 0.05) compared to that in the NF soil (1.76 mg kg⁻¹). The level of soil available Zn under the EP was significantly lower (11.91; P < 0.05) than that of soils under the control NF soil (19.0 mg kg⁻¹). No significant difference was observed between the EP and NF in terms of available Cu.

Total potassium (K), total calcium (Ca), and total magnesium (Mg) of plant leaf litter fall were all significantly lower in EP than in control NF. Plant total N and total P recorded for the EP litter were all significantly lower (P < 0.05) than that of NF. On the other hand, plant litter TOC of the EP was significantly higher than that of NF. The mean concentration of total plant litter trace elements, Cupper, Iron, Zinc, and Manganese, were all significantly lower (P < 0.05) in EP litter than that of NF.

### 5.2 Conclusion

The results obtained in this study indicated that *Eucalyptus* spp. plantation significantly decreased the soil moisture and lowered the soil pH, leading to a decline in soil total nitrogen and soil total organic carbon concentrations, as well as increased concentration of soil available micro-nutrients such as manganese and iron. Soils under the *Eucalyptus* spp. were also found to have significant higher soil exchangeable acidity, which would have caused decline in soil available phosphorus concentration, due to increased phosphorus fixation rendering it unavailable for plant use. Decomposition of the *Eucalyptus* spp. litter also caused significant
decline in concentrations of plant total N and total P, due to higher rates of immobilization of these nutrients in the *Eucalyptus* spp. litter.

In conclusion, the study rejected the null hypothesis that no significant differences exist between *Eucalyptus* spp. plantations and native forest in their effects on soil physical properties (soil moisture and soil bulk density). The null hypothesis that no significant difference exist between EP and NF in their effects on soil chemical properties was also rejected for soil pH, soil available phosphorus, total nitrogen, total organic carbon, soil exchangeable acidity, soil available Mn and Zn, and accepted for soil exchangeable bases (Ca, Mg, K, and Na). The null hypothesis that no significant differences exist between EP and NF litter fall in their nutrient amount was therefore rejected for all parameters.

The study demonstrated that sole cultivation of *Eucalyptus* spp. had the tendency to affect the soil physico-chemical properties and so it is advisable to interplant *Eucalyptus* spp. with other leguminous species, in addition to good agronomic practices such as nitrogenous and phosphate fertilizer application to replenish the loss of essential soil nutrients such as N and P associated with *Eucalyptus* spp. planting and also to ensure sustainability of *Eucalyptus* spp. cultivation on the soil resources.

### 5.3 Recommendations

i. The soil should be possibly limed to increase soil pH and base saturation at the end of each rotation before replanting. This will make soil exchangeable cations (such as Ca, Mg, and K), soil nitrogen and phosphorus which are mainly deficient in *Eucalyptus* spp. plantations available for plant growth.
ii. Planting of *Eucalyptus* spp. should be supplemented with fertiliser application using appropriate nitrogenous and phosphate fertilisers. This will ensure that soil nutrients such as nitrogen and phosphorus are not exhausted.

iii. Leguminous species should be planted at the site where *Eucalyptus* spp. plantation was harvested previously to help quicken and restore the lost fertility. This will ensure successful plantation of the next crop on the site.

iv. For sustainability of the water resources and to ensure food security, *Eucalyptus* spp. should not be planted in close proximity to water sources in the Thiririka sub-catchment since the extensive root nature of the specie sucks, reduces and dries up water points.

v. Policy on *Eucalyptus* spp. planting that it should be planted 15 m away from water sources and 6 m away from the neighbour’s farm should be enforced.

### 5.4 Areas for Further Research

Potential areas for further research and *Eucalyptus* spp. plantation management and sustainability in the sub-catchment include:

i. Allelopathic effects of *Eucalyptus* spp. on neighbouring plants and crop productivity

ii. Effects of *Eucalyptus* spp. on water resources

iii. Effects of *Eucalyptus* spp. on soil biological properties

iv. Farmers perception on the environmental effects of *Eucalyptus* spp. plantation

v. Effects of *Eucalyptus* spp. plantation on biodiversity and undergrowth population
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## APPENDICES

### Table 5.1: Sample Size, Means, Standard Deviations and Standard Error Means of Tested Soil Physico-chemical Parameters

<table>
<thead>
<tr>
<th>Soil Parameter</th>
<th>TREATMENT</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAND</td>
<td>EUCALYPTUS</td>
<td>5</td>
<td>13.0000</td>
<td>1.00000</td>
<td>.44721</td>
</tr>
<tr>
<td></td>
<td>NATURAL FOREST</td>
<td>5</td>
<td>47.6000</td>
<td>3.28634</td>
<td>1.46969</td>
</tr>
<tr>
<td>CLAY</td>
<td>EUCALYPTUS</td>
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<td>75.2000</td>
<td>2.28035</td>
<td>1.01980</td>
</tr>
<tr>
<td></td>
<td>NATURAL FOREST</td>
<td>5</td>
<td>27.0000</td>
<td>1.00000</td>
<td>.44721</td>
</tr>
<tr>
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<td>EUCALYPTUS</td>
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<td>12.0000</td>
<td>2.44949</td>
<td>1.09545</td>
</tr>
<tr>
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<td>28.0000</td>
<td>2.82843</td>
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</tr>
<tr>
<td>SM</td>
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Table 5.2: Sample Size, Means, Standard Deviations and Standard Error Means of Tested Plant Litter Parameters

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Figure 5.1: Soil textural triangle showing the percentages of sand, silt and clay in the textural classes. Source: Bashour and Sayegh (2007).