EFFECTS OF NITROGENOUS FERTILIZER APPLICATION RATES AND INTERVALS AND PRUNINGS MANAGEMENT ON SOIL PROPERTIES, MATURE LEAF NUTRIENTS AND TEA YIELDS IN KENYA

BY

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN CHEMISTRY

SCHOOL OF PHYSICAL AND BIOLOGICAL SCIENCES

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DECLARATION

I certify that the work presented herein is my original work and this thesis has not been presented for a degree in Maseno University or any other recognized University. All sources of information have been supported by relevant citations.

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ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to Professor Philip O. Owuor who was my thesis advisor and supervisor. The door to Professor Owuor's office was always open whenever I had questions concerning my research. His patience, motivation, immense knowledge and inspiration greatly contributed towards completion of this work. I would also like to acknowledge Dr David M. Kamau and Dr Bowa O. Kwach for their encouragement, insightful comments and endless support that enabled me complete this work.

The National Commission for Science, Technology and Innovation (NACOSTI) is greatly appreciated for the financial support during this work. I also thank the managers of Tea Research Institute (TRI), Kericho, for availing their laboratory facilities and personnel during the entire period of data collection. Special thanks to the TRI laboratory staff and particularly, Mr. Robert Bii, Mr Methusela Rop, Mr. Joel Cheruiyot, Mr L. Kimutai, Ms Betty Cherotich and Mr. J. Nyandoro for their unreserved assistance during laboratory work.

Special regards to my fellow postgraduate student and friend, Mr. Robert Ombori with whom we walked together the difficult path in pursuit of knowledge. He provided me with unfailing support throughout my years of study. I must also express my profound gratitude to those not mentioned but who assisted me towards completion of this work.

My heartfelt appreciation is extended to my beloved wife Leah Amoit for giving me unfailing support and taking good care of our children during the entire period of my study.

Lastly, I thank the Almighty God for granting me favour, good health, determination and wisdom during this work.

DEDICATION

This work is dedicated to my beloved sons Samuel Nahando and Jared Wamalwa and daughters Patience Nanjala and Rose Nafuna.

ABSTRACT

High tea production depletes soil nutrients through harvesting. Leaching, surface run-offs and fixation also degrade soils. To improve soil quality and tea production, lost nutrients are replenished. In Kenya, Nitrogen Phosphorus Potassium Sulphur (NPKS) fertilizer application at rates between 100 and 250 kgN/ha/year is recommended in single/split doses. Nitrogen application improves tea yields but degrades soils. Single annual application may be uneconomical. Biennial NPKS application gives similar yields as annual NPKS application under short term trials. It is not established if such interval of fertilizer application can influence soil and leaf nutrients to levels that can sustain high tea yields. Pruning rejuvenates growth and maintains plucking tables of tea bushes. Prunings left *in-situ* may return nutrients to soils to improve tea yields and soil quality. Farmers in smallholder tea sector have been getting low yields probably due to removal of prunings. It is unknown if removal of prunings reduces soil nutrients to levels that influence leaf nutrients and yields. This study assessed effects of rates and intervals of NPKS fertilizer application and pruning management on soil and mature leaf nutrients and tea yields in Kenya. Trial involved clone 12/12 in Kangaita (Kirinyaga) and seedling tea in Timbilil Estate (Kericho). NPKS was applied at rates (0, 60, 120, 180 kgN/ha/year) and intervals (12, 24months) in 4x2 factorial arrangement (NxF) with NPKS rates split for pruning management (prunings removed/left *in-situ*) in randomized complete block design, replicated thrice. Soil pH was determined digitally; soil and leaf N by Kjeldahl method; other soil and leaf nutrients (P, K, Ca, Mg, Mn, Al, Fe, Cu, Zn) spectrophotometrically. Yields were recorded over two years. Correlations were determined using Pearson's product moment ($p \leq 0.05$). Soil pH levels significantly decreased with increasing fertilizer rates at Timbilil implying that high rates of NPKS fertilizer increase soil acidity. While soil N levels at Kangaita increased with increasing NPKS rates, soil N levels at Timbilil reduced. Other soil nutrients levels responded sporadically to NPKS rates with high CVs hence no conclusive trends were established. Mature leaf N levels and tea yields significantly increased due to increasing rates of fertilizer application in both sites. Biennial NPKS application significantly decreased soil N levels at Timbilil while increasing levels of soil N at Kangaita. However, the longer interval of fertilizer application significantly reduced mature leaf N levels and tea yields at Kangaita. At depth 0-15 cm, prunings left *in situ* increased ($p \leq 0.05$) levels of soil N, Ca, Mg and Mn at Kangaita and Al at Timbilil. Mature leaf Ca and Mn levels and tea yields increased ($p \leq 0.05$) due to prunings left *in situ* at Kangaita.Individual soil nutrient levels were not related to their levels in mature leaves of tea. Tea yields were positively correlated to Zn and Cu levels in lowest soil depth at Kangaita but negatively correlated to soil Al at depth 0-15 cm and Zn at depth 15-30 cm at Timbilil. It is recommended that NPKS fertilizer be applied at rates upto 120 kg/ha/year but still rates upto 100 kg/ha/year could be adequate. Immediately after pruning, tea prunings should not be removed from tea farms for improved soil quality and tea yields. Mature leaf analysis be used in establishing nutrients demands of tea. This study has shown that NPKS fertilizer application at rates upto 120 kg/ha/year can sustain high yields and reduce cost of production. Prunings left *in situ* improve soil quality and would reduce amounts of NPKS fertilizer requirements for tea. This would reduce costs while creating a more sustainable farming system.

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LIST OF ABBREVIATIONS/ACRONYMS

AI	Application interval of fertilizer
Al	Aluminium
AMSL	Above mean sea level
ANOVA	Analysis of variance
Ca	Calcium
Cu	Copper
CV	Coefficient of variation
Fe	Iron
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectrophotometer (ICP- AES)
K	Potassium
KgN/ha/year	Kilogram of nitrogenous fertilizer applied per hectre annually
LSD	Least significant difference
Mg	Magnesium
Mn	Manganese
N	Nitrogen
NPK	Nitrogen Phosphorus Potassium fertilizer formulation
NPKS	Nitrogen Phosphorus Potassium Sulphur fertilizer formulation
P	Phosphorus
Prunings *in situ*	Cuttings from tea plants are left in their original position after pruning
Prunings removal	Cuttings from tea plants are taken away from tea plantations after pruning
PM	Pruning management type, either prunings removed or prunings retained
$p \leq 0.05$	Probability at 95% confidence level
ppm	Parts per million
r	Correlation coefficient
TRFK	Tea Research Foundation of Kenya
TRI	Tea Research Institute (Kenya)
Zn	Zinc

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CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Camellia sinensis L. O. kuntze plant is an important cash crop in many countries, grown for processing various tea beverages (Howard, 1978). Commercial tea production is done under different climatic conditions with latitudes ranging from 45^{o}N (Russia) to 30^{o}S (South Africa), longitudes 150^{o}E (New Guinea) to 60^{o}W (Argentina) (Shoubo, 1989) and altitudes ranging from sea level in Japan and Sri Lanka (Anandacumaraswamy *et al*., 2000) to upto 2,700m above mean sea level (amsl) in Eastern Africa (Owuor *et al*., 2008a). Tea industry in Kenya comprises of the estates and smallholder sectors. The industry creates employment opportunities especially in rural areas (Anon, 2001) where development is slow and economic opportunities are rare (Owuor *et al*., 2013a). In Kenya, tea is grown on the foothills of Aberdare ranges and Mount Kenya in the east and Mau ranges, Nandi, Kisii and Kakamega hills west of the Rift Valley (Anon, 2005).

Areas in east and west of the Rift Valley are classified into different agro-ecological zones (Jaetzold *et al*., 2007) due to proximity to Aberdares and Mount Kenya and Lake Victoria, respectively. These areas widely differ in elevation, soil type, temperatures as well as total rainfall and its distribution (Jaetzold *et al*., 2007). For example, average temperatures in the western highlands are usually between 15 and 25^{o}C while temperatures experienced in tea areas in the eastern highlands normally fall in the range 15-18^{o}C. Consequently, tea grows faster in the western highlands as compared to tea in the eastern region (Mangenya *et al*., 2014) and this leads to differences in yields (Nyabundi *et al*., 2016). Variations in total rainfall and its distribution (Carr and Stephens, 1992), temperature (Tanton, 1982) and altitude (Squire *et al*., 1993) cause differences in tea yields. Drastic fall in temperatures suppress tea growth rates (Squire *et al*., 1993; Burgess and Carr, 1997) that lower yields (Tanton, 1982). Increased tea growth rates make harvesting more intensive in the western highlands as compared to eastern highlands. This suggests that nutrients losses from soils through the harvested crop (Kamau *et al*., 2005) may vary in these different tea growing regions. However, the recommended fertilizer application rates for replenishment of lost nutrients in Kenya (Othieno, 1988) are the same for tea in both high and low altitude areas.

Tea plants can last over 100 years of economic production under good agronomic and management practices. However, continuous tea cropping (Dang, 2002), high nutrients leaching (Owuor *et al*., 1997), harvesting (Kamau *et al*., 2005) and surface run offs (Bonheure and Willson, 1992; Othieno, 1988) deplete soil nutrients making the soils unable to supply adequate levels of nutrients to tea plants. In tea plantations yielding 4000 kg of made tea ha^{-1} $year^{-1}$, approximately 160 kg N, 12 kg P_2O_5 and 84 kg K_2O are removed from soils through the harvested crop (TRFK, 2010). To sustain soil quality and economic production over such long periods, replenishment of lost nutrients through application of nitrogenous fertilizers is recommended (Othieno, 1988). Different tea growing countries use varying rates of nitrogenous fertilizers on tea. The recommendations for nitrogenous fertilizers range from 36-40 kg N ha^{-1} $year^{-1}$ in Vietnam to 800 kg N ha^{-1} $year^{-1}$ in Japan (Bonheure and Willson, 1992). In Kenya, rates between 100 and 250 kg N ha^{-1} $year^{-1}$ are recommended (Othieno, 1988). Despite the recommendations, some farmers apply in excess of these rates in the belief that yield responses would remain linear (Takeo, 1992). However, this is not true as tea yields increase with increasing rates of nitrogenous fertilizers upto some point, beyond which, the yields decline (Venkatesan *et al*., 2004; Owuor *et al*., 2008b; Kamau *et al*., 2008a). Continuous application of nitrogen in excess of recommended rates has negative impacts on tea productivity as it leads to increased soil acidity and levels of aluminium (Ruan *et al*., 2006) and manganese (Kebeney *et* *al*., 2010) with a reduction in levels of soil phosphorus (Owuor *et al*., 2011b) and base cations (Kebeney *et al*., 2010). The nutrients imbalances may create a state of moribundness in soils leading to reduced yields. However, optimal nitrogen rates for balanced soil nutrients have not been determined. While increasing rates of nitrogenous fertilizers increase uptake of nutrients like nitrogen (Kebeney *et al*., 2010; Kwach *et al*., 2012) and manganese (Kwach *et al*., 2012) as reflected in mature leaf analysis, levels of other leaf nutrients like potassium, calcium and magnesium decline (Kebeney *et al*., 2010; Kwach *et al*., 2012). Despite differences in mature leaf nutrients levels, norms for advisory purposes are uniform across the country (Othieno, 1988; Anonymous, 2002). Such recommendations may disadvantage tea growers in some regions. Different tea growing areas may therefore require specific rates of nitrogenous fertilizers which have not been documented.

Tea yields increase quadratically with increasing rates of nitrogenous fertilizers upto some rate, beyond which, the yields decline (Barbora, 1991; Owuor *et al*., 1991, 2008b; Kamau *et al*., 2000, 2008a). In North East India, tea yields declined with nitrogen application rates above 165 kg N/ha/year (Barbora, 1991). In Kenya, yields responded to high nitrogen fertilizer application rates upto 200 kg N/ha/year above which, there was no significant response (Owuor *et al*., 1991; Kamau *et al*., 2000). Despite using similar rates of nitrogenous fertilizers, tea yields in Kenya widely vary in different tea growing areas (Owuor *et al*., 2011a; Msomba *et al*., 2014; Nyabundi *et al*., 2016), even in same cultivars (Wachira *et al*., 2002), probably due to different levels of soil and leaf nutrients. Variations in soil and leaf nutrients levels may stagnate or cause decline in tea yields in the long run. Different tea growing areas may require specific rates of NPKS, which have not been determined in Kenya.

In Kenya, fertilizer application intervals have conservatively been done once per year or by splitting upto four times, especially in large estates (Kamau *et al*., 2000). Similarly, trials on fertilizer application have concentrated on annual single application versus splitting for both low and high yielding teas. Past results showed that splitting annual nitrogen applications had no yield benefits (Owuor *et al*., 1991, 1992; Kamau *et al*., 2000). Therefore there is a possibility that even the annual nitrogen application maybe too close before soil and leaf nutrients become limiting. Longer intervals of nitrogen application may give similar yields but with lower production costs. Indeed, levels of soil and leaf macronutrients like phosphorus, calcium, magnesium and potassium were adequate when nitrogenous fertilizers were applied at 24 months intervals (Kebeney *et al*., 2010). However, tea yields were not determined. It therefore remains unknown if such intervals of nitrogenous fertilizer application influence soil and mature leaf nutrients to levels that can sustain high tea yields.

Pruning is a management practice in tea cultivation that maintains the plucking table (Anonymous, 2002). The practice can be a major source of nutrients recycling towards balanced soil-plant systems (Ranganathan, 1972). Nutrients locked up in tea plants can be returned to soils when prunings are left *in situ* (Othieno, 1981). This may restore lost nutrients in soils and improve fertility. In India, retention of tea prunings *in situ* returned approximately 317 kilograms of nitrogen per hectre, 56 kilograms of phosphorus per hectre and 77 kilograms of potassium per hectre to the soils (Ranganathan, 1972, 1977). Such results suggest that tea prunings can return essential nutrients to tea soils and improve fertility. This may sustain high yields of tea without excess use of inorganic fertilizers. However, in smallholder tea sector, prunings are often removed from tea fields for use as firewood (M’Imwere, 1997). The practice may have adverse effects on soil fertility, tea nutrition and consequently, tea yields. As a result of prunings removal, soils below tea plants are left bare and more vulnerable to weed growth and erosion. Before the canopies regenerate fully, reasonable amounts of soil nutrients are lost through weeds, erosion and leaching. Nutrients locked in plant portions are also carried away from tea plantations in form of firewood. Tea production levels in smallholder tea sector is relatively low as compared to that from the estates (Ogola and Kibiku, 2004; Mbadi and Owuor, 2008). Yields are lower despite the smallholder tea growers using high yielding clones than seedling dominated tea estates (Wachira, 2002). Removal of prunings from tea farms in smallholder tea sector may be reducing soil nutrients leading to lower yields. However, it is not established if removal of prunings influences soil nutrients to levels that can affect nutrient uptake and tea yields hence the need for this study.

Both leaf and soil analyses are extensively used in predicting soil nutritional status for optimal crop production (Kamau *et al*., 2005; Kwach *et al*., 2012; Venkatesan *et al*., 2004). Leaf chemical analysis determines nutrients available in soils for uptake by tea plants (Nathan and Warmund, 2008). This provides the potential of soils to supply nutrients and the ability of the plants to extract those nutrients (Anonymous, 2002; Kamau *et al*., 2008a). However, for smallholder farmers, use of both techniques is expensive and often unavailable. It is not known if relationships exist between individual soil and leaf nutrients and if use of soil or leaf chemical analysis alone can be adequate in predicting nutrients demands of tea bushes. It is also not established how soil and mature nutrients levels will relate to tea yields under different rates and intervals of NPKS fertilizer application and pruning management.

1.2 Statement of the Problem

Despite use of uniform rates of NPKS fertilizer in Kenya, yields vary from region to region even in same cultivars. Different tea growing areas may require specific rates of NPKS, which have not been determined. Biennial NPKS fertilizer application give similar yields as annual NPKS fertilizer application under short term trials. It is not established if such interval of fertilizer application can influence soil and mature leaf nutrients to levels that can sustain high tea yields. Prunings left *in situ* may improve soil quality and tea yields. However, removal of prunings from tea farms, especially in smallholder tea sector may be reducing soil nutrients leading to lower yields. It is not established if prunings left *in situ* under biennial NPKS fertilizer application can influence soil nutrients to levels that can affect mature leaf nutrients and tea yields. Farmers currently use both soil and mature leaf chemical analyses in assessing tea nutrients demands but the use of both techniques is expensive. It is not documented if individual soil nutrients levels are related to their levels in mature leaves of tea and if use of soil or mature leaf diagnosis alone can be adequate in establishing nutrients demands of tea. It is also unknown how soil and mature nutrients levels will relate to tea yields under different rates and intervals of NPKS fertilizer application and pruning management.

1.3 Broad Objective

To evaluate the influence of rates and intervals of NPKS fertilizer application and pruning management on soil and leaf nutritional status and tea yields in east and west of Rift Valley.

1.4 Specific Objectives

i. To determine effect of different rates and intervals of NPKS fertilizer application and pruning management on soil pH and nutrients levels, east and west of Rift valley.

ii. To determine effect of different rates and intervals of NPKS fertilizer application and pruning management on mature leaf nutrients levels, east and west of Rift valley.

iii. To determine effect of different rates and intervals of NPKS fertilizer application and pruning management on tea yields, east and west of Rift Valley.

iv. To determine if individual soil nutrients levels are related to mature leaf nutrients levels in tea and if soil and mature nutrients levels are related to tea yields.

1.5 Null Hypotheses (H_0)

i. Soil pH and nutrients levels are not influenced by rates and intervals of NPKS fertilizer application and pruning management.

ii. Mature leaf nutrients levels are not influenced by rates and intervals of NPKS fertilizer application and pruning management.

iii. Tea yields are not influenced by rates and intervals of NPKS fertilizer application and pruning management.

iv. Individual soil nutrients levels are not related to mature leaf nutrients levels in tea and soil and mature leaf nutrients levels are not related to tea yields.

NB: If the null hypotheses (**H_0**) do not hold, then alternative hypotheses (**H_1**) shall be accepted.

1.6 Justification of the Study

Annual application of nitrogenous fertilizers in tea cultivation is expensive. If nitrogenous fertilizers are applied at intervals of 24 months, costs of tea production may reduce while prolonging the economic lifespan of tea soils. Retention of tea prunings in fields may improve soil quality and reduce on the annual fertilizer requirements. Such technology may help in creation of a more sustainable farming system and improve tea yields.

CHAPTER TWO

LITERATURE REVIEW

2.1 Tea sectors in Kenya

Tea (*Camellia sinensis*) is a perennial crop, of the family *Theaceae* that is grown widely in tropical, subtropical and temperate climates (Howard, 1978). The crop is successfully grown in areas located between latitudes 45^{o}N (Russia) and 30^{o}S (South Africa), longitudes 150^{o}E (New Guinea) and 60^{o}W (Argentina) (Shoubo, 1989) and elevations ranging from sea level in Japan and Sri Lanka (Anandacumaraswamy *et al*. 2000) to upto 2,700 m above mean sea level (amsl) in Kenya and Rwanda (Owuor *et al*., 2008a). The tea industry creates employment opportunities especially in rural areas (Anon, 2001) with slow development and fewer economic opportunities (Owuor *et al*., 2013a). The tender shoots of tea are harvested at regular rounds (6-25 days) (Verma, 1997) for processing various tea beverages.

In Kenya, tea industry has two vibrant sectors; estates and smallholder sectors. The estates comprise of multinationals who have holdings of over 50 ha while smallholder sector is composed of mainly Kenyans with tea holdings averaging about 0.22 ha (Mbadi and Owuor, 2008). The smallholder sector has undergone rapid development and accounts for over 80% of land under tea and over 60% produced tea (Owuor *et al*., 2007). Although the smallholder sector accounts for more than 80% of land under tea, tea yields per unit area from the sector amounts to about 50% of that from estates (Ogola and Kibiku, 2004). This is despite the fact that most smallholder tea growers cultivate high yielding tea clones (Wachira, 2002) unlike the estates that mainly grow low yielding seedling tea, probably due to inefficient management (Othieno, 1994) and inefficient use of fertilizers (Anon, 2002; Othieno, 1988). Use of the same recommended agronomic inputs such as nitrogen rates (100 -250 kg N/ha/year) (Othieno, 1988) has given different yield responses (Nyabundi *et al*., 2016; Msomba *et al*., 2014) and tea quality (Owuor *et* *al*., 2013a) even under the same geographical location. Such differences indicate that nutrients requirements for tea in different locations could be different and may require different agronomic practices. However, region specific agronomic practices such as rates of nitrogenous fertilizers, application intervals and pruning management in different tea growing areas in Kenya have not been established.

2.2 Nitrogenous Fertilizers Rates in Tea Production

2.2.1 Nitrogenous Fertilizers and Soil pH and Available Nutrients

Like all other plants, tea requires the macronutrients nitrogen, phosphorus, potassium, calcium and magnesium in relatively large quantities and the micronutrients zinc, copper, iron, aluminium and manganese in smaller proportions for normal growth and development (Bonheure and Willson, 1992; Kamau *et al*., 2008b). Under normal circumstances, plants absorb essential nutrients from soils (Lasheen *et al*., 2008), except for small quantities of nitrogen and elements like hydrogen, carbon and oxygen which can directly be absorbed by leaves from air and rain water (Kamau, 2008). Due to continuous tea cropping (Dang, 2002), high nutrients leaching (Owuor *et al*., 1997) and surface run offs (Othieno, 1988) in high rainfall areas where tea is grown, most soils can not supply adequate amounts of both macro and micronutrients to tea plants as soil nutrients reserves get depleted. Large amounts of nutrients are removed from tea plantations via the harvested crop (Kamau *et al*., 2005). On average, tea plantations yielding 4000 kg made tea ha^{-1} $year^{-1}$ lose approximately 160-200 kg of nitrogen, 12-15 kg of phosphorus as phosphorus oxide and 84-100 kg of potassium as potassium oxide from soils through the harvested crop (TRFK, 2010). In order to replenish the lost nutrients and sustain high yields, tea growers apply fertilizers, mainly nitrogenous fertilizers (Bonheure and Willson, 1992; Venkatesan *et al*., 2004; Kamau *et al*., 2008a) as tea plants require nitrogen in large quantities (Ranganathan and Natesan, 1985; Othieno, 1988). The nutrient promotes rapid vegetative growth of harvestable shoots (Odhiambo, 1989) thereby increasing tea yields (Kamau *et al*., 2008a; Owuor *et al*., 2008b; Venkatesan *et al*., 2003, 2004). Nitrogenous fertilizer application is an expensive undertaking that comes second after harvesting (Bonheure and Willson, 1992) but its beneficial effects on yields (Venkatesan *et al*., 2003, 2004; Kamau *et al*., 2008a; Owuor *et al*., 2008b) make it a compulsory activity in tea production.

Rates of nitrogenous fertilizers application vary in different tea growing countries. In Vietnam, rates between 36 and 40 kg N/ha/year have been used in tea farms while rates of upto 800 kg N/ha/year have been reported in Japan (Bonheure and Willson, 1992). Nitrogenous fertilizer application at rates between 100 and 250 kg N ha^{-1} $year^{-1}$ are recommended for tea growing in East Africa (Othieno, 1988). Despite documentation of recommended rates, some farmers, especially in smallholder tea sector, use various fertilizer rates that are high in belief that extra fertilization will translate into improved returns. In Japan, for example, farmers have applied upto 1200 kg N/ha/year but tea yields were not linear (Takeo, 1992).

Increasing rates of nitrogenous fertilizers increase tea yields (Owuor *et al*., 2008b; Msomba *et al*., 2014) upto some point but continuous use of nitrogen in excess of recommended rates has negative impacts on tea productivity. In tea soils, higher rates of nitrogenous fertilizers than the recommended rates increase soil acidity (Ruan *et al*., 2006; Venkatesan *et al*., 2004) which influences solubility and availability of other soil nutrients (Ruan *et al*., 2006; Kamau *et al*., 2008) and tea yields (Venkatesan *et al*., 2004). Tea thrives in a range of acidic soils with pH between 4.0 and 6.0 (Ranganathan, 1977; Othieno, 1992) but its optimal growth is in soils with pH between 4.5 and 6.5 (Ranganathan and Natesan, 1985; Othieno, 1988; Anonymous, 2002). Although the plant can tolerate strongly acidic conditions, it is unlikely to grow well in soils with very low pH as nutrients availability problems may arise. Low soil pH promotes leaching of calcium, magnesium and potassium (Owuor and Wanyoko, 1996; Ruan *et al*., 2006; Kamau *et al*., 2008), fixation of phosphorus (Kebeney *et al*., 2010; Owuor *et al*., 2011b) as insoluble phosphates of Al and Fe (Chong, 2008) and accumulation of aluminium (Ruan *et al*., 2006; Owuor and Cheruiyot, 1989) and manganese (Kebeney *et al*., 2010) in soils. Studies done overseas (Gabisoniya and Gabisoniya., 1973; Shen *et al*., 2010; Hu *et al*., 2011) and in Kenya (Kamau *et al*., 2005; Kebeney *et al*., 2010; Owuor *et al*., 2011b) have demonstrated that increasing rates of nitrogenous fertilizers lower soil pH. Consequently, levels of aluminium and iron (Gabisoniya and Gabisoniya., 1973) and manganese (Kebeney *et al*., 2010) increase in soils with a reduction in phosphorus (Owuor *et al*., 2011b) and base cations (Kebeney *et al*., 2010). Rise in levels of some nutrients with a decrease in levels of others creates soil nutrient imbalances. Such nutrient imbalances in soils may impair growth rate of tea plants and hinder economic production as aluminium toxicity is recognized to reduce availability of other nutrients (Allam, 1994). However, in Kenya, optimal nitrogen rates for balanced soil nutrients availability have not been established.

2.2.2 Nitrogenous Fertilizers and Mature Leaf Nutrients in Tea Production

Leaf analysis is extensively used in establishing nutritional demands of the tea plants (Venkatesan *et al*., 2004; Anon, 1990; Kamau *et al*., 2005; Kwach *et al*., 2012). The leaf type adopted for use in establishing nutrients levels in tea plants varies with tea growing countries (Bonheure and Willson, 1992). Countries such as Russia, Taiwan and India use the young second, third or fourth leaf in foliar analysis for assessment of nutrients requirements of tea plants (Ranganathan *et al*., 1988). In eastern (Tolhurst, 1976; Othieno, 1988; Kwach *et al*., 2011) and central Africa (Anon, 1990) tea growing zones, mature leaf analysis is the recommended guide for advisory purposes and fertilizer application programmes. Agronomic inputs affect uptake of nutrients and levels of such nutrients in mature leaves of tea plants (Kamau *et al*., 2005). Nitrogenous fertilizer application is an important agronomic practice that influences nutrients levels in tea plants (Bonheure and Willson, 1992; Owuor *et al*., 2009, 2010a). Mature leaf nutrients like nitrogen (Owuor *et al*., 2011; Kwach *et al*., 2014), zinc (Owuor *et al*., 1993; Kwach *et al*., 2014), copper and iron (Kwach, 2013; Kwach *et al*., 2014) increase with increasing rates of nitrogenous fertilizers. However, reduction in mature leaf aluminium (Owuor *et al*., 1988b), calcium and potassium (Kwach *et al*., 2014) levels with increasing rates of nitrogenous fertilizers has also been reported. An increase in levels of leaf nutrients like N, Zn, Cu and Fe with a decrease in levels of Al, Ca and K creates nutrient imbalances in tea plants which may impair tea growth and yields. Nitrogen rates as currently recommended may be causing existence of some nutrients in tea plants while creating deficiencies in others.

Excess and/or inadequate levels of some nutrients in mature tea leaves may have deleterious effects on growth rates (Squire *et al*., 1993; Mangenya *et al*., 2014) and consequently, tea yields. For example, excessively high levels of iron in tea plants suppress photosynthesis leading to decline in yields (Kuzhandaivel and Venkatesan, 2011). Excessive supply of nitrogen in soils lead to nitrogen toxicity to plants (Salisbury and Ross, 1992) which inhibits plant growth and development and cause decline in yields (Caicedo *et al*., 2000). Copper is a constituent part of the enzyme polyphenol oxidase responsible for fermentation during manufacture of black tea (Harler, 1971). Tea with adequate levels of copper ferment well during manufacture of black tea (Harler, 1971) but inadequate levels of Cu in harvested tea produce black tea of poor quality. In contrast, excess levels of copper in tea plants inhibit photosynthesis and enzyme activities that may reduce yields (Yruela, 2005). Zinc is a structural component of several enzymes (Iwasa, 1977) and its deficiency reduces growth rates of tea plants (Tolhurst, 1973) leading to decline in yields. Increasing rates of nitrogenous fertilizers could be introducing nutrients imbalances in tea plants leading to variations in growth rates (Squire *et al*., 1993; Mangenya *et al*., 2014) and yields (Nyabundi *et al*., 2016; Msomba *et al*., 2014; Wachira *et al*., 2002) from diverse geographical areas where tea is grown. Despite differences in levels of mature leaf nutrients and growth rates of tea (Mangenya *et al*., 2014), norms for advisory purposes in Kenya are uniform (Othieno, 1988; Anonymous, 2002). Such blanket recommendations may disadvantage farmers in particular tea growing regions. Different tea growing areas in Kenya may, therefore, require specific NPKS fertilizer application rates for optimal levels of leaf nutrients and growth of tea. However, region specific optimal rates of NPKS fertilizer application for balanced mature leaf nutrients levels have not been established and this deserves attention.

2.2.3 Nitrogenous Fertilizers and Tea Yields

Several studies (Venkatesan *et al*., 2004; Owuor *et al*., 1991, 2008b; Kamau *et al*., 2000, 2008a; Kwach *et al*., 2014) have shown that tea yields increase with increasing rates of nitrogenous fertilizers upto some point, beyond which, yields either stagnate or decline. In North East India, tea yields increased with increasing rates of nitrogenous fertilizers upto a rate of 165 kilogram per hectare per year, above which, the yields declined (Barbora, 1991). Similarly, in Kenya (Owuor *et al*., 1991; Kamau *et al*., 2000), tea yields improved with an increase in rates of nitrogenous fertilizers upto 200 kg N/ha/year. However, there was no significant response above this rate. Nitrogenous fertilizer application at rates above 300 kg N/ha/year also resulted in reduced yields of clone S15/10 (Owuor *et al*., 2008). These results demonstrated that use of higher nitrogenous fertilizer application rates may have no yield benefits even for a high yielding variety like clone S15/10 (Oyamo, 1992). Large variations in yields responses also occur in different tea growing areas despite using the same recommended rates of nitrogenous fertilizers across the country (Wachira *et al*., 2002; Owuor *et al*., 1993, 2010b, 2011a; Nyabundi *et al*., 2016). This happens even when the same cultivar is used (Wachira *et al*., 2002). For example, when same rates of nitrogenous fertilizers were applied on clone BBK35 in four different locations; Timbilil, Changoi, Sotik highlands and Kipkebe (Owuor *et al*., 2013), maximum yields were obtained at 223, 249, 386 and 290 kg N/ha/year, respectively. The results showed that obtaining maximum yields, clone BBK35 would require different nitrogenous fertilizers rates in different locations. However, fertilizer recommendations in Kenya are uniform for both high and low yielding tea varieties (Othieno, 1988). Consequently, tea growers in some areas may continuously be disadvantaged as region specific optimal rates have not been determined.

2.3 Nitrogen Fertilizers Application Intervals in Tea Cultivation

Nitrogenous fertilizers on tea are normally applied on 12 months basis in most tea growing countries. In Kenya, nitrogenous fertilizers application on tea is done annually (Anonymous, 2002; Othieno, 1988; Bonheure and Willson, 1992), either as a single dose or split applications (Owuor *et al*., 1997; Kamau *et al*., 2000), mainly in large tea estates. Trials on nitrogenous fertilizer application have mainly concentrated on annual single application versus splitting annual application for both high and low yielding tea varieties. Annual nitrogenous fertilizer application regimes as practiced now were designed to concur with the financial years of tea companies or organizations. However, in tea estates, annual nitrogenous fertilizer application is done by splitting twice (after every 6 months), thrice (after every 4 months) or upto four times (after every 3 months) a year (Owuor *et al*., 1997; Kamau *et al*., 2000). Splitting annual nitrogenous fertilizer applications are done with the assumption that there would be a steady supply of essential nutrients to tea plants throughout the growing season, thereby increasing tea yields. In South India (Ranganathan and Natesan, 1987) and Malawi (Mkwaila, 1993), splitting annual applications of nitrogenous fertilizers improved tea yields. However, previous research in Kenya (Owuor *et al*., 1991, 1992, 1994, 2008; Kamau *et al*., 1999, 2000) demonstrated that there were no significant yield benefits accruing from splitting annual nitrogenous fertilizer applications. Consequently, splitting annual fertilizer applications could be done for other reasons such as cash flow management, uniform distribution of fertilizers on the ground, ease of storage and adequate availability of fertilizers but not yield benefits. Such results suggest that annual nitrogenous fertilizer application could be too soon before nutrients become limiting. Indeed, soils have been shown (Kebeney *et al*., 2010) to have ability to supply adequate levels of macronutrients like phosphorus, calcium, magnesium and potassium to tea plants when nitrogenous fertilizers were applied biennially. The results suggested that high yields of tea may be achieved if nitrogenous fertilizer application is done at 24 months intervals. However, tea yields were not determined under such interval of NPKS fertilizer application. It is not known how soil nutrients, mature leaf nutrients and yields will vary under such interval of NPKS fertilizer application. This is an area that may improve fertilizer use, soil quality and tea yields hence need to be studied.

2.4 Pruning Management in Tea Nutrition

Pruning is a mandatory practice in commercial tea production, to restore the plucking table and generate new vigorous shoots (Anonymous, 2002). In Kenya, it is done periodically every 3-5 years (Mwakha, 1997). The practice can be a major source of nutrients recycling which can contribute to the mineral balance of soil-plant systems as tea leaves and prunings serve as effective mulching materials and source of nutrients if left *in situ* (Ranganathan, 1972). The nutrients locked up in tea plants can be returned to soils when the prunings are left *in situ* (Othieno, 1981). This may restore lost nutrients in soils and improve fertility and minimize wastage of fertilizers.

In India (Ranganathan, 1972, 1977), there was return of approximately 317 kg N, 56 kg P and 77 kg K through return of tea prunings to tea gardens. Similarly, use of tea prunings in tea cultivation resulted to release of 180-250 kg N as nitrate or ammonium ions, 200-250 kg, 90-100 kg and 60-90 kg as oxides of K, Mg and P, respectively, into the soils (Krishnapillai, 1984). Such results suggested that tea prunings can return essential nutrients to tea fields and improve soil fertility which may sustain high yields of tea without excess use of inorganic fertilizers. However, in smallholder tea sector, prunings are often removed from tea fields for use as firewood (M'Imwere, 1997). The practice may have adverse effects on soil fertility, tea nutrition and consequently, tea yields. As a result of prunings removal, soils below the tea plants are left bare and more vulnerable to weed growth and erosion. Before the plants regenerate their canopies fully after pruning, the exposed tea fields lose substantial amounts of nutrients due to erosion, weeds and leaching. Essential nutrients are also removed with prunings from tea fields further reducing soil fertility and possibly tea yields.

Fertilizer recommendations (Anonymous, 2002; Othieno, 1988) for tea in Kenya are similar for both estates and smallholder tea sectors but tea production in smallholder tea sector is relatively low as compared to that from the estates (Ogola and Kibiku, 2004; Owuor, 1999; Mbadi and Owuor, 2008). This happens despite the fact that smallholder tea growers use mostly clonal teas with high yield potentials than estates dominated seedling tea plantations (Wachira, 2002). Part of the low yields could be attributed to management practices including removal of tea prunings from tea plantations and lack of funds to purchase fertilizers. Removal of prunings may be reducing soil nutrients levels leading to need for higher nutrient supply through application of nitrogenous fertilizers. However, it is not established if removal of prunings influences soil nutrients to levels that can affect nutrient uptake by tea plants. This area requires attention in order to enhance tea yields.

Decomposition of tea prunings in soils maintains supply of essential nutrients to plants (Swift *et al*., 1979) leading to improved tea yields. In Sri Lanka (Anandacumaraswamy, 1999) and Australia (De Silva, 2007), incorporation of tea prunings in tea gardens increased tea yields, suggesting that there was improved supply of nutrients with retention of tea prunings *in situ*. In Kenya, influence of tea prunings left *in situ* on yields is not documented. It is also unknown if prunings left *in situ* can significantly reduce the amounts of nitrogenous fertilizers requirements for tea plants and help save on extra costs incurred during fertilizer application.

2.5 Importance of Soil and Leaf Analyses in Tea Production

Tea grows in a wide range of soil types derived from diverse parent materials (Eden, 1976). Apart from climatic conditions, soil is the most limiting factor that influences growth and the ultimate yields of tea (Eden, 1976; Wallis, 1997). The plant thrives well in acidic soils but soil pH must always be maintained within the required range for proper growth and development (Othieno, 1992). Besides pH, the essential soil nutrients must be available to tea plants at reasonable levels for ideal tea production. A check on the nutritional status of soils is therefore necessary for determining the suitability of the soil for tea cultivation as well as assessing the fertilizer requirements (Anonymous, 2002; Othieno, 1988). Plant tissue analysis forms a basis for establishing the plants nutrients status and demands (Tolhurst, 1976; Bonheure and Willson, 1992; Owuor and Wanyoko, 1983; Kamau *et al*., 2005). Soil and mature leaf analyses have been used as indicators for soil quality and nutrients availability (Kamau *et al*., 2005; Venkatesan *et al*., 2004). Leaf chemical analysis elucidates available nutrients in soils that were recently taken up by the plants (Nathan and Warmund, 2008). Thus, it provides information on the potential of such soils to continue supplying such nutrients and the ability of the plant to extract those nutrients (Anonymous, 2002; Kamau *et al*. 2008a). It is important to ensure adequate levels of the required nutrients in both soils and leaf tissues if high yields are to be sustained (Bokuchava and Skobeleva, 1969) in tea cultivation. In assessing nutrients demands of tea, both soil and leaf analyses are usually done. However, due to financial constrains, use of both methods is often unavailable and expensive to many tea growers. Use of either soil or leaf analysis may be affordable to farmers especially in smallholder tea sector. However, no study has established if there is a relationship between specific soil and leaf nutrients levels and if soil chemical analysis can be sufficient to predict nutrients levels in the leaf and *vice versa*.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Description of Study Sites

This study was superimposed on an on-going collaborative experiment between the Tea Research Institute in Timbilil (Formerly, Tea Research Foundation of Kenya) and Kangaita Tea Farm under Kenya Tea Development Agency (KTDA). Kangaita lies on latitude 0^o30'S and longitude 37^o 16'E and is situated within the highlands of Mount Kenya in Kirinyaga at an elevation of 2100 m above mean sea level (amsl). The soils in this area are characterized as red clay humic acrisols (Jaetzold and Schmidt, 1982; Muchena and Gachene, 1988). The area experiences a weakly bimodal rainfall distribution of 2040 mm annually, with peaks in April/May and October/November (Mutuku *et al*., 2016). Timbilil Tea Estate lies on latitude 0^o22'S and longitude 35^o21'E in the west of Rift Valley, in Kericho at an altitude of 2180 m amsl (TRFK, 2014). The soils here are basically humic nitosols that are well drained (Jaetzold and Schmidt, 1982). The area receives convectional rainfall (mean annual rainfall of 2000 mm) that is well distributed throughout the year.

3.2 Research Design

At each site, the experiment was laid out in a 4x2 factorial arrangement (NxF) and N rates split for pruning managements (prunings removed or prunings left *in situ*) in a randomized complete block design and replicated 3 times (Appendix I).

3.3 Experimental Treatments

Timbilil site comprised of seedling tea planted in 1962 while Kangaita had clone TRFK 12/12 planted in 1968. Each site consisted of 48 experimental plots, each measuring approximately 35 m^2. In each experimental plot, there were 30 mature tea plants, planted at a spacing of 5 x 2.5 feet (152 cm x 76 cm) which were managed according to the recommended guidelines (Othieno,

1988) in tea production. Nitrogen was applied as NPKS 25:5:5:5 at four different rates (0, 60, 120 and 180 kg/ha/year) as the main treatments, with control plots not receiving any fertilizers. NPKS fertilizer was applied using either 12 or 24 months intervals as the sub treatments. Fertilizer application using 24 months was done in January 2011 and repeated in January 2013 while application using 12 months was done yearly from January 2011-2014. The experimental plots were pruned in the year 2011 and in some plots, tea prunings were removed immediately after pruning (prunings removed) while in others prunings were left in their original positions after pruning (prunings *in situ*) in order to study the effects of pruning management (PM) on soil and leaf nutritional status (Appendix 1).

3.4 Soil Sampling and Analysis

3.4.1 Soil Sampling and Sample Preparation

Soil samples were collected in January 2015. Soil sampling was done at depths 0-15, 15-30 and 40-60 cm from each of the experimental plots in three replicates using a soil auger (Oakfield Apparatus Company, USA). The three depths were adopted because most of the feeder roots of mature tea plants are predominantly found within these depths. Within each plot, three spots were randomly chosen and soil samples collected for each depth. The collected soil samples were bulked to form composites and kept in a freezer containing dry ice before transportation to the laboratory at Tea Research Institute in Kericho where they were air dried, ground and sieved to pass through a 2.00 mm pore sieve using a mortar and pestle. Air dried soil samples were placed in labeled envelopes and kept in a dry cabinet before determination of extractable nutrients.

3.4.2 Soil pH Determination

The pH of the soil samples was determined using a 1:1 soil to water ratio as recommended by Othieno (1988). Exactly 25 g of freshly sampled soils were mixed with 25 mL of distilled water in 100 mL plastic beakers and stirred using clean glass rods. The slurry was allowed to settle for 30 minutes and soil pH determined electrometrically by glass electrode and a digital pH meter (Jenway 3305).

3.4.3 Soil Nitrogen Extraction and Determination

Soil extractable nitrogen was determined using Kjeldahl method adopted from Bremner and Mulveney, (1982). Exactly 1.00 gram of the air dried and sieved soil samples were digested in a block digester (Gerhardt, Germany) using 3 mL of concentrated sulphuric acid (Analar grade) in the presence of a copper-selenium-potassium catalyst mixture for 4.5 hours at a temperature of 350^{o}C. After cooling and addition of 10 mL distilled water, the digests were distilled in a steam distiller (Vapodest 50 series, Germany) using 40% NaOH and 2% boric acid mixed with indicator as the receiving solution. Ammonia gas was driven off by steam from the sample solutions and rapidly condensed before being allowed to drip into the receiving solution. The digests were then titrated automatically using standardized hydrochloric acid in the steam distiller and the quantities of available nitrogen in soil samples determined using the formula:

Soil available N = (ppm in extractant – blank) x 10

3.4.4 Extraction of Soil P, K, Ca, Mg, Mn, Cu, Zn, Al and Fe

Mehlich 3 method (Mehlich, 1984) was adopted in extraction of phosphorus, potassium, calcium, magnesium, manganese, copper, zinc, aluminium and iron from soil samples. The method was adopted as it extracts more phosphorus and is applicable on soils with wide range of pH; from strongly acidic to neutral soils (Zhang *et al*., 2006). The soil available nutrients were extracted using the Mehlich extractant in a 1:10 soil to extracting solution ratio. Exactly 5 grams of air dried and sieved soil samples were accurately weighed using a digital analytical balance (Mettler Toledo, Switzerland) with ±0.0001 gram precision and mixed with 50 mL of the extracting solution in 100 mL plastic bottles. The soil-extractant mixtures were then shaken at 180 oscillations per minute using a reciprocating mechanical shaker for 10 minutes in order to extract nutrients. After extraction, the mixtures were filtered using Whatman number 2 filter papers and filtrates collected in clean boiling tubes before determination of nutrients.

3.4.5 Determination of Soil P, K, Ca, Mg, Mn, Cu, Zn, Al and Fe

Soil nutrients P, K, Ca, Mg, Al, Zn, Cu, Mn and Fe were determined using the ICPE-9000 series (Shimadzu, Japan) of simultaneous inductively coupled plasma (ICP) Atomic Emission Spectrometers (ICPE 9000). The instrument was calibrated using multiple element standards following the manufacturer's recommendations. Six standards of concentrations 0, 1.0, 2.0, 5.0, 10.0 and 20.0 ppm were prepared from a commercial standard and used in the calibration of the instrument for determination of soil extractable nutrients. Three standards with concentrations 0, 25.0 and 50.0 ppm were also made from a different commercial standard and used in instrument calibration for determination of phosphorus. After instrument calibration and programming, filtrates of the soil samples were simultaneously analyzed for determination of extractable nutrients using ICPE 9000 in automated mode. Soil nutrients levels were electronically determined using in-built computer software and displayed on the PC screen in parts per million (ppm).

3.5 Leaf Sampling and Analysis

3.5.1 Mature Leaf Sampling

Mature leaf samples were collected in January 2015. The first mature leaf samples which are the most sensitive to nutrients changes as noted by Tolhurst, (1976) were sampled by hand plucking randomly from each of the experimental plots following the recommended procedures by Tolhurst, (1976). The leaf samples were put in envelopes which were then labeled and transported to the laboratory at TRI in Kericho. Leaf samples were oven-dried at 105^{o}C using

Memmert oven (D-91126) for 4.5 hours and ground to powder form using an electric motor grinder (Moulinex AR1043) before chemical analysis for determination of leaf nutrients.

3.5.2 Mature Leaf Nitrogen Extraction and Determination

Nitrogen in leaf samples was determined using Kjeldahl acid digestion, adopted from Bremner and Mulveney, (1982), and followed by rapid steam distillation and titration using Vapodest 50 series (Gerhardt, Germany) steam distiller. Using an electric balance (Mettler Toledo, Switzerland), 0.1 gram of powdered leaf samples were accurately weighed into specimen tubes and micro-Kjedahl digested for 4.5 hours using 1 mL of concentrated sulphuric acid (Analar grade) in the presence of a catalyst mixture consisting of selenium, copper sulphate and potassium sulphate in a block digester. The digests were allowed to cool to 25^{o}C and 10 mL of distilled water added. The digests were then subjected to rapid steam distillation in a steam distiller (Vapodest 50 series, Germany) using 40% NaOH for ammonia gas to be driven off by steam. Ammonia was rapidly condensed and allowed to drip into 2% boric acid mixed with an indicator mixture (methyl red and bromocresol green) as the receiving solution. The resultant mixtures were titrated with 0.5 N hydrochloric acid solution in automated mode using a Vapodest 50 S distiller. The quantities of nitrogen in leaf samples were determined using the formula:

Soil available N = (ppm in extractant – blank) x 10

3.5.3 Extraction and Determination of Mature Leaf P, K, Ca, Mg, Mn, Cu, Zn, Al and Fe

A modified standard procedure described in AOAC (2000) was adopted for preparation of leaf samples for chemical analysis. Using a digital analytical balance (Mettler Toledo, Switzerland), 0.1 gram of powdered leaf samples were accurately weighed into ashing tubes and kept in a muffle furnace for ashing at 450^{o}C for 4.5 hours until a grey-white ash was obtained. The ashed samples were cooled to 25^{o}C before being digested with 0.5 mL mixture of double acid (HCl and

HNO_3 in 1:1 ratio) and hydrogen peroxide in the ratio 2:3 (double acid: hydrogen peroxide in ratio 2:3). The digests were evaporated to complete dryness on a hot plate under low heat and ventilation. The final residues were cooled and then extracted using 25 mL of 0.5 N HCl solution. After instrument (ICP- AES 9000) calibration using nine standards of different concentrations (same as in section 3.4.5), the extracts were analyzed for simultaneous determination of mature leaf nutrients as described earlier in section 3.4.5.

3.6 Yields Data

Yields were recorded according to the plucking standards used (after every 10 days) for two years (2013 and 2014) before conversion to yields of made tea (mt) per hectre per year using the formula;

Made tea/ha/year = kg of green leaf x 8611 x 0.225/30 where kg green leaf = weight of green harvested leaf per plot, 8611 = number of tea bushes per hectre using 5 x 2.5 ft spacing, 0.225 = conversion factor, 30 = number of tea bushes per plot (Anon, 2002).

3.7 Statistical Analysis

Analysis of variance (ANOVA) in soil and leaf nutrients and tea yields was done as per the experimental design using appropriate statistical package (GENSTAT) and the means separated using the Least Significant Differences (LSD) method at 95% confidence level to determine significant differences. Correlation coefficient (r) values were obtained at 95% confidence using Pearson's product moment.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Variations in Soil pH and Available Nutrients Due to Rates and Intervals of NPK(S) 25:5:5:5 Fertilizer Application and Pruning Management

4.1.1 Soil pH

Soil pH data for the analysed samples from Kangaita and Timbilil were determined (Tables 4.1-4.3). At both sites, soil pH generally decreased with increasing rates of nitrogenous fertilizers. This trend had also been observed in earlier studies (Venkatesan *et al*., 2004; Dogo *et al*., 1994; Kamau *et al*., 1998; Kebeney *et al*., 2010). Although pH declined with rates of nitrogen at Kangaita, the decrease did not reach significant level. Overall soil pH levels decreased significantly ($p \leq 0.05$) with increasing rates of nitrogenous fertilizers at all depths at Timbilil. In particular, at 0-15 cm, soil pH levels obtained when fertilizer was applied at 120 and 180 kg/ha/year were significantly ($p \leq 0.05$) lower than pH levels in control plots. In the two lower soil depths, pH levels in all NPKS-treated plots were significantly ($p \leq 0.05$) lower than pH in control plots. The results confirmed that NPKS fertilizer has acidifying effects and negative impact on soils as reported elsewhere (Kebeney *et al*., 2010).

There are three mechanisms through which nitrogenous fertilizers acidify soils. During the ammonification process, microbial oxidation of the ammonium ion (NH_4^+) to nitrate ion (NO_3^-) releases hydrogen ions, responsible for acidity in soils (Dogo *et al*., 1994). Soils also become more acidic when tea plants exude hydrogen ions into the soil solution (Marchner, 1986). For every ammonium ion taken up by the tea plant, the root releases a hydrogen ion into the soil which increases acidity. Hydrogen ions can also accumulate in soils as a result of soil variable charges that are pH dependant (Brady and Weil, 1972). Low pH makes aluminium and manganese ions the most predominant ions in soil solution. These ions displace base ions through leaching (Kamau *et al*., 1998; Kebeney *et al*., 2010; Owuor *et al*., 2011b) leading to increased soil acidity. A decreasing trend in pH values down the profile was observed at Timbilil. The high pH values at surface soils may have resulted from continuous return of prunings and leaf drops that increase base ions, especially at surface soils (Kamau *et al*., 2008). Soil pH levels at Kangaita increased down the soil profile as observed earlier in a similar study (Kebeney *et al*., 2010). Lower pH values in the upper soil depth could be attributed to the added nitrogenous fertilizers which produce hydrogen ions during the ammonification process (Dogo *et al*., 1994). Generally, pH levels recorded were below 4.0, considered optimum for tea plants (Anon, 2002) and this showed that tea plants can tolerate low pH in soils. The tea plants did not show visual signs of ill health and Othieno (1992) also contends that tea can grow well in soils with pH upto 3. Nevertheless, regular checks on soil pH are necessary as tea is unlikely to grow well in soils with pH less than 3.0.

Soil pH was not significantly different between the two intervals of fertilizer application, suggesting that intervals of nitrogenous fertilizer application did not affect soil pH. Similarly, splitting annual nitrogenous fertilizer applications had no effect on soil pH (Dogo *et al*., 1994). However, in a similar study by Kebeney *et al*. (2010), splitting fertilizer application over two years had significant effect on soil pH levels. The 24 months application interval had lesser acidifying effects than 12 months interval of nitrogen application. This could have been attributed to reduced microbial oxidation of the ammonium ions since fertilizer application was biennial and less ammonium ions were taken up by tea plants.

Table 4.1: Variations in soil pH levels due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 0-15 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	3.26	3.28	3.30	3.23	3.27	3.27
		24	3.31	3.28	3.28	3.22	3.27	
		Mean rates	3.29	3.28	3.29	3.23		
		CV (%)			4.8			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	3.28	3.15	3.23	3.28	3.24	3.26
		24	3.38	3.27	3.25	3.19	3.27	
		Mean rates	3.33	3.21	3.24	3.24		
		CV (%)			5.0			
		LSD(p≤0.05)			NS		NS	
	Overall	12	3.27	3.22	3.27	3.26	3.26	
		24	3.35	3.28	3.27	3.21	3.27	
		Mean rates	3.31	3.25	3.27	3.24		
		CV (%)			4.9			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	3.98	4.12	3.68	3.92	3.93	3.98
		24	4.33	3.85	4.01	3.89	4.02	
		Mean rates	4.15	3.99	3.84	3.90		
		CV (%)			7.7			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	4.40	4.22	3.89	3.97	4.12	4.09
		24	4.31	4.01	4.00	3.91	4.06	
		Mean rates	4.35	4.11	3.94	3.94		
		CV (%)			7.3			
		LSD(p≤0.05)			NS		NS	
	Overall	12	4.19	4.17	3.79	3.95	4.03	
		24	4.32	3.93	4.01	3.90	4.04	
		Mean rates	4.26	4.05	3.90	3.93		
		CV (%)			7.5			
		LSD(p≤0.05)			0.25		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.2: Variations in soil pH levels due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 15-30 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	3.39	3.29	3.35	3.37	3.35	3.33
		24	3.30	3.35	3.31	3.27	3.31	
		Mean rates	3.35	3.32	3.33	3.32		
		CV (%)			3.8			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	3.31	3.20	3.18	3.23	3.23	3.28
		24	3.33	3.32	3.33	3.30	3.32	
		Mean rates	3.32	3.26	3.26	3.27		
		CV (%)			4.9			
		LSD(p≤0.05)			NS		NS	
	Overall	12	3.35	3.25	3.27	3.30	3.29	
		24	3.32	3.34	3.32	3.29	3.32	
		Mean rates	3.34	3.30	3.30	3.30		
		CV (%)			4.4			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	3.96	3.87	3.48	3.77	3.77	3.81
		24	4.07	3.68	3.86	3.80	3.85	
		Mean rates	4.01	3.77	3.67	3.79		
		CV (%)			5.3			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	4.07	3.93	3.73	3.59	3.83	3.88
		24	4.05	3.82	3.95	3.89	3.93	
		Mean rates	4.06	3.87	3.84	3.74		
		CV (%)			5.3			
		LSD(p≤0.05)			NS		NS	
	Overall	12	4.02	3.90	3.61	3.68	3.80	
		24	4.06	3.75	3.91	3.85	3.89	
		Mean rates	4.04	3.83	3.76	3.77		
		CV (%)			6.0			
		LSD(p≤0.05)			0.19		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.3: Variations in soil pH levels due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 40-60 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	3.48	3.26	3.36	3.30	3.35	3.35
		24	3.37	3.39	3.32	3.31	3.35	
		Mean rates	3.43	3.32	3.34	3.31		
		CV (%)			3.7			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	3.35	3.24	3.22	3.24	3.26	3.31
		24	3.32	3.35	3.40	3.32	3.35	
		Mean rates	3.33	3.30	3.31	3.28		
		CV (%)			4.2			
		LSD(p≤0.05)			NS		NS	
	Overall	12	3.42	3.25	3.29	3.27	3.31	
		24	3.35	3.37	3.36	3.32	3.35	
		Mean rates	3.39	3.31	3.33	3.30		
		CV (%)			4.0			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	4.06	3.75	3.42	3.66	3.72	3.75
		24	3.85	3.65	3.75	3.83	3.77	
		Mean rates	3.95	3.70	3.59	3.75		
		CV (%)			7.0			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	3.93	3.69	3.69	3.37	3.67	3.75
		24	4.07	3.60	3.75	3.90	3.83	
		Mean rates	4.00	3.65	3.72	3.64		
		CV (%)			7.2			
		LSD(p≤0.05)			NS		NS	
	Overall	12	4.00	3.72	3.56	3.52	3.70	
		24	3.96	3.63	3.75	3.87	3.80	
		Mean rates	3.98	3.68	3.66	3.70		
		CV (%)			7.1			
		LSD(p≤0.05)			0.22		NS	NS

Insignificant interactions are not shown, NS means not significant

The pH values obtained in this study were generally lower than those obtained earlier (Kebeney *et al*., 2010). This could be due to differences in soil moisture contents as sampling was done in different seasons. Previously, soil sampling was done during wet season (October) when soil moisture content was high unlike in this study where sampling was done in dry season (January). Soil pH is usually lower during dry spells as a result of soil drying and nitrification of nitrogenous fertilizers (Brady and Weil, 1999). Added fertilizers can also concentrate near the soil surface as the soil dries which displaces hydrogen ions from cation exchange complex and lower pH. Tea prunings left *in situ* did not influence soil pH levels at both sites.

4.1.2 Soil Available Nitrogen

Increasing rates of nitrogenous fertilizers significantly ($p \leq 0.05$) increased soil nitrogen levels at all depths in Kangaita (Tables 4 to 6). This trend conformed to patterns reported in earlier studies (Hamid *et al*., 1993; Hamid, 2006). The increasing levels of soil nitrogen could be attributed to the applied nitrogenous fertilizers. The results demonstrated that soil N deficiencies in Kangaita can be corrected through application of nitrogenous fertilizers. Responses in soil available N levels were rather different at Timbilil where increasing rates of nitrogenous fertilizers significantly decreased ($p \leq 0.05$) N levels at all depths. Surprisingly, control plots that never received fertilizer treatments had higher levels of soil available nitrogen than all nitrogen fertilizer treated plots. This result showed that increasing rates of nitrogenous fertilizers decreased available N in soils at this site. As reported elsewhere (Kamau *et al*., 1998; Sarwar *et al*., 2011), addition of nitrogenous fertilizers increases the mineralization process which induces leaching of the nitrate ions especially in high rainfall areas where tea grows. This reduces the levels of soil nitrogen that can be available to plants. Nitrate ions can also be lost in form of nitrous oxide as a result of excess nitrogen application (Oh *et al*., 2006).

Table 4.4: Variations in soil nitrogen levels (%) to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 0-15 cm)

Site	Pruning Management (PM)	Application (AI) interval (months)	Nitrogen rates in kg N/ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	0.623	0.628	0.538	0.705	0.623	0.636
		24	0.568	0.612	0.686	0.725	0.648	
		mean N rates	0.596	0.620	0.612	0.715		
		CV (%)			11.4			
		LSD (p≤0.05)			0.065		0.046	
		Interaction; N x AI			0.092			
	Prunings *in situ*	12	0.617	0.633	0.652	0.723	0.656	0.743
		24	0.701	0.792	0.906	0.919	0.830	
		mean N rates	0.659	0.713	0.779	0.821		
		CV (%)			11.8			
		LSD (p≤0.05)			0.067		0.048	
		Interaction; N x AI			0.053			
	Overall	12	0.620	0.631	0.595	0.714	0.640	
		24	0.635	0.702	0.796	0.822	0.739	
		mean N rates	0.627	0.666	0.696	0.768		
		CV (%)			4.0			
		LSD (p≤0.05)			0.023		0.016	0.016
		Interaction; N x AI			0.032			
		Interaction; N x PM			0.032			
		Interaction; AIxPM			0.023			
Timbilil	Prunings removed	12	0.613	0.489	0.441	0.433	0.494	0.471
		24	0.506	0.461	0.411	0.414	0.448	
		mean N rates	0.559	0.475	0.426	0.424		
		CV (%)			11.9			
		LSD (p≤0.05)			0.046		0.033	
		Interaction; N x AI			0.065			
	Prunings *in situ*	12	0.696	0.574	0.393	0.407	0.517	0.467
		24	0.400	0.411	0.426	0.433	0.417	
		mean N rates	0.548	0.492	0.409	0.420		
		CV (%)			12.96			
		LSD (p≤0.05)			0.111		NS	
		Interaction; N x AI			0.158			
	Overall	12	0.654	0.531	0.417	0.420	0.506	
		24	0.453	0.436	0.419	0.423	0.433	
		mean N rates	0.554	0.484	0.418	0.422		
		CV (%)			10.5			
		LSD (p≤0.05)			0.041		0.029	NS
		Interaction; N x AI			0.058			

Insignificant interactions not shown, NS means not significant

Table 4.5: Variations in soil nitrogen levels (%) to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 15-30 cm)

Site	Pruning Management (PM)	Application (AI) interval (months)	Nitrogen rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	0.786	0.745	0.783	0.831	0.786	0.754
		24	0.729	0.675	0.712	0.767	0.721	
		mean N rates	0.757	0.710	0.748	0.799		
		CV (%)			14.0			
		LSD (p≤0.05)			0.082		NS	
		Interaction; N x AI			0.117			
	Prunings *in situ*	12	0.478	0.578	0.736	0.816	0.652	0.672
		24	0.843	0.660	0.544	0.723	0.693	
		mean N rates	0.660	0.619	0.640	0.770		
		CV (%)			14.9			
		LSD (p≤0.05)			NS		0.062	
	Overall	12	0.632	0.661	0.759	0.824	0.719	
		24	0.786	0.667	0.628	0.745	0.707	
		mean N rates	0.709	0.664	0.694	0.784		
		CV (%)			9.5			
		LSD (p≤0.05)			0.056		NS	0.040
		Interaction; N x AI			0.080			
		Interaction; AI x PM			0.056			
		N x AI x PM			0.112			
Timbilil	Prunings removed	12	0.572	0.498	0.488	0.459	0.504	0.449
		24	0.455	0.436	0.353	0.331	0.394	
		mean N rates	0.514	0.467	0.420	0.395		
		CV (%)			11.4			
		LSD (p≤0.05)			0.041		0.029	
	Prunings *in situ*	12	0.502	0.473	0.395	0.344	0.428	0.419
		24	0.435	0.438	0.384	0.381	0.410	
		mean N rates	0.468	0.455	0.389	0.363		
		CV (%)			13.6			
		LSD (p≤0.05)			0.049		NS	
	Overall	12	0.537	0.485	0.441	0.401	0.466	
		24	0.445	0.437	0.368	0.356	0.402	
		mean N rates	0.491	0.461	0.405	0.379		
		CV (%)			9.2			
		LSD (p≤0.05)			0.033		0.024	0.024
		Interaction; AI x PM			0.033			

Insignificant interactions not shown, NS means not significant

Table 4.6: Variations in soil nitrogen levels (%) to different rates and intervals of NPKS25:5:5:5 fertilizer application and pruning managements (soil depth; 40-60 cm)

Site	Pruning Management (PM)	Application (AI) interval (months)	Nitrogen rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	0.710	0.714	0.726	0.752	0.725	0.744
		24	0.717	0.727	0.776	0.833	0.763	
		mean N rates	0.713	0.721	0.751	0.792		
		CV (%)			10.8			
		LSD (p≤0.05)			NS		NS	
		Interaction; N x PM			0.092			
	Prunings *in situ*	12	0.800	0.544	0.587	0.624	0.639	0.714
		24	0.881	0.771	0.769	0.736	0.789	
		mean N rates	0.840	0.658	0.678	0.680		
		CV (%)			10.7			
		LSD (p≤0.05)			NS		NS	
		Interaction; N x PM			0.091			
	Overall	12	0.755	0.629	0.656	0.688	0.682	
		24	0.799	0.749	0.773	0.785	0.776	
		mean N rates	0.777	0.689	0.715	0.736		
		CV (%)			6.8			
		LSD (p≤0.05)			0.041		0.029	0.029
		Interaction; N x PM			0.058			
		Interaction; AI x PM			0.041			
Timbilil	Prunings removed	12	0.587	0.494	0.370	0.368	0.455	0.411
		24	0.424	0.378	0.313	0.352	0.367	
		mean N rates	0.505	0.436	0.341	0.360		
		CV (%)			10.2			
		LSD (p≤0.05)			0.046		0.033	
		Interaction; N x AI			0.108			
	Prunings *in situ*	12	0.304	0.360	0.388	0.366	0.354	0.343
		24	0.344	0.354	0.299	0.329	0.331	
		mean N rates	0.324	0.357	0.343	0.348		
		CV (%)			8.3			
		LSD (p≤0.05)			NS		NS	
		Interaction; N x AI			0.074			
	Overall	12	0.445	0.427	0.379	0.367	0.405	
		24	0.384	0.366	0.306	0.340	0.349	
		mean N rates	0.415	0.396	0.342	0.354		
		CV (%)			9.5			
		LSD (p≤0.05)			0.030		0.021	0.021
		Interactions; N x PM			0.042			
		AI x PM			0.030			
		N x AI x PM			0.059			

Insignificant interactions are not shown, NS means not significant

Increased uptake of ammonium ions by tea plants (Marchner, 1986; Kebeney *et al.*, 2010) with increasing nitrogenous fertilizer application rates also reduces soil nitrogen. These factors compounded with N losses through continuous harvesting (Hamid, 2004) may account for the observed trend at Timbilil. These results have shown that Timbilil soils have more nitrogen and may not need regular NPKS fertilizer application unless deficiency is detected. The results also demonstrate that each site may require specific fertilizer application rates in order to sustain high yields of tea.

In Timbilil, soil N levels were higher at surface layers but decreased linearly down the soil depths (Tables 4.4-4.6) as had been reported in previous studies (Hamid *et al*., 1993; Hamid, 2006; Thenmozhi *et al*., 2012). High levels of soil nitrogen at surface soils could be attributed to leaf drops, retention of prunings *in situ* and immobilization of nitrogen in humic matter. Nitrogen-rich humic matter locks up N in the humus fraction making it less readily mineralized (Sivapalan, 1982). These results suggest that nitrogen in these soils is less mineralized and ends up being locked in humus fraction. In Kangaita, soil available N levels increased with increasing soil depths (Tables 4.4 to 4.6), similar to earlier findings (Sarwatar *et al*., 2011). The increase in N levels down the profile suggests that nitrogen leached to lower soil depths. This is possible because the nitrate ion is very mobile and largely moves with percolating water to lower soil depths (Sarwatar *et al*., 2011). Generally, soil N levels at all depths in Kangaita were above the suggested critical value (0.1-0.4%) for tea (Gilbert, 1983; Adiloğlu and Adiloğlu, 2006). This implies that nitrogen availability may not be a problem at this location. The varied levels of soil N at the two sites demonstrate that soil characteristics widely differ and each site may require specific agronomic inputs in order to maintain soil fertility and sustain high tea yields.

At all soil depths in Timbilil, 12 months interval of fertilizer application showed significantly higher ($p \leq 0.05$) levels of soil available N as compared to 24 months fertilizer application interval (Tables 4.4-4.6). However, in Kangaita, with an exception of soil depth 15-30 cm, biennial

NPKS fertilizer application had significantly ($p \leq 0.05$) higher levels of soil available N than annual NPKS fertilizer application. This was attributed to relatively lower amounts of nitrogen applied when fertilizer application was biennial. This probably reduced the ammonium ions taken up by tea plants and hydrogen ions released into the soils, thereby increasing soil pH (Tables 4.1-4.3) and available N. These results demonstrate that application of NPKS 25:5:5:5 fertilizer biennially increases levels of soil available N at Kangaita. Biennial fertilizer application appears the most suitable way of applying NPKS fertilizer at this location. Therefore, if tea yields do not become limiting, application of NPKS fertilizer biennially may be the most economic way of fertilization at Kangaita. The observed trend in Timbilil could be a reflection of excess nitrogen when fertilizer application was done annually. As observed earlier, increasing nitrogen rates reduced levels of soil available N (Tables 4-6) at this site. However, soil N levels obtained were within the optimal range of 0.12 to 0.40 % for tea (Gilbert, 1983; Sillanpaa, 1990; Adiloğlu and Adiloğlu, 2006). This demonstrates that annual fertilizer application as currently recommended (Anon, 2002) may not create a problem in N availability at Timbilil. Indeed, Timbilil site may require fertilizer application intervals longer than 24 months.

Prunings left *in situ* significantly ($p \leq 0.05$) increased levels of soil available nitrogen at surface soils (depth 0-15 cm) at Kangaita (Tables 4.4-4.6), similar to previous results in India (Ranganathan, 1973, 1977) and Kenya (Othieno, 1981; Kamau, 2008). This reflected the high levels of nitrogen in tea prunings. Increased levels of soil N were attributed to decomposition and mineralization of tea prunings as high levels of nitrogen are found in leafy portions of tea (Dogo, 1994). This result meant that prunings left *in situ* improve soil N availability at Kangaita. Noticeably, the effect of prunings *in situ* on soil N was only seen in the uppermost depth as soil N levels in the two lower depths were significantly ($p \leq 0.05$) lower with tea prunings left *in situ* in fields than when prunings were removed. Decrease in levels of available nitrogen in lower soil depths implies that beneficial effects of tea prunings mulch on N availability are restricted at surface soils. In Timbilil, soil N levels were significantly ($p \leq 0.05$) lower with prunings left *in situ* than prunings removed at the two lower depths. This effect was also seen at surface soils but was not significant. Sivapalan (1982) observed that addition of nitrogen poor residues to soils results to N immobilization that reduces mineralization. Prunings also contain insoluble polyphenols (tannins and phenolics) which inhibit the nitrification process (Sivapalan, 1982). This lowers the amount of nitrogen released into the soil. Tea prunings with wider carbon: nitrogen ratios decompose slowly and even immobilize the N applied as fertilizer (Dogo, 1994). These results show that factors controlling mineralization of prunings and release of N in soils differ with location of production. Thus, pruning management practice adopted for tea should be region specific if soil N availability is to be sustained. Farmers at Kangaita can be encouraged to leave prunings in tea plantations for improved N availability and sustained crop yields.

4.1.3 Soil Available Phosphorus

Soil extractable phosphorus levels at the three different depths are presented in Tables 4.7-4.9. The levels of available P in soils were high at the upper soil depth but reduced in lower depths. This was in agreement with previous findings (Bonheure and Willson, 1992; Kebeney *et al*., 2010; Owuor *et al*., 2011b). As observed earlier (Dogo *et al*., 1994), mobility of P in soils is usually low due to immobilization in the soil organic matter or fixation on variable soil charges (Brady and Weil, 2002). The low levels of soil extractable P in lower depths demonstrated that phosphorus is immobile and gets adsorbed on adsorption sites with long term use of NPKS fertilizer. This may explain the observed build up of the nutrient at surface soil layers. However, available P contents were above the deficiency levels of 10 ppm (Nazrul *et al*., 2013) and may not be a constraint in tea production.

Levels of soil extractable phosphorus increased with increasing nitrogenous fertilizer rates at all depths. This may be a reflection of the phosphorus supplied in the NPKS fertilizers used. Although not significant, responses to fertilizer rates appeared quadratic, with peaks at 60 and 120 kg N/ha/year at Timbilil and Kangaita, respectively. Above these maxima points, soil extractable P contents declined as observed in previous studies (Wanyoko *et al*., 1992a; Dogo *et al*., 1994; Kebeney *et al*., 2010). This could be attributed to decrease in soil pH (Tables 4.1-4.3). As soil pH decreased with increasing rates of NPKS fertilizer application, much of the applied P seemed to be locked up. Decrease in soil pH with increasing nitrogenous fertilizer rates fixes and reduces P availability in soils (Wanyoko *et al*., 1992a; Bonheure and Willson, 1992). In this study, levels of available phosphorus increased despite a decrease in soil pH especially in Kangaita. This was attributed to increased amounts of phosphorus added to the soils through application of NPKS fertilizers. Decline in levels of soil extractable P at higher nitrogen rates was more pronounced at Timbilil, possibly due to the higher rate of soil acidification at this site (Tables 4.1-4.3). At low pH, phosphates ($H_2PO_4^-$) normally react with Al, Fe and Mn ions in soils forming insoluble hydroxyl phosphates (Brady and Weil, 2002; Othieno, 1980) which render the nutrient unavailable. The levels of soil available P obtained were, however, above 13 ppm, considered deficiency limit for tea. Nevertheless, soil pH may be a limiting factor to availability of phosphorus and crop production especially at Timbilil.

Table 4.7: Variations in soil available P levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 0-15 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	41.3	35.0	53.0	54.7	46.0	44.6
		24	39.0	62.3	30.0	41.7	43.2	
		Mean rates	40.2	48.7	41.5	48.2		
		CV (%)			64.1			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	31.0	31.7	44.3	43.7	37.7	42.8
		24	52.7	62.0	40.3	37.0	48.0	
		Mean rates	41.8	46.8	42.3	40.3		
		CV (%)			42.3			
		LSD(p≤0.05)			NS		NS	
	Overall	12	36.2	33.3	48.7	49.2	41.8	
		24	45.8	62.2	35.2	39.3	45.6	
		Mean rates	41.0	47.8	41.9	44.2		
		CV (%)			54.7			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	18.0	20.3	14.7	15.0	17.0	19.6
		24	19.7	21.3	21.7	26.3	22.3	
		Mean rates	18.8	20.8	18.2	20.7		
		CV (%)			41.2			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	19.7	26.3	22.3	14.0	20.6	21.5
		24	20.3	21.3	23.7	24.3	22.4	
		Mean rates	20.0	23.8	23.0	19.2		
		CV (%)			42.7			
		LSD(p≤0.05)			NS		NS	
	Overall	12	18.8	23.3	18.5	14.5	18.8	
		24	20.0	21.3	22.7	25.3	22.3	
		Mean rates	19.4	22.3	20.6	19.9		
		CV (%)			42.0			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.8: Variations in soil available P levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 15-30 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	17.0	24.0	32.7	31.0	26.2	28.5
		24	21.3	40.7	34.3	26.7	30.8	
		Mean rates	19.2	32.3	33.5	28.8		
		CV (%)			49.4			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	18.3	26.0	37.0	34.7	29.0	28.2
		24	28.0	32.0	24.0	25.3	27.3	
		Mean rates	23.2	29.0	30.5	30.0		
		CV (%)			49.6			
		LSD(p≤0.05)			NS		NS	
	Overall	12	17.7	25.0	34.8	32.8	27.6	
		24	24.7	36.3	29.2	26.0	29.0	
		Mean rates	21.2	30.7	32.0	29.4		
		CV (%)			49.5			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	18.0	18.0	14.7	14.0	16.2	18.1
		24	19.0	22.3	17.7	21.3	20.1	
		Mean rates	18.5	20.2	16.2	17.7		
		CV (%)			24.3			
		LSD(p≤0.05)			NS		3.8	
	Prunings *in-situ*	12	18.3	20.0	20.0	13.3	17.9	20.1
		24	19.0	21.7	17.7	-	22.3	
		Mean rates	18.7	20.8	18.8	22.2		
		CV (%)			44.4			
		LSD(p≤0.05)			NS		NS	
	Overall	12	18.2	19.0	17.3	13.7	17.0	
		24	19.0	22.0	17.7	26.2	21.2	
		Mean rates	18.6	20.5	17.5	19.9		
		CV (%)			36.8			
		LSD(p≤0.05)			NS		4.1	NS

Insignificant interactions are not shown, NS means not significant

Table 4.9: Variations in soil available P levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 40-60 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	16.3	19.3	30.7	29.7	24.0	24.2
		24	17.3	34.3	22.0	23.7	24.3	
		Mean rates	16.8	26.8	26.3	26.7		
		CV (%)			43.2			
		LSD($p \leq 0.05$)			NS		NS	
	Prunings *in-situ*	12	16.3	22.7	37.7	25.7	25.6	25.2
		24	24.3	28.3	23.3	23.0	24.8	
		Mean rates	20.3	25.5	30.5	24.3		
		CV (%)			48.4			
		LSD($p \leq 0.05$)			NS		NS	
	Overall	12	16.3	21.0	34.2	27.7	24.8	
		24	20.8	31.3	22.7	23.3	24.5	
		Mean rates	18.6	26.2	28.4	25.5		
		CV (%)			46.0			
		LSD($p \leq 0.05$)			NS		NS	NS
Timbilil	Prunings removed	12	17.0	19.3	20.3	13.0	17.4	18.5
		24	18.0	22.0	17.3	20.7	19.5	
		Mean rates	17.5	20.7	18.8	16.8		
		CV (%)			30.0			
		LSD($p \leq 0.05$)			NS		NS	
	Prunings *in-situ*	12	17.3	20.3	19.0	14.3	17.8	18.7
		24	18.3	20.0	16.7	23.3	19.6	
		Mean rates	17.8	20.2	17.8	18.8		
		CV (%)			31.1			
		LSD($p \leq 0.05$)			NS		NS	
	Overall	12	17.2	19.8	19.7	13.7	17.6	
		24	18.2	21.0	17.0	22.0	19.5	
		Mean rates	17.7	20.4	18.3	17.8		
		CV (%)			30.6			
		LSD($p \leq 0.05$)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Though not significant, levels of soil extractable P appeared higher during 24 months interval of fertilizer application as compared to 12 months durations at all depths and sites. This was expected as fertilizer application over 2 years period reduced the added N leading to increased pH in the soil. Soils with low pH tend to have low levels of available phosphorus as the nutrient is fixed as insoluble phosphates of aluminium, iron and manganese (Bhattacharya and Dey, 1983; Brady and Weil, 2002). However, with higher pH, there seem to be reactions taking place in soils that increase solubility of the phosphates thus releasing more phosphorus. Indeed, as seen in Table 4.2, longer duration of NPKS application improved soil pH by 0.09 units (depth 15-30 cm) in Timbilil leading to significantly ($p \leq 0.05$) higher levels of extractable P. Previous findings (Kebeney *et al*., 2010) showed that application of NPKSs fertilizers annually had higher levels of soil extractable P than biennial fertilization. This was attributed to past use of NPKS fertilizers. The contrasting results show that apart from soil pH, environmental factors play a role in determining availability of P in soils. These results have demonstrated that one way of improving availability of phosphorus in tea soils, especially at Timbilil, is by raising the pH. Application of NPKS fertilizer using 24 months intervals would therefore be recommended for tea in Timbilil, provided tea yields do not decline.

The levels of soil available P at all depths in the two sites were not significantly different due to the pruning managements used. However, with prunings retained *in situ*, levels of soil available P appeared higher in all studied depths at Timbilil as compared to P levels obtained with prunings removed. This pattern was similar to results obtained in earlier studies (Ranganathan, 1973; Kamau, 2008). Higher soil P levels could be due to mineralization of prunings in soils. The trend was different in Kangaita where lower levels of available P were obtained at all soil depths with prunings left *in situ* than when removed. This implied that either P in prunings was not mineralized or any mineralized phosphorus was locked up in organic matter. In past studies (Ranganathan, 1973; Othieno, 1980; Kamau, 2008), leaving prunings *in situ* significantly increased levels of soil available phosphorus. Lack of significance could imply existence of other factors such as quantity/quality of prunings, soil type and climatic conditions that determine availability of P in soils. However, retaining prunings *in situ* at Timbilil seem beneficial in improving availability of soil phosphorus.

4.1.4 Soil Available Potassium

The effects of rates and intervals of NPKS fertilizer application and pruning management types on soil extractable potassium are summarized in Tables 4.10-4.12. Soil available potassium levels were high at the uppermost depth but decreased down the profile in both sites. This was in agreement with previous findings (Kamau *et al*., 2008; Kebeney *et al*., 2010). The higher contents of exchangeable K at surface soils than subsoils could be attributed to continuous application of NPKS fertilizers, addition of leaf litter (Owuor *et al*., 1987; Kamau *et al*., 1998), release of labile potassium from organic residues and upward translocation of potassium with capillary rise of ground water (Rao *et al*., 1997). Available potassium in these soils was far above the critical value of 80-100 ppm (Alam, 1999; Ruan *et al*., 2013) for tea. These soils contain excess levels of potassium which had also been reported in Kericho (Wanyoko and Mwakha, 1991; Ng'etich *et al*., 1995). Thus, potassium availability to tea plants may not be a problem as most feeder roots of tea are concentrated in the 0-15 cm soil depth.

Table 4.10: Variations in soil available K levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 0-15 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	406	777	350	541	518	448
		24	683	414	151	263	378	
		Mean rates	544	596	250	402		
		CV (%)			69.3			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	681	609	543	715	637	555
		24	402	446	741	302	473	
		Mean rates	542	527	642	508		
		CV (%)			76.6			
		LSD(p≤0.05)			NS		NS	
	Overall	12	544	693	446	628	578	
		24	543	430	446	283	425	
		Mean rates	543	561	446	455		
		CV (%)			74.2			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	301	406	379	344	358	349
		24	263	301	381	416	340	
		Mean rates	282	353	380	380		
		CV (%)			38.3			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	359	602	337	808	526	480
		24	343	411	615	364	433	
		Mean rates	351	506	476	586		
		CV (%)			78.7			
		LSD(p≤0.05)			NS		NS	
	Overall	12	330	504	358	576	442	
		24	303	356	498	390	387	
		Mean rates	316	430	428	483		
		CV (%)			68.4			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.11: Variations in soil available K levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 15-30 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Pruning removed	12	165	475	239	488	342	326
		24	338	379	332	191	310	
		Mean rates	252	427	285	340		
		CV (%)			56.8			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	326	341	432	787	471	390
		24	379	306	288	260	308	
		Mean rates	352	324	360	523		
		CV (%)			53.0			
		LSD(p≤0.05)			NS		NS	
	Overall	12	246	408	335	638	407	
		24	358	342	310	226	309	
		Mean rates	302	375	323	432		
		CV (%)			54.8			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	263	316	317	278	294	290
		24	205	245	331	365	286	
		Mean rates	234	280	324	321		
		CV (%)			42.8			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	278	447	288	440	363	376
		24	348	279	554	372	388	
		Mean rates	313	363	421	406		
		CV (%)			59.2			
		LSD(p≤0.05)			NS		NS	
	Overall	12	271	381	303	359	328	
		24	276	262	442	369	337	
		Mean rates	274	322	372	364		
		CV (%)			54.1			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.12: Variations in soil available K levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (Soil depth; 40-60 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	177	319	218	515	307	271
		24	252	278	238	174	235	
		Mean rates	214	298	228	344		
		CV (%)			54.7			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	280	279	402	446	352	327
		24	371	299	307	233	303	
		Mean rates	326	289	354	339		
		CV (%)			61.4			
		LSD(p≤0.05)			NS		NS	
	Overall	12	229	299	310	480	330	
		24	311	288	273	203	269	
		Mean rates	270	294	291	342		
		CV (%)			59.0			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	300	223	289	222	258	240
		24	164	211	266	248	222	
		Mean rates	232	217	277	235		
		CV (%)			53.1			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	195	359	227	293	269	292
		24	231	233	450	344	314	
		Mean rates	213	296	339	318		
		CV (%)			54.8			
		LSD(p≤0.05)			NS		NS	
	Overall	12	248	291	258	257	263	
		24	198	222	358	296	268	
		Mean rates	223	256	308	276		
		CV (%)			54.4			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Increasing rates of NPKS fertilizer resulted into irregular patterns in soil available potassium contents (Tables 4.10-4.12). However, the general trend was that increasing NPKS fertilizer application rates caused an overall increase in soil exchangeable K contents at all depths, except surface depth at Kangaita. Such sporadic changes in potassium levels had also been reported in previous work (Kamau *et al*., 2008). The data herein appeared to reveal a positive quadratic trend in soil extractable K (depths 15-30 and 40-60 cm) levels with increasing fertilizer rates at Timbilil. Similar responses had been reported in an earlier study (Wanyoko *et al*., 1996). The effects of nitrogen rates on soil K contents were not significant, demonstrating that rates of NPKS fertilizer did not affect potassium levels in these soils. This may be due to past use of NPKS fertilizer coupled with high K contents in parent materials from which these soils formed. Generally, levels of potassium were very high and above the threshold value of 80-100 ppm for tea (Ruan *et al*., 2013), suggesting that the nutrient was abundant in these soils.

Fertilizer application intervals did not have significant effects on levels of soil extractable potassium at all studied depths at both sites. This was in agreement with findings in a past study (Dogo *et al*., 1994) where splitting annual fertilizer application resulted into non significant effects on soil extractable potassium levels. Both fertilizer application intervals showed soil available potassium levels that were above the deficiency limit of 80-100ppm (Alam, 1999) in tea soils. This suggested that the nutrient is adequate in these soils, probably due to past use of NPKS fertilizers or the soils were naturally rich in potassium. These results demonstrate that NPKS fertilizers may be applied annually or biennially depending on factors such as cash flow, availability of fertilizers, etc, provided tea yields do not decline.

Soil extractable K levels were not significantly affected by pruning management types but the levels were generally high when tea prunings were left *in situ* in tea fields as compared to prunings removed from fields. Though the differences in soil available K due to different pruning management types were not significant, the high levels with prunings retained in fields supported earlier observations (Wanyoko *et al*., 1996; Ranganathan, 1973) that extractable potassium levels are usually high when prunings are left *in situ.* Lack of significant differences in potassium levels due to pruning management types indicated adequate levels of this nutrient in these soils.

4.1.5 Soil Available Calcium

Soil extractable calcium as influenced by rates and intervals of NPKS fertilizer application and pruning management are presented in Tables 4.13-4.15. High exchangeable calcium levels were observed at the surface soils (0-15 cm) but decreased down the profiles. These results agree with findings in previous studies (Kamau *et al*., 1998; Kebeney *et al*., 2010). The high levels of calcium at the soil surface might have resulted from increased organic matter content from continuous leaf fall and tea prunings.

Calcium contents in soils had varied responses to the nitrogenous fertilizer application rates at the two locations. There was a consistent nonsignificant decrease in soil available calcium levels with increasing NPKS fertilizer application rates at all depths in Timbilil. The results were in agreement with past research works (Wanyoko *et al*., 1992a; Kamau *et al*., 2008; Kebeney *et al*., 2010).

Table 4.13: Variations in soil available Ca levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 0-15 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	371	446	413	390	405	436
		24	462	807	186	411	467	
		Mean rates	416	627	300	400		
		CV (%)			65.7			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	457	867	376	992	673	768
		24	546	1108	702	1099	864	
		Mean rates	502	987	539	1046		
		CV (%)			69.2			
		LSD(p≤0.05)			NS		NS	
	Overall	12	414	656	394	691	539	
		24	504	958	444	755	665	
		Mean rates	459	807	419	723		
		CV (%)			70.9			
		LSD(p≤0.05)			NS		NS	251
Timbilil	Prunings removed	12	226	300	274	216	254	292
		24	486	269	300	265	330	
		Mean rates	356	285	287	241		
		CV (%)			85.3			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	470	475	301	115	340	349
		24	416	338	260	421	359	
		Mean rates	443	407	280	268		
		CV (%)			66.8			
		LSD(p≤0.05)			NS		NS	
	Overall	12	348	388	287	165	297	
		24	451	304	280	343	344	
		Mean rates	399	346	283	254		
		CV (%)			75.3			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.14: Variations in soil available Ca levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 15-30 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	159	240	319	396	279	319
		24	230	501	392	311	359	
		Mean rates	195	371	355	354		
		CV (%)			72.2			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	468	455	310	376	402	427
		24	559	398	370	480	452	
		Mean rates	514	426	340	428		
		CV (%)			50.5			
		LSD(p≤0.05)			NS		NS	
	Overall	12	314	348	314	386	340	
		24	395	450	381	395	405	
		Mean rates	354	399	348	391		
		CV (%)			59.8			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	213	238	240	197	222	229
		24	336	222	194	192	236	
		Mean rates	274	230	217	194		
		CV (%)			57.6			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	394	283	215	118	252	253
		24	303	190	210	312	254	
		Mean rates	348	237	213	215		
		CV (%)			72.2			
		LSD(p≤0.05)			NS		NS	
	Overall	12	303	261	228	157	237	
		24	319	206	202	252	245	
		Mean rates	311	233	215	204		
		CV (%)			66.1			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.15: Variations in soil available Ca levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 40-60 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	175	244	386	343	287	285
		24	262	368	247	254	283	
		Mean rates	219	306	316	298		
		CV (%)			65.5			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	280	368	279	275	300	389
		24	507	423	484	500	478	
		Mean rates	394	396	381	387		
		CV (%)			55.9			
		LSD(p≤0.05)			NS		NS	
	Overall	12	228	306	333	309	294	
		24	385	396	365	377	381	
		Mean rates	306	351	349	343		
		CV (%)			60.1			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	163	204	247	116	183	186
		24	238	150	167	202	189	
		Mean rates	200	177	207	159		
		CV (%)			65.3			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	238	199	242	174	213	235
		24	277	191	203	354	256	
		Mean rates	257	195	222	264		
		CV (%)			67.6			
		LSD(p≤0.05)			NS		NS	
	Overall	12	200	201	244	145	198	
		24	257	171	185	278	223	
		Mean rates	229	186	215	212		
		CV (%)			67.2			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Reduction in soil exchangeable calcium levels could be attributed to leaching that is triggered by increased acidity in soils following application of high rates of nitrogenous fertilizers (Kebeney *et al*., 2010; Kamau *et al*., 1998; Owuor *et al*., 1988; Dogo *et al*., 1994). Even with no fertilizers added, control plots at this site had higher levels of soil available calcium than all nitrogen treated plots at all depths. This was probably due to high base accumulation resulting from continuous use of tea prunings with slow mineralization. However, with addition of nitrogen fertilizers, the mineralization process increased such that the tea plant was able to absorb higher amounts of soil available calcium hence reducing the Ca contents in soils. The results demonstrate that heavy application of nitrogenous fertilizers reduces accumulation of calcium in soils and may affect yields of tea. In Kangaita, soil exchangeable calcium levels showed a general increase with increasing N rates at all depths. However, the effects of nitrogen rates on soil Ca contents were sporadic and non significant but factors causing the sporadic responses were not discernable.

Intervals of NPKS fertilizer application did not cause significant changes on soil available calcium levels. Similar results had been reported in earlier works (Dogo, 1994; Kebeney *et al*., 2010). Though the changes were not significant, soil extractable calcium levels appeared higher during 24 months fertilizer applications as compared to 12 months applications at all depths in both sites. Generally, soil calcium contents obtained were above 90 ppm, suggested as the critical lower limit for tea (Alam, 1999). The results showed that application of nitrogenous fertilizers using either 12 or 24 months intervals does not influence calcium levels in tea soils.

Tea prunings left *in situ* significantly ($p \leq 0.05$) increased levels of soil available calcium at depth 0-15 cm in Kangaita. However, in the other two lower soil depths at Kangaita and all soil depths at Timbilil, effects of pruning management types on soil calcium contents were not significant. Continuous return of tea prunings and leaf drops increase base accumulation in the upper soil surfaces (Kamau *et al*., 1998) which may have caused the observed rise in calcium levels. Tea prunings contain reasonable levels of calcium in leaf portions (Dogo, 1994) and upon their decomposition and mineralization in tea plantations, substantial amounts of calcium are released into the soils. This increases the levels of exchangeable calcium in tea soils. Therefore, leaving tea prunings *in situ* is an important factor towards increasing availability of calcium in tea soils. This may improve productivity of tea and partly reduce the impact of nitrogenous fertilizers.

4.1.6 Soil Available Magnesium

Tables 4.16-4.18 show changes in soil available magnesium contents as influenced by rates and intervals of NPKS fertilizer application and pruning managements. At Timbilil, soil extractable magnesium levels were high at the upper depth of 0-15 cm but decreased down the soil profiles, similar to past findings (Kamau *et al*., 1998). This pattern was also observed in soil pH (Tables 4.1-4.3). The surface soils with higher pH values had high levels of extractable magnesium. Accumulation of Mg at surface soils may have also resulted from high organic matter due to thick mulch from leaf fall and prunings. This conservation measure leads to increased available magnesium in soils (Kamau, 2008). At Kangaita, there was a general decrease in magnesium contents from depth 0-15 cm to 15-30 cm followed by an increase at the lowest depth of 40-60 cm. This trend had also been observed in a similar study (Kebeney *et al*., 2010). The rise in levels of magnesium at lowest depth of 40-60 cm suggest leaching of this nutrient to lower soil depths due to increasing rates of nitrogenous fertilizers application (Bonheure and Willson, 1992; Kamau *et al*., 1998; Kebeney *et al*., 2010). This demonstrates that addition of nitrogenous fertilizers at 100-250 kg/ha/year eliminates magnesium from top soils at Kangaita which may induce deficiencies. The current rates may need to be reviewed downwards as they seem inappropriate at this site. However, farmers at Timbilil can continue applying N fertilizers using the current rates.

Table 4.16: Variations in soil available Mg levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 0-15 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	60	97	53	45	64	70
		24	77	88	44	97	77	
		Mean rates	69	93	49	71		
		CV (%)			54.2			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	83	127	60	96	91	95
		24	92	108	87	110	99	
		Mean rates	87	117	73	103		
		CV (%)			43.9			
		LSD(p≤0.05)			NS		NS	
	Overall	12	72	112	57	70	78	
		24	85	98	66	103	88	
		Mean rates	78	105	61	87		
		CV (%)			48.4			
		LSD(p≤0.05)			NS		NS	24
Timbilil	Prunings removed	12	40	45	70	38	48	50
		24	47	25	59	71	51	
		Mean rates	44	35	65	55		
		CV (%)			96.9			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	61	69	71	13	54	61
		24	71	67	52	87	69	
		Mean rates	66	68	61	50		
		CV (%)			77.3			
		LSD(p≤0.05)			NS		NS	
	Overall	12	51	57	70	26	51	
		24	59	46	56	79	60	
		Mean rates	55	52	63	52		
		CV (%)			86.1			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.17: Variations in soil available Mg levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 15-30 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	48	48	45	57	49	61
		24	56	76	59	97	72	
		Mean rates	52	62	52	77		
		CV (%)			51.3			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	86	66	65	67	71	75
		24	97	63	69	89	80	
		Mean rates	92	65	67	78		
		CV (%)			40.0			
		LSD(p≤0.05)			NS		NS	
	Overall	12	67	57	55	62	60	
		24	77	70	64	93	76	
		Mean rates	72	63	59	77		
		CV (%)			45.1			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	44	47	65	37	48	49
		24	53	59	40	49	50	
		Mean rates	49	53	53	43		
		CV (%)			93.4			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	53	59	55	21	47	51
		24	74	23	39	82	55	
		Mean rates	64	41	47	52		
		CV (%)			89.9			
		LSD(p≤0.05)			NS		NS	
	Overall	12	49	53	60	29	48	
		24	64	41	40	66	53	
		Mean rates	56	47	50	47		
		CV (%)			91.6			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.18: Variations in soil available Mg levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 40-60 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	48	75	45	59	57	64
		24	81	67	53	82	71	
		Mean rates	65	71	49	71		
		CV (%)			58.1			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	65	93	63	59	70	84
		24	109	66	116	105	99	
		Mean rates	87	79	90	82		
		CV (%)			61.9			
		LSD(p≤0.05)			NS		NS	
	Overall	12	56	84	54	59	63	
		24	95	66	85	94	85	
		Mean rates	76	75	69	76		
		CV (%)			61.2			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	33	60	65	20	44	44
		24	61	22	32	59	43	
		Mean rates	47	41	49	40		
		CV (%)			100.4			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	49	51	60	34	48	51
		24	61	19	50	87	54	
		Mean rates	55	35	55	60		
		CV (%)			87.1			
		LSD(p≤0.05)			NS		NS	
	Overall	12	41	55	63	27	46	
		24	61	21	41	73	49	
		Mean rates	51	38	52	50		
		CV (%)			93.3			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

There was a general decrease in levels of available magnesium at all depths and sites, except at depth 0-15 cm at Timbilil where soil magnesium contents increased in a quadratic manner with increasing rates of NPKS fertilizers application. The nitrogen effects were not significant but trends agreed with past studies (Wanyoko *et al*., 1992; Dogo *et al*., 1994; Kamau *et al*., 1998, 2008; Kebeney *et al*., 2010) where increased nitrogenous fertilizer rates reduced soil magnesium contents. In this study, soil pH (Tables 4.1-4.3) decreased with increasing rates of NPKS fertilizer application to levels lower than the recommended pH 4.5-5.6 (Othieno, 1988) for tea.

Increased acidity in soils coupled with high rainfall in tea growing areas trigger leaching of magnesium to lower soil depths. Therefore, low pH in these soils could be responsible for the observed decline in levels of magnesium as reported in other studies (Kamau *et al*., 1998; Ruan *et al*., 2006). These results have shown that high rates of nitrogenous fertilizers reduce soil magnesium contents.

Levels of soil exchangeable magnesium were not significantly affected by intervals of fertilizer application at both sites. Nonetheless, extractable magnesium concentrations were higher during 24 months intervals of NPKS application as compared to 12 months intervals. The mean intervals (Tables 16-18) showed that levels of available magnesium recorded for all depths during 12 months intervals of N application ranged between 46 and 51 ppm at Timbilil and 60 and 78 ppm at Kangaita. Similarly, magnesium levels recorded in 24 months intervals of fertilizer application were in the range 49-60 ppm and 76-88 ppm, at Timbilil and Kangaita, respectively. These values were comparable to soil magnesium contents in literature (Kamau *et al*., 2008; Kebeney *et al*., 2010) and also above the threshold value of 25 ppm (Alam, 1999) for tea plants. The results supported earlier observations (Dogo *et al*., 1994) that soil extractable nutrients levels are not influenced by frequency of fertilizer application. Therefore both intervals of nitrogen application can enhance adequate supply of magnesium in soils at the two sites.

Tea prunings left *in situ* in fields increased ($p \leq 0.05$) levels of soil extractable magnesium at depth 0-15 cm at Kangaita, similar to report elsewhere (Wang *et al*., 1997). However, in the other soil depths at Kangaita and all the depths at Timbilil, effects of pruning management types on soil magnesium contents were not significant. The higher levels of soil magnesium obtained with prunings *in situ* may have resulted from the mineralization process of tea prunings in fields as had been reported in China (Wang *et al*., 1997). Upon decomposition of tea prunings, substantial amounts of magnesium are released into the soil solution as the leafy parts of tea plants contain high levels of magnesium (Dogo, 1994). This increases the levels of extractable magnesium in soils. The results herein have shown that mineralization of tea prunings in soils increased soil available magnesium contents at Kangaita. The observed increase could increase uptake of magnesium leading to improved crop production. Therefore, retaining prunings *in situ* in Kangaita tea farm is a management practice that can improve soil quality and sustain optimal yields of tea.

4.1.7 Soil Available Manganese

In tea soils, manganese levels in the range 4-14 ppm are classified as low, 14-50 ppm - sufficient, 50-170 ppm - high and above 170 ppm - very high (FAO, 1990). According to Lindsay and Norvell (1978), 1.0 ppm of soil extractable Mn is the critical limit for plant available manganese. The soil extractable manganese levels are presented in Tables 4.19-4.21. High concentrations of soil extractable manganese were in the top soils but decreased in lower depths. The declining trend of Mn with soil depths had also been observed in tea soils of India (Nath, 2013), Tanzania (Meliyo *et al*., 2015) and Kenya (Kamau *et al*., 1998; Kebeney *et al*., 2010; Sitienei *et al*., 2016). The observed behavior is associated with soil organic matter that serves as a reservoir for most micronutrients (Brady and Weil, 2002; Nath, 2013). Soils with high organic matter tend to have higher micronutrients levels in top soils as the micronutrient is retained in organic matter fraction (Nath, 2013). In regard to the suggested critical limits for tea, soils at Kangaita had sufficient levels of Mn while levels of this micronutrient were high at Timbilil. The high levels of manganese in these soils could be due to low soil pH (Tables 4.1-4.3) which favours dissolution of Mn compounds as well as inherently high contents of this element in the parent material. Low pH in these soils may induce manganese toxicities.

There were varied responses in soil available manganese to increasing rates of NPKS fertilizers application at the two sites. While increasing rates of applied nitrogen increased soil extractable Mn at all depths in Timbilil, a general decline in levels of manganese was observed at all depths, except 15-30 cm at Kangaita. Several studies at Timbilil (Wanyoko *et al*., 1992a; Kamau *et al*., 1998; Kebeney *et al*., 2010) previously reported increase in soil available manganese with increasing N rates and therefore, the trend at Timbilil was expected. Increasing nitrogen rates normally reduce soil pH which increases solubilization and availability of manganese (Bhattacharya and Dey, 1983; Wanyoko and Mwakha, 1991) in soils. In this study, increasing rates of nitrogen application reduced soil pH and this could explain the observed increase in manganese levels at Timbilil. The concentration of extractable Mn also increases with increase in soil organic matter content (Nath, 2013), suggesting that soils at Timbilil could be high in organic matter content. Levels of zinc above 8 ppm are very high (Özyazici *et al*., 2011) and such high levels reduce availability of manganese in soils (Francis and Masilamoni, 2012).

Table 4.19: Variations in soil available Mn levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 0-15 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	19	14	12	14	15	15
		24	17	20	13	12	16	
		Mean rates	18	17	13	13		
		CV (%)			48.0			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	15	23	20	26	21	21
		24	19	29	20	19	22	
		Mean rates	17	26	20	22		
		CV (%)			41.3			
		LSD(p≤0.05)			NS		NS	
	Overall	12	17	18	16	20	18	
		24	18	25	17	16	19	
		Mean rates	17	21	16	18		
		CV (%)			44.3			
		LSD(p≤0.05)			NS		NS	5
Timbilil	Prunings removed	12	88	108	112	83	98	133
		24	140	219	110	207	169	
		Mean rates	114	164	111	145		
		CV (%)			82.5			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	104	150	160	126	135	147
		24	130	168	179	160	159	
		Mean rates	117	159	169	143		
		CV (%)			71.4			
		LSD(p≤0.05)			NS		NS	
	Overall	12	96	129	136	104	116	
		24	135	194	144	184	164	
		Mean rates	116	161	140	144		
		CV (%)			76.7			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.20: Variations in soil available Mn levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 15-30 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	12	13	10	12	12	14
		24	19	18	13	13	16	
		Mean rates	16	16	12	12		
		CV (%)			67.8			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	12	16	23	18	17	17
		24	15	17	15	18	16	
		Mean rates	13	17	19	18		
		CV (%)			49.5			
		LSD(p≤0.05)			NS		NS	
	Overall	12	12	14	17	15	14	
		24	17	18	14	15	16	
		Mean rates	14	16	15	15		
		CV (%)			57.9			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	94	78	115	59	86	112
		24	109	160	97	180	137	
		Mean rates	101	119	106	119		
		CV (%)			89.3			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	90	134	109	104	109	108
		24	81	141	86	119	106	
		Mean rates	85	137	97	111		
		CV (%)			70.5			
		LSD(p≤0.05)			NS		NS	
	Overall	12	92	106	112	81	98	
		24	95	150	92	150	122	
		Mean rates	93	128	102	115		
		CV (%)			80.8			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.21: Variations in soil available Mn levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 40-60 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	13	11	11	12	12	14
		24	13	23	12	13	15	
		Mean rates	13	17	12	13		
		CV (%)			66.2			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	14	18	22	14	17	17
		24	18	19	12	17	17	
		Mean rates	16	19	17	16		
		CV (%)			51.6			
		LSD(p≤0.05)			NS		NS	
	Overall	12	14	14	17	13	14	
		24	15	21	12	15	16	
		Mean rates	14	18	14	14		
		CV (%)			58.1			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	54	54	166	44	80	97
		24	57	152	77	173	115	
		Mean rates	55	103	122	108		
		CV (%)			84.2			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	60	104	101	93	90	82
		24	56	84	74	87	75	
		Mean rates	58	94	88	90		
		CV (%)			69.9			
		LSD(p≤0.05)			NS		NS	
	Overall	12	57	79	134	68	85	
		24	57	118	76	130	95	
		Mean rates	57	98	105	99		
		CV (%)			78.8			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Zinc levels in Kangaita soils were above 8 ppm (results presented elsewhere in tables 4.31-4.33). This may account for the decline in extractable Mn levels at Kangaita. However, this requires further experimentation to establish the true cause. Generally, levels of extractable manganese were quite high as compared to the threshold value (Lindsay and Norvell, 1978) for tea, indicating that current N rates could be creating manganese toxicities which may negatively affect tea growth and yields.

Intervals of NPKS application did not have significant effects on soil extractable manganese at all depths in both sites. This was in agreement with findings in a past study (Dogo *et al*., 1994) where extractable soil nutrients were not altered by splitting annual nitrogenous fertilizers application. At all depths under discussion, levels of extractable Mn during 24 months fertilizer application appeared higher than those recorded using 12 months application intervals but the differences were not significant. The results showed that intervals of fertilizer application did not influence availability of manganese in these soils. Farmers can therefore choose interval of fertilizer application based on other factors like ease of fertilizer storage, its availability and uniform fertilizer distribution on the ground but not manganese availability to tea plants.

With tea prunings left *in situ* in fields, levels of soil extractable manganese significantly increased ($p \leq 0.05$) at depth 0-15 cm in Kangaita. However nonsignificant effects were observed at depths 15-30 and 40-60 centimeters in Kangaita and all the three depths in Timbilil. The observed increase in Mn levels was due to mineralization of tea prunings. The leafy portions of tea prunings comprise of sizeable levels of manganese (Dogo, 1994) which upon decomposition and mineralization, release reasonable amounts of Mn into the soils. Therefore, retention of tea prunings in Kangaita may create Mn toxicities and possible nutrient imbalances that may lower soil quality and crop productivity.

4.1.8 Soil Available Aluminium

Tables 4.22-4.24 summarize the effects of NPKS application rates and intervals and pruning managements on soil extractable aluminium at all studied depths. Levels of extractable Al showed varied trends down the profiles in the different intervals of fertilizer application. In 12 months intervals, soil aluminium contents at Timbilil decreased with depths but the levels of the nutrient increased down the soil profile at Kangaita. However, in 24 months intervals of fertilizer application, the trends reversed such that aluminium levels increased down the soil depths at Timbilil with a reduction being recorded at Kangaita. The inconsistent patterns indicated variability of aluminium in these soils, probably due to differences in soil types, climatic factors and past geological activities. The areas may require different nutrient management practices.

Increasing rates of NPKS fertilizer application increased soil available aluminium at all depths in Kangaita, which was consistent with data in literature (Owuor and Cheruiyot, 1989; Wanyoko *et al*., 1992a; Ruan *et al*., 2004, 2006). However, progressive rise in rates of NPKS fertilizer application had an opposite effect of reducing levels of extractable Al at all depths in Timbilil. Though the decrease in Al levels at the two lower depths appeared sporadic, the pattern at 0-15 cm was linear. Overall, the differences in soil Al levels due to increasing rates of NPKS fertilizers were not significant in both locations. The increase in soil exchangeable aluminium was expected as soils became more acidic (with pH less than 4.0) (Tables 4.1-4.3).

Table 4.22: Variations in soil available Al levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 0-15 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	192	167	208	228	199	202
		24	165	191	266	199	205	
		Mean rates	179	179	237	213		
		CV (%)			39.7			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	182	166	208	220	194	192
		24	187	200	207	170	191	
		Mean rates	184	183	207	195		
		CV (%)			30.2			
		LSD(p≤0.05)			NS		NS	
	Overall	12	187	167	208	224	197	
		24	176	196	236	184	198	
		Mean rates	182	181	222	204		
		CV (%)			35.5			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	143	95	104	110	113	100
		24	126	58	67	97	87	
		Mean rates	135	76	85	104		
		CV (%)			58.7			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	162	178	96	108	136	138
		24	168	126	97	168	140	
		Mean rates	165	152	97	138		
		CV (%)			30.2			
		LSD(p≤0.05)			NS		NS	
	Overall	12	153	136	100	109	125	
		24	147	92	82	132	113	
		Mean rates	150	114	91	121		
		CV (%)			42.8			
		LSD(p≤0.05)			NS		NS	30

Insignificant interactions are not shown, NS means not significant

Table 4.23: Variations in soil available Al levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 15-30 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	200	163	208	278	212	200
		24	169	209	176	197	188	
		Mean rates	184	186	192	238		
		Mean rates	184	186	192	238		
		CV (%)			32.0			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	156	162	210	219	187	188
		24	154	210	180	205	187	
		Mean rates	155	186	195	212		
		CV (%)			31.4			
		LSD(p≤0.05)			NS		NS	
	Overall	12	178	162	209	248	199	
		24	161	210	178	201	188	
		Mean rates	170	186	193	225		
		CV (%)			31.7			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	97	151	102	111	115	116
		24	142	113	71	144	118	
		Mean rates	119	132	87	128		
		CV (%)			45.7			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	162	170	93	101	132	122
		24	111	94	82	164	113	
		Mean rates	137	132	88	132		
		CV (%)			48.1			
		LSD(p≤0.05)			NS		NS	
	Overall	12	130	161	98	106	124	
		24	126	104	76	154	115	
		Mean rates	128	132	87	130		
		CV (%)			47.0			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.24: Variations in soil available Al levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 40-60 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	201	156	207	263	207	201
		24	176	207	196	199	194	
		Mean rates	188	182	202	231		
		CV (%)			28.5			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	188	167	207	231	198	193
		24	169	180	200	205	189	
		Mean rates	178	173	204	218		
		CV (%)			23.2			
		LSD(p≤0.05)			NS		NS	
	Overall	12	194	162	207	247	203	
		24	172	193	198	202	191	
		Mean rates	183	177	203	225		
		CV (%)			26.0			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	94	163	94	94	111	105
		24	100	84	66	146	99	
		Mean rates	97	123	80	120		
		CV (%)			56.7			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	100	110	88	113	103	122
		24	155	94	152	166	142	
		Mean rates	128	102	120	140		
		CV (%)			43.3			
		LSD(p≤0.05)			NS		NS	
	Overall	12	97	136	91	104	107	
		24	128	89	109	156	120	
		Mean rates	112	113	100	130		
		CV (%)			51.8			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Generally, increasing rates of nitrogenous fertilizers lower soil pH (Dogo *et al*., 1994; Kamau *et al*., 1998; Venkatesan *et al*., 2004; Kebeney *et al*., 2010) which increases solubilization and levels of available aluminium in soils (Owuor and Cheruiyot, 1989; Wanyoko and Mwakha, 1991; Ruan *et al*., 2006). Although high aluminium levels in soils stimulates growth rate in young tea plants (Ishigaki, 1984; Kinoshi *et al*., 1985), improves phosphorus uptake (Bhattacharya and Dey, 1983; Kinoshi *et al*., 1985) and tea quality (Edmonds and Gudnason, 1979), it reduces availability of base cations in soils (Ruan *et al*., 2006) and their uptake by tea plants (Kebeney *et al*., 2010; Kwach *et al*., 2014) which may reduce yields. The results demonstrate that high rates of nitrogenous fertilizers may induce Al toxicity and create nutrients imbalances in soils which may reduce tea yields.

Decrease in concentrations of soil extractable aluminium with increasing nitrogen rates at depth 0-15 cm in Timbilil was unexpected in such strongly acidic soils. This unusual response of aluminium to nitrogen fertilizers may have been caused by the amelioration effects of the bases especially calcium and magnesium (Mora *et al*., 2002). In Sri Lanka (Pathirana, 2000; Kavitha *et al*., 2015), reduction in soil aluminium levels was reported due to high magnesium contents in tea soils. High levels of soil available Ca (Tables 4.13-4.15) and Mg (Tables 16-18) were also observed in the current study. However, more trials are needed to ascertain the true cause.

There were no significant differences in soil extractable aluminium between the two intervals of fertilizer application in both sites. This suggested that intervals of NPKS fertilizer application were not among the factors affecting availability of aluminium in these soils. When the effects of pruning management were considered, extractable levels of aluminium increased significantly ($p \leq 0.05$) with tea prunings retained *in situ* at soil depth 0-15 cm in Timbilil. This was in agreement with observations made in China (Wang *et al*., 1997). However, at the other soil depths at both sites, pruning managements did not influence levels of soil extractable aluminium. Tea plants are high aluminium accumulators and in old leaves, levels upto 30,000 mg kg^{-1} had been recorded (Matsumoto *et al*., 1976). Upon mineralization of tea prunings in fields, substantial quantities of Al are released into the soil, making the nutrient more available. This may explain the observed increase in concentrations of aluminium at depth 0-15 cm in Timbilil. Therefore retention of tea prunings *in situ* in fields may create Al toxicity and create nutrients imbalances in soils at Timbilil which may affect crop yields.

4.1.9 Soil Available Iron

Levels of extractable iron in soils are considered low when less than 2.5 ppm and high when greater than 4.5 ppm (Lindsay and Novell, 1978). Soil extractable iron levels at the three depths are presented in Tables 4.25-4.27. Iron levels were high at surface depth but then decreased with increasing soil depth at both locations. The trend was similar to results obtained in previous research (Nath, 2013; Meliyo *et al*., 2015; Sitienei *et al*., 2016). The high levels of iron in top soils could be attributed to high contents of soil organic matter that has capacity to form complexes with Fe and render it more available (Brady and Weil, 2002; Nath, 2013). Based on the suggested critical limits, soil available iron contents in the study areas were too high and in excess, even at lowest soil depths. The excess levels of iron in soils could be attributed to low pH. At low soil pH, levels of iron in soils are usually high (Gabisoniya and Gabisoniya., 1973; Yemane *et al*., 2008; Nath, 2013). Adequate levels of Fe in tea plants ensure high yields and quality of tea (Kuzhandaivel and Venkatesan, 2011). However, excessively high levels of iron reported herein may pose soil fertility problems like P fixation, boron deficiency as well as Fe and Mn toxicities (Singh, 2009). Excess levels of Fe in the leaves suppress photosynthesis and may reduce yields.

Contents of iron in soils increased at all depths and sites due to increasing rates of NPKS fertilizer application as seen in Tables 4.25-4.27. The trends were similar to earlier results obtained in Russia (Gabisoniya and Gabisoniya., 1973), Ethiopia (Yemane *et al*., 2008) and Kenya (Sitienei *et al*., 2016) but the changes were not statistically different. Increasing nitrogen rates normally increase soil acidity (Kamau *et al*., 1998; Venkatesan *et al*., 2004; Kebeney *et al*., 2010) which increases solubilization and amounts of extractable iron in soils (Yemane *et al*., 2008; Nath, 2013). This makes the nutrient to become more available. Data herein show that increasing NPKS application rates reduced soil pH and this possibly accounted for the increased iron levels in these soils. Lack of significant differences due to varying rates of fertilizers implies high abundance of iron in these soils.

Concentrations of iron in soils were generally higher when NPKS fertilizer applications were done biennially as compared to annual nitrogen applications. However, extractable Fe levels in the two intervals of fertilization were not significantly different. Irrespective of the interval of fertilizer application, iron levels obtained were too high in comparison to set limits for tea (Lindsay and Novell, 1978), possibly due to high iron in parent material of these soils. From the results, it can be concluded that interval of fertilizer application has no impact on levels of iron in these soils. With tea prunings left *in situ*, levels of soil extractable iron seemed higher than levels obtained with prunings removed. However, there were no significant differences in Fe levels obtained due to different pruning managements applied. This implied that Fe availability in these soils is not influenced by pruning management applied.

Table 4.25: Variations in soil available Fe levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 0-15 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	109	59	127	148	111	106
		24	101	116	81	108	102	
		Mean rates	105	87	104	128		
		CV (%)			102.6			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	88	97	113	125	106	117
		24	130	97	143	147	129	
		Mean rates	109	97	128	136		
		CV (%)			93.2			
		LSD(p≤0.05)			NS		NS	
	Overall	12	98	78	120	137	108	
		24	115	106	112	128	115	
		Mean rates	107	92	116	132		
		CV (%)			97.6			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	46	46	45	28	41	45
		24	31	65	42	58	49	
		Mean rates	38	56	44	43		
		CV (%)			68.6			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	64	53	54	37	52	54
		24	34	51	59	79	56	
		Mean rates	49	52	56	58		
		CV (%)			80.0			
		LSD(p≤0.05)			NS		NS	
	Overall	12	55	49	49	33	47	
		24	33	58	51	68	52	
		Mean rates	44	54	50	51		
		CV (%)			75.8			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.26: Variations in soil available Fe levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 15-30 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	71	49	94	113	82	87
		24	73	88	111	95	92	
		Mean rates	72	68	102	104		
		CV (%)			100.8			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	69	80	107	99	89	89
		24	94	66	99	100	90	
		Mean rates	81	73	103	100		
		CV (%)			97.1			
		LSD(p≤0.05)			NS		NS	
	Overall	12	70	64	100	106	85	
		24	83	77	105	98	91	
		Mean rates	77	71	103	102		
		CV (%)			98.9			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	42	45	38	24	37	41
		24	33	55	40	54	45	
		Mean rates	37	50	39	39		
		CV (%)			71.5			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	49	41	54	32	44	44
		24	32	47	40	59	45	
		Mean rates	40	44	47	46		
		CV (%)			71.6			
		LSD(p≤0.05)			NS		NS	
	Overall	12	46	43	46	28	41	
		24	32	51	40	57	45	
		Mean rates	39	47	43	42		
		CV (%)			71.6			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.27: Variations in soil available Fe levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 40-60 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	61	73	90	114	85	86
		24	65	79	94	110	87	
		Mean rates	63	76	92	112		
		CV (%)			100.6			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	65	94	107	93	90	87
		24	83	61	102	88	83	
		Mean rates	74	78	104	91		
		CV (%)			103.0			
		LSD(p≤0.05)			NS		NS	
	Overall	12	63	84	99	104	87	
		24	74	70	98	99	85	
		Mean rates	68	77	98	101		
		CV (%)			101.8			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	29	48	43	25	36	39
		24	29	49	35	52	41	
		Mean rates	29	48	39	39		
		CV (%)			75.9			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	41	58	47	25	43	41
		24	31	42	31	53	39	
		Mean rates	36	50	39	39		
		CV (%)			83.8			
		LSD(p≤0.05)			NS		NS	
	Overall	12	35	53	45	25	39	
		24	30	45	33	53	40	
		Mean rates	32	49	39	39		
		CV (%)			80.2			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

4.1.10 Soil Available Copper

The maximum permissible limits for copper in soils are 2 to 250 ppm (Nath, 2013) but Lindsay and Novell (1978) suggested 0.2 ppm of soil extractable Cu as the critical limit for normal plant growth. Tables 4.28-4.30 show levels of soil exchangeable copper from the two experimental sites. Copper levels were high at surface soils but decreased down the soil depths, similar to previous studies (Nath, 2013; Meliyo *et al*., 2015), probably due to high organic mulch in top soils. Based on the critical levels set for tea, extractable Cu levels were quite high, suggesting that the parent materials from which these soils were formed were rich in copper. Adequate levels of Cu in tea plants improve fermentation during manufacture of black tea (Bonheure and Willson, 1992; Harler, 1971) but excess levels inhibit photosynthesis and enzyme activities which suppress tea growth rates and reduce yields (Yruela, 2005). Management practices geared towards reduction of copper in these soils are recommended.

There was an overall increase in levels of soil extractable copper with increase in NPKS fertilizer application rates at all studied depths and sites, except 0-15 cm at Timbilil where the levels seemed to reduce. However, the observed effects of nitrogen were not significant at both sites. The observed increase in copper levels followed similar patterns obtained in recent studies (Pitigala *et al*., 2013; Sitienei *et al*., 2016) and was attributed to increased soil acidity (Tables 4.1-4.3). At low pH, there is increased solubilization of copper that makes the nutrient more available in soils (Mozaffari *et al*., 1996). Generally, copper levels recorded at all depths were higher compared to the critical level (0.2 ppm) set for tea (Lindsay and Norvell, 1978). This may be detrimental to growth rates of tea and consequently, tea yields. In view of this, current rates of NPKS fertilizer application may need a downward review provided yields do not decrease.

Table 4.28: Variations in soil available Cu levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 0-15 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	1.0	6.3	5.0	5.3	4.4	4.4
		24	7.0	4.3	3.7	2.7	4.4	
		Mean rates	4.0	5.3	4.3	4.0		
		CV (%)			107.2			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	1.3	6.0	6.0	6.7	5.0	4.0
		24	3.3	1.7	1.7	5.7	3.1	
		Mean rates	2.3	3.8	3.8	6.2		
		CV (%)			102.7			
		LSD(p≤0.05)			NS		NS	
	Overall	12	1.2	6.2	5.5	6.0	4.7	
		24	5.2	3.0	2.7	4.2	3.8	
		Mean rates	3.2	4.6	4.1	5.1		
		CV (%)			105.3			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	2.7	3.7	1.0	1.7	2.3	2.5
		24	2.7	2.7	2.7	3.3	2.8	
		Mean rates	2.7	3.2	1.8	2.5		
		CV (%)			79.1			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	2.7	2.7	3.7	1.7	2.7	2.8
		24	2.7	3.0	2.3	3.3	2.8	
		Mean rates	2.7	2.8	3.0	2.5		
		CV (%)			53.5			
		LSD(p≤0.05)			NS		NS	
	Overall	12	2.7	3.2	1.8	2.5	2.5	
		24	2.7	2.8	2.5	3.3	2.8	
		Mean rates	2.7	3.0	2.2	2.7		
		CV (%)			66.6			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.29: Variations in soil available Cu levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 15-30 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	1.3	4.3	6.0	4.3	4.0	4.0
		24	3.3	6.0	4.3	2.3	4.0	
		Mean rates	2.3	5.2	5.2	3.3		
		CV (%)			121.4			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	1.7	3.3	5.7	5.7	4.1	4.0
		24	6.7	2.0	4.7	2.7	4.0	
		Mean rates	4.2	2.7	5.2	4.2		
		CV (%)			89.3			
		LSD(p≤0.05)			NS		NS	
	Overall	12	1.5	3.8	5.8	5.0	4.0	
		24	5.0	4.0	4.5	2.5	4.0	
		Mean rates	3.3	3.9	5.2	3.8		
		CV (%)			106.4			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	2.3	3.0	3.3	1.7	2.6	2.7
		24	2.3	2.7	2.0	4.0	2.8	
		Mean rates	2.3	2.8	2.7	2.8		
		CV (%)			84.5			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	2.7	2.3	4.0	1.3	2.6	2.5
		24	3.0	3.0	1.7	2.3	2.5	
		Mean rates	2.8	2.7	2.8	1.8		
		CV (%)			71.8			
		LSD(p≤0.05)			NS		NS	
	Overall	12	2.5	2.7	3.7	1.5	2.6	
		24	2.7	2.8	1.8	3.2	2.6	
		Mean rates	2.6	2.8	2.8	2.3		
		CV (%)			78.8			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.30: Variations in soil available Cu levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 40-60 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	1.1	4.8	5.2	4.7	4.0	3.9
		24	4.6	4.4	3.9	2.3	3.8	
		Mean rates	2.9	4.7	4.6	3.5		
		CV (%)			107.2			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	1.6	3.6	5.7	5.2	4.0	3.8
		24	5.0	3.3	2.7	3.6	3.7	
		Mean rates	3.3	3.5	4.2	4.4		
		CV (%)			102.7			
		LSD(p≤0.05)			NS		NS	
	Overall	12	1.3	4.2	5.4	5.0	4.0	
		24	4.8	3.9	3.3	2.9	3.7	
		Mean rates	3.1	4.0	4.4	4.0		
		CV (%)			100.6			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	2.0	4.0	3.3	0.3	2.4	2.6
		24	2.7	3.0	2.3	3.3	2.8	
		Mean rates	2.4	3.5	2.8	1.8		
		CV (%)			81.5			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	2.7	2.7	3.7	1.3	2.6	2.7
		24	3.0	3.0	2.3	2.3	2.7	
		Mean rates	2.9	2.9	3.0	1.8		
		CV (%)			66.0			
		LSD(p≤0.05)			NS		NS	
	Overall	12	2.3	3.3	3.5	0.8	2.5	
		24	2.8	3.0	2.3	2.8	2.7	
		Mean rates	2.6	3.2	2.9	1.8		
		CV (%)			74.2			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Fertilizer application interval did not significantly affect soil available copper contents at both sites. Copper levels obtained in both intervals of NPKS fertilizer application were above what is considered the minimum level for tea (Lindsay and Novell, 1978). The results show that Cu availability in these soils is not influenced by intervals of NPKS fertilizers application. Similarly, Cu contents in soils did not change significantly with pruning management types, implying that pruning management type is not a contributor to the availability of copper in these soils.

4.1.11 Soil Available Zinc

Zinc levels in tea soils lying in the range 0.2-0.7 ppm are considered low, 0.7-2.4 ppm sufficient, 2.4-8.0 ppm high and above 8.0 ppm– very high (FAO, 1990; Özyazici *et al*., 2011). The amounts of extractable zinc observed at the three soil depths are presented in Tables 4.31-4.33. Levels of zinc were lower at surface soils but then increased with increasing soil depths at both sites. This trend differed from observations made in India (Nath, 2013) and Tanzania (Meliyo *et al*., 2015) but was in agreement with findings in Kenya (Sitienei *et al*., 2016). The higher levels observed in lower soil depths were attributed to leaching of Zn as was recently reported (Sitienei *et al*., 2016). Generally, levels of zinc were high at Timbilil and very high at Kangaita, showing differences in ability of these soils to supply zinc to tea plants. An increased zinc level in soils improves tea yields (Barua and Dutta, 1972; Sedaghathoor *et al*., 2009). It therefore becomes important to maintain high levels of Zn in soils for improved tea production. Organic matter contents shows positive correlation with soil zinc levels (Nath, 2013) and increasing organic matter may be one way of maintaining high levels of zinc for improved yields.

Table 4.31: Variations in soil available Zn levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 0-15 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	6.3	6.0	11.7	8.3	8.1	8.1
		24	9.3	8.7	6.3	8.0	8.1	
		Mean rates	7.8	7.3	9.0	8.2		
		CV (%)			55.5			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	6.7	9.0	11.3	9.0	9.0	8.7
		24	8.0	10.0	7.3	8.3	8.4	
		Mean rates	7.3	9.5	9.3	8.7		
		CV (%)			56.6			
		LSD(p≤0.05)			NS		NS	
	Overall	12	6.5	7.5	11.5	8.7	8.5	
		24	8.7	9.3	6.8	8.2	8.3	
		Mean rates	7.6	8.4	9.2	8.4		
		CV (%)			56.1			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	10.0	7.0	6.0	5.0	7.0	6.5
		24	5.3	4.3	6.7	8.0	6.1	
		Mean rates	7.7	5.7	6.3	6.5		
		CV (%)			77.0			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	8.7	9.0	5.7	5.0	7.1	7.5
		24	9.7	5.7	6.7	10.0	8.0	
		Mean rates	9.2	7.3	6.2	7.5		
		CV (%)			77.3			
		LSD(p≤0.05)			NS		NS	
	Overall	12	9.3	8.0	5.8	5.0	7.0	
		24	7.5	5.0	6.7	9.0	7.0	
		Mean rates	8.4	6.5	6.3	7.0		
		CV (%)			77.3			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.32: Variations in soil available Zn levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 15-30 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	7.7	6.7	12.0	9.0	8.8	8.8
		24	8.7	10.0	8.0	8.7	8.8	
		Mean rates	8.2	8.3	10.0	8.8		
		CV (%)			60.3			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	7.7	7.7	11.3	9.7	9.1	8.8
		24	7.7	9.3	8.7	8.7	8.6	
		Mean rates	7.7	8.5	10.0	9.2		
		CV (%)			65.5			
		LSD(p≤0.05)			NS		NS	
	Overall	12	7.7	7.2	11.7	9.3	9.0	
		24	8.2	9.7	8.3	8.7	8.7	
		Mean rates	7.9	8.4	10.0	9.0		
		CV (%)			63.0			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	14.3	7.0	6.3	5.3	8.2	7.4
		24	6.0	5.0	6.7	8.7	6.6	
		Mean rates	10.2	6.0	6.5	7.0		
		CV (%)			96.2			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	9.3	9.0	6.7	6.7	7.9	9.0
		24	14.3	5.7	6.3	13.7	10.0	
		Mean rates	11.8	7.3	6.5	10.2		
		CV (%)			98.2			
		LSD(p≤0.05)			NS		NS	
	Overall	12	11.8	8.0	6.5	6.0	8.1	
		24	10.2	5.3	6.5	11.2	8.3	
		Mean rates	11.0	6.7	6.5	8.6		
		CV (%)			97.9			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.33: Variations in soil available Zn levels (ppm) due to rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements (soil depth; 40-60 cm)

Site	Pruning management (PM)	Application Intervals	N rates in kg N/ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	7.3	7.1	11.8	9.2	8.9	8.8
		24	8.8	10.0	7.4	8.4	8.7	
		Mean rates	8.1	8.6	9.6	8.8		
		CV (%)			55.5			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	7.0	8.6	11.3	9.2	9.0	9.0
		24	8.3	9.7	8.3	9.3	8.9	
		Mean rates	7.7	9.2	9.8	9.3		
		CV (%)			56.6			
		LSD(p≤0.05)			NS		NS	
	Overall	12	7.2	7.8	11.6	9.2	8.9	
		24	8.6	9.8	7.9	8.9	8.8	
		Mean rates	7.9	8.8	9.7	9.1		
		CV (%)			52.9			
		LSD(p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	26.7	8.0	6.3	4.7	11.4	9.6
		24	6.7	4.7	7.3	12.7	7.8	
		Mean rates	16.7	6.3	6.8	8.7		
		CV (%)			149.7			
		LSD(p≤0.05)			NS		NS	
	Prunings *in-situ*	12	16.7	9.3	7.0	5.7	9.7	10.3
		24	13.3	4.7	7.7	18.0	10.9	
		Mean rates	15.0	7.0	7.3	11.8		
		CV (%)			113.9			
		LSD(p≤0.05)			NS		NS	
	Overall	12	21.7	8.7	6.7	5.2	10.5	
		24	10.0	4.7	7.5	15.3	9.4	
		Mean rates	15.8	6.7	7.1	10.2		
		CV (%)			131.9			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Responses in levels of zinc in soils to varying rates of NPKS fertilizer application were different at the two sites. At all soil depths, increasing rates of nitrogenous fertilizer application increased zinc levels at Kangaita but reduced levels of zinc at Timbilil. The decrease in available Zn was similar to earlier observations (Wanyoko and Mwakha, 1991). The differences in responses could be due to differences in soil properties at the two sites. Factors like soil pH, nature of parent material and organic matter (OM) influence availability of Zn in soils (Alloway, 2008). Among these conditions, soil pH and organic matter contents have more pronounced effects on zinc. Low pH and high organic matter in soils reduce levels of zinc as the nutrient is strongly bound to OM fraction (Zhang *et al*., 2006). However, in most soils, low pH increases concentrations of the micronutrients iron, copper, manganese and zinc (Nath, 2013; Meliyo *et al*., 2015). Results herein show that soil pH (Tables 4.1-4.3) decreased with increasing nitrogen rates which could explain the observed increase in zinc levels at Kangaita. The results are in agreement with previous observations (Owuor, 1984). The different responses to same rates of NPKS fertilizer application suggest that each site may require specific rates of NPKS fertilizers application to realize optimal production.

Zinc contents in soils were not significantly influenced by intervals of NPKS fertilizer application at both locations. This indicates that availability of zinc in these soils is not affected by intervals of fertilizer application. This observation is coherent with earlier findings (Dogo *et al*., 1994) where splitting annual nitrogenous fertilizer application had no effect on soil nutrients levels. High levels of organic matter reduce levels of zinc (Zhang *et al*., 2006) as the nutrient is strongly bound to the organic matter fraction. In this study, levels of soil extractable zinc appeared higher when prunings were left *in situ* in fields than when removed. However, the effects were not significant. Thus pruning management types did not affect levels of soil available Zn at the two sites.

4.2 Summary on the Effects of Different Rates and Intervals of NPKS 25:5:5:5 Fertilizer Application and Pruning Managements on Soil pH and Extractable Nutrients Levels

Increasing rates and intervals of NPKS fertilizer application and pruning managements had varied effects on soil pH (Tables 4.1-4.3) and available soil nutrients (Tables 4.4-4.33) as discussed in previous sections. Except for soil pH and available nitrogen levels, the CVs for other soil nutrients levels were generally high. Such high CVs are common in tea soils, especially with nitrogenous fertilizer treatments (Kamau *et al*., 2003). This is mainly due to large errors in soil sampling caused by difficulty in spreading fertilizers uniformly on experimental plots. The high coefficients of variation imply that these soils are highly heterogenous and soil analysis may not be giving a fair estimate of nutrients levels available for tea plants. Due to the high CVs obtained, no conclusive trends could be established for soil nutrients availability. This suggested that mature leaf analysis may be a fair way of assessing nutrients availability in tea cultivation.

4.3 Variations in Mature Leaf Nutrients Levels with Rates and Intervals of NPKS 25:5:5:5 Fertilizer Application and Pruning Managements

4.3.1 Leaf Nitrogen

Variations in levels of nitrogen in mature leaves are presented in Table 4.34. Mature leaf nitrogen levels significantly increased ($p \leq 0.05$) with increasing rates of NPKS fertilizer application in both sites. The observed linear response was similar to trends reported in earlier studies (Kebeney *et al*., 2010; Owuor *et al*., 2011b; Kwach *et al*., 2011, 2012, 2014). The pattern in leaf nitrogen followed that observed in soils (Tables 4.4-4.6) especially at Kangaita where soil nitrogen levels increased with increasing fertilizer rates. The results demonstrate that nitrogen deficiencies in tea can be corrected by application of nitrogenous fertilizers as previously observed (Kebeney *et al*., 2010; Kwach *et al*., 2014). However, the data revealed disparity in trends observed in soil and leaf nitrogen contents at Timbilil. While an increase in nitrogenous fertilizer rates decreased soil N levels (Tables 4.4-4.6), it caused an increase in mature leaf nitrogen contents. This observation showed that either soil chemical analysis may not be measuring exactly the quantities of nitrogen that tea plants are able to take or the plants only extract what is enough for their growth. Therefore, leaf chemical analysis can fairly assess the efficiency of nitrogen extraction from the soils. This confirmed that mature leaf analysis is more precise in assessing nutritional demands of tea as recommended (Kamau *et al*., 2005; Kwach *et al*., 2011).

Mature leaf nitrogen levels below 3.00% are considered deficient while levels between 3.00% and 3.50% are mildly deficient/borderline and above 3.50% are adequate for tea growing in East Africa (Tolhurst, 1976; Othieno, 1988). In Kangaita, application of NPKS fertilizer annually resulted to significantly ($p \leq 0.05$) higher leaf N levels as compared to N levels obtained in biennial fertilizer application. This was in agreement with observations made in a similar study (Kebeney *et al.*, 2010). Similar pattern was observed at Timbilil but the changes were not significant. Data on soil chemical analysis (Tables 4.4-4.6) showed that annual application of NPKS fertilizer significantly reduced ($p \leq 0.05$) levels of soil extractable nitrogen which was expected to be reflected in leaf N contents as soil analysis estimates what the plant may be able to take (Nathan and Warmund, 2008). The inconsistency between soil and leaf N contents suggests inability of soil analysis to fairly estimate nutrients that can be absorbed by tea plants.

Table 4.34: Variations in mature leaf nitrogen levels (%) due to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	3.19	3.39	3.64	4.38	3.65	3.33
		24	2.82	3.10	3.13	2.99	3.01	
		Mean rates	3.00	3.24	3.38	3.69		
		CV (%)			10.8			
		LSD (p≤0.05)			0.44		0.31	
	Prunings *in situ*	12	3.00	3.08	3.92	3.59	3.40	3.35
		24	2.97	3.40	3.41	3.47	3.31	
		Mean rates	2.98	3.24	3.66	3.53		
		CV (%)			5.7			
		LSD (p≤0.05)			0.23		NS	
	Overall	12	3.10	3.23	3.78	3.98	3.52	
		24	2.89	3.25	3.27	3.23	3.16	
		Mean rates	3.00	3.24	3.52	3.61		
		CV (%)			8.6			
		LSD (p≤0.05)			0.24		0.17	NS
		Interaction						
		N x AI			0.33			
Timbilil	Prunings removed	12	3.16	3.16	3.25	4.01	3.40	3.32
		24	2.95	3.39	3.42	3.19	3.24	
		Mean rates	3.06	3.27	3.33	3.60		
		CV (%)			12.4			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	2.88	3.37	3.36	3.32	3.23	3.24
		24	3.04	3.32	3.23	3.42	3.25	
		Mean rates	2.96	3.34	3.30	3.37		
		CV (%)			5.5			
		LSD (p≤0.05)			0.22		NS	
	Overall	12	3.02	3.26	3.31	3.67	3.31	
		24	3.00	3.35	3.33	3.31	3.25	
		Mean rates	3.01	3.31	3.32	3.49		
		CV (%)			9.7			
		LSD (p≤0.05)			0.27		NS	NS

Insignificant interactions are not shown, NS means not significant

In both intervals of fertilizer application, mature leaf nitrogen contents recorded were above what is considered deficiency limit (3.00-3.50%) for tea. However, application of NPKS fertilizers biennially may reduce leaf N to levels below what is considered adequate for proper tea growth and possibly affect yields in the long run.

The levels of leaf nitrogen were not affected by pruning managements at both locations. This was in agreement with past results (Tolhurst, 1973) but at variance with other previous findings (Othieno, 1981). Soil analysis data (Tables 4.4-4.6) indicated that pruning management had significant effects on soil extractable N which was expected to affect uptake of nitrogen. The lack of significant effect on leaf N levels suggested that soil analysis was unable to estimate the quantities of nitrogen that tea plants were able to extract. Hence mature leaf analysis may be a fair nutrient diagnostic tool for establishing nutrients deficiencies in tea bushes. The significant interaction between rates and intervals of NPKS fertilizer application at Kangaita indicated that variations in leaf nitrogen contents did not follow the same patterns.

4.3.2 Leaf Phosphorus

Increasing rates of the nitrogenous fertilizer application had varying effects on phosphorus uptake at the two sites (Table 4.35). An increase in rates of NPKS fertilizer application linearly decreased mature leaf phosphorus at Kangaita, similar to results reported previously (Wanyoko *et al*., 1992a; Kebeney *et al*., 2010; Owuor *et al*., 1990f, 2011b; Kwach *et al*., 2014). However, increasing fertilizer rates did not affect leaf phosphorus contents at Timbilil. This observation has also been noted elsewhere in past studies (Venkatesan *et al*., 2004; Kwach *et al*., 2014). The effects of fertilizer rates on leaf P were not significant at both sites. Past studies (Wanyoko *et al*., 1992a; Kebeney *et al*., 2010; Owuor *et al*., 2011) showed that decrease in mature leaf phosphorus resulted from fixation of the nutrient in soils following application of higher rates of nitrogenous fertilizers. In the present study, increasing rates of nitrogenous fertilizers improved levels of soil available phosphorus at all depths, especially in Kangaita (Tables 4.7-4.9) but this was not reflected in leaf analysis. Instead, mature leaf phosphorus levels declined with increasing nitrogen rates. Even at Timbilil where soil available P increased before showing a decline with progressive increase in fertilizer rates, leaf phosphorus contents were not affected. The results implied that high amounts of P in soils do not indicate higher uptake of this nutrient by tea plants. There seems to be a continuous equilibrium between fixed and available P in soils that controls the supply of phosphorus to tea plants. Therefore, the most appropriate tool for establishing P availability to tea plants may be mature leaf analysis. This supported earlier findings (Tolhurst, 1976; Kamau *et al*., 2005; Kwach *et al*., 2011) that foliar analysis using the mature leaf is more precise in assessing nutrients demand in tea cultivation.

For tea growing in East African region, mature leaf phosphorus levels below 0.15% are considered deficient, within 0.15-0.17% borderline and above 0.17% adequate (Owuor and Wanyoko, 1983; Othieno, 1988). Though leaf phosphorus levels appeared higher in 24 months fertilization intervals as compared to the 12 months intervals, the differences were not significant, suggesting that intervals of nitrogenous fertilizer application did not affect the uptake of phosphorus by tea plants. The results conformed to findings in a similar study at Kangaita (Kebeney *et al*., 2010). Lack of significant differences between leaf P levels obtained in the different intervals of NPKS fertilizer application was surprising as the biennial fertilizer application improved availability of soil P at depth 15-30cm in Timbilil (Table 4.8).

Table 4.35: Variations in mature leaf phosphorus levels (%) due to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings Removed	12	0.18	0.20	0.23	0.14	0.19	0.20
		24	0.25	0.22	0.16	0.21	0.21	
		Mean rates	0.21	0.21	0.20	0.17		
		CV (%)			49.6			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	0.20	0.18	0.20	0.13	0.18	0.19
		24	0.25	0.23	0.15	0.18	0.20	
		Mean rates	0.23	0.21	0.18	0.15		
		CV (%)			41.9			
		LSD (p≤0.05)			NS		NS	
	Overall	12	0.19	0.19	0.22	0.13	0.18	
		24	0.25	0.23	0.16	0.19	0.21	
		Mean rates	0.22	0.21	0.19	0.16		
		CV (%)			46.1			
		LSD (p≤0.05)			NS		NS	NS
Timbilil	Prunings Removed	12	0.15	0.14	0.16	0.14	0.15	0.15
		24	0.15	0.16	0.14	0.15	0.15	
		Mean rates	0.15	0.15	0.15	0.15		
		CV (%)			26.5			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	0.15	0.14	0.17	0.13	0.15	0.15
		24	0.16	0.18	0.12	0.15	0.15	
		Mean rates	0.16	0.16	0.15	0.14		
		CV (%)			28.2			
		LSD (p≤0.05)			NS		NS	
	Overall	12	0.15	0.14	0.17	0.14	0.15	
		24	0.16	0.17	0.13	0.15	0.15	
		Mean rates	0.15	0.15	0.15	0.14		
		CV (%)			27.4			
		LSD (p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Feeder roots of tea plants are predominantly found within this depth and the uptake of phosphorus was expected to improve with longer interval of NPKS fertilizer application. The results further demonstrated that soil chemical analysis may not be suitable in estimating nutrients availability to plants. Considering the set critical limits, mean intervals showed that leaf phosphorus levels were adequate in tea plants at Kangaita but within borderline for tea in Timbilil. However, at the two sites, mature leaf P contents recorded in both intervals of fertilizer application were above deficiency levels for tea plants. Therefore, interval of fertilizer application was not a limiting factor in the uptake of phosphorus by tea plants. As observed in soil analytical data, levels of phosphorus in the mature leaf of tea were not influenced by pruning management applied.

4.3.3 Leaf Potassium

Mature leaf K contents of tea linearly decreased with increasing rates of nitrogenous fertilizers (Table 4.36) at both sites but not significantly. These patterns are similar to observations made in previous studies (Owuor *et al*., 1987, 1990f, 1993b, 2011; Sitienei *et al*., 2013; Kwach *et al*., 2014). Decline in levels of potassium in the mature leaf occurred even with concurrent increase in applied potassium in NPKS fertilizer. It appeared that the fertilizers either inhibited potassium uptake by tea plants or increased leaching of this nutrient in tea soils as reported in other studies (Owuor *et al*., 1987; Kebeney *et al*., 2010; Kwach *et al*., 2014). Even with an increase in soil available K (Tables 10-12) to high levels (above 100 ppm), mature leaf potassium contents still decreased. The decrease in mature leaf K levels may have resulted from the competition for potassium uptake by the ammonium ions in NPKS fertilizers (Wanyoko *et al*., 1990). These results reaffirmed earlier recommendations (Owuor *et al*., 1993b; Kamau *et al*., 1999; Sitienei *et al*., 2013) that application of nitrogen and potassium on tea need to be staggered by at least three months.

Table 4.36: Variations in mature leaf potassium levels (%) due to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings Removed	12	1.52	1.41	1.59	1.31	1.46	1.45
		24	1.56	1.75	1.25	1.19	1.44	
		Mean rates	1.54	1.58	1.42	1.25		
		CV (%)			25.9			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	1.53	1.53	1.32	1.17	1.39	1.38
		24	1.29	1.48	1.39	1.30	1.37	
		Mean rates	1.41	1.51	1.35	1.24		
		CV (%)			16.9			
		LSD (p≤0.05)			NS		NS	
	Overall	12	1.52	1.47	1.45	1.24	1.42	
		24	1.42	1.62	1.32	1.25	1.40	
		Mean rates	1.47	1.54	1.39	1.24		
		CV (%)			22.1			
		LSD (p≤0.05)			NS		NS	NS
Timbilil	Prunings Removed	12	1.41	1.09	1.35	1.15	1.25	1.22
		24	1.28	1.21	1.09	1.20	1.20	
		Mean rates	1.34	1.15	1.22	1.18		
		CV (%)			20.8			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	1.38	1.18	1.15	1.26	1.24	1.29
		24	1.39	1.42	1.34	1.24	1.35	
		Mean rates	1.38	1.30	1.25	1.25		
		CV (%)			13.8			
		LSD (p≤0.05)			NS		NS	
	Overall	12	1.39	1.14	1.25	1.20	1.25	
		24	1.33	1.32	1.22	1.22	1.27	
		Mean rates	1.36	1.23	1.23	1.21		
		CV (%)			17.5			
		LSD (p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Generally, levels of potassium in mature leaves were above 1.20%, considered the deficiency limit for seedling tea (Tolhurst, 1976; Othieno, 1988) and thus tea plants in these sites are not likely to suffer from potassium deficiencies. However, there is need to review the regular inclusion of this nutrient in NPKS fertilizer formulations when deficiencies have not been shown. This may reduce the costs of production.

Leaf potassium contents were not significantly influenced by intervals of NPKS fertilizer application at both locations. Similar responses had also been observed earlier at Kangaita and Michimikuru (Kebeney *et al*., 2010). The observation on leaf K contents was similar to that made in soils (Tables 4.10-4.12), confirming that intervals of fertilizer application did not affect availability and uptake of potassium by tea plants. Levels of mature leaf potassium below 1.20% are considered deficient while levels between 1.20 and 1.50% are within borderline for tea growing in East Africa (Owuor and Wanyoko, 1983; Othieno, 1988). At both intervals of nitrogen application, leaf K levels were within the borderline range but above the deficiency limit. This result indicated that tea soils under study were rich in this nutrient as had been observed earlier on East African teas (Willson, 1975b). Thus tea yield responses to additional potassium in fertilizer formulations are unlikely. There were no significant responses in mature leaf potassium levels to pruning management applied. The same observation was made on these tea soils.

4.3.4 Leaf Calcium

Diagnostic mature leaf calcium levels have not been set for tea growing regions within East Africa but the nutrient is beneficial for proper growth of tea plants (Bonheure and Willson, 1992). The changes in mature leaf calcium contents are presented in Table 4.37. Increasing rates of nitrogenous fertilizers significantly reduced ($p \leq 0.05$) leaf calcium contents at Timbilil but had an opposite effect of increasing leaf Ca contents at Kangaita. Several studies (Willson, 1975c; Owuor *et al*., 1988, 1990b; Wanyoko *et al*., 1990; Kebeney *et al*., 2010; Kwach *et al*., 2012, 2014) have demonstrated decrease in mature leaf Ca levels with increasing quantities of applied nitrogen and the current Timbilil results are in agreement with these findings. The decline in mature leaf calcium levels has always been attributed to leaching triggered by higher rates of nitrogenous fertilizers. The observed pattern in leaf calcium levels at Timbilil closely followed trends observed in soil available calcium at this site (Tables 4.13-4.15). This confirmed that increasing rates of nitrogenous fertilizers reduce availability of calcium in soils leading to reduced uptake by tea plants which may impair crop production.

Rise in mature leaf calcium levels with increase in rates of nitrogen application at Kangaita was unusual as most studies (Wanyoko *et al*., 1990; Kebeney *et al*., 2010; Kwach *et al*., 2012, 2014) on calcium nutrition in tea have shown decrease in this nutrient with higher rates of applied nitrogen. The increase observed in the current study was however, similar to what had been observed in one study in Kenya (Owuor *et al*., 1988) where mature leaf calcium increased with increasing nitrogen rates, especially after pruning. The rise in uptake of calcium could be attributed to increased leaf fall and tea prunings left *in situ* in tea gardens as prunings contain reasonable calcium levels (Dogo, 1994). Data on soil chemical analysis (Tables 4.13) showed that retention of tea prunings *in situ* significantly increased levels of soil available calcium. This could explain the observed increase in leaf calcium contents. Generally, levels of calcium in the mature leaves obtained during biennial NPKS fertilizer application were higher as compared to those recorded when fertilizer was applied annually.

Indeed, at Kangaita, leaf calcium contents were significantly higher ($p \leq 0.05$) during biennial fertilizer application.

Table 4.37: Variations in mature leaf calcium levels (%) due to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings Removed	12	0.69	0.76	0.76	0.55	0.69	0.75
		24	0.70	0.85	0.86	0.84	0.81	
		Mean rates	0.69	0.80	0.81	0.69		
		CV (%)			22.3			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	0.78	0.81	0.87	0.81	0.82	0.85
		24	0.92	0.88	0.89	0.85	0.89	
		Mean rates	0.85	0.85	0.88	0.83		
		CV (%)			15.9			
		LSD (p≤0.05)			NS		NS	
	Overall	12	0.74	0.78	0.81	0.68	0.75	
		24	0.81	0.87	0.88	0.84	0.85	
		Mean rates	0.77	0.83	0.85	0.76		
		CV (%)			19.0			
		LSD (p≤0.05)			NS		0.09	0.09
Timbilil	Prunings Removed	12	0.85	0.88	0.78	0.70	0.80	0.80
		24	0.91	0.82	0.75	0.69	0.80	
		Mean rates	0.88	0.85	0.77	0.70		
		CV (%)			18.3			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	0.92	0.81	0.66	0.61	0.75	0.80
		24	0.99	0.89	0.73	0.72	0.82	
		Mean rates	0.95	0.89	0.68	0.68		
		CV (%)			18.0			
		LSD (p≤0.05)			0.18		NS	
	Overall	12	0.89	0.84	0.72	0.65	0.78	
		24	0.95	0.89	0.73	0.72	0.82	
		Mean rates	0.92	0.87	0.72	0.69		
		CV (%)			18.1			
		LSD (p≤0.05)			0.12		NS	NS

Insignificant interactions are not shown, NS means not significant

Earlier studies (Owuor *et al*., 1988, 1990b) reported that splitting annual application of NPKS fertilizers did not affect mature leaf Ca contents. However, results herein show that NPKS fertilizer application biennially increase calcium levels in tea plants. This observation is in agreement with findings in a similar study (Kebeney *et al*., 2010). In this study, uptake of Ca and its levels in tea leaves appeared to follow trends observed in soil calcium levels (Tables 4.13-4.15).

Soil available calcium levels seemed to be higher with longer intervals of nitrogen application. Reduction in soil acidification with longer intervals of fertilization (Tables 4.1-4.3) may have resulted to increased levels of calcium as reported earlier (Kebeney *et al*., 2010). The longer durations of NPKS fertilizer application seem to reduce leaching of calcium from soils, hence increasing its availability and uptake by tea plants. This could lengthen the economic life of the soils in Kangaita.

Considering the effects of pruning managements, it was observed that with tea prunings left *in situ*, leaf calcium levels were significantly higher ($p \leq 0.05$) than those obtained when prunings were removed at Kangaita. However, in Timbilil, leaf Ca levels were not affected by pruning managements. The trend observed at Kangaita was a reflection of what was observed in soils at this site (Table 4.13). Soil available calcium levels also increased with prunings left *in situ*. Tea prunings contain substantial amounts of Ca (Dogo, 1994) and upon mineralization in soils, reasonable quantities of this nutrient become available to plants. Leaf analysis results confirmed increased Ca availability in these soils. This demonstrates that retention of tea prunings *in situ* increase availability of calcium in these soils and its uptake by tea which may improve tea yields at Kangaita.

4.3.5 Leaf Magnesium

Magnesium is considered deficient, borderline and adequate for tea when the levels are less than 0.10%, within 0.10 to 0.13% and above 0.13%, respectively (Owuor and Wanyoko, 1983). Table 38 summarizes the variations in levels of magnesium in the first mature leaf of tea plants. There was a general decrease in mature leaf magnesium levels with increasing rates of NPKS fertilizer application in both locations. The nitrogen effects on magnesium levels were however, not statistically different at both sites. Similar decrease in mature leaf magnesium contents following a rise in nitrogenous fertilizer rates had been observed in earlier studies (Willson, 1975d; Wanyoko *et al*., 1990, 1992a, 1997; Owuor *et al*., 1997; Kebeney *et al*., 2010; Kwach *et al*., 2014). Results herein show that decrease in leaf Mg contents with increasing rates of nitrogenous fertilizers was similar to what was observed on soil magnesium contents (Tables 16-18). This confirmed that nitrogenous fertilizers enhance leaching of magnesium that reduces its available quantities to tea. This was in support of earlier findings (Kamau *et al*., 1998, 2008). Generally, in this study, leaf Mg contents were within the borderline range of 0.10 to 0.13 % for seedling tea (Tolhurst, 1976; Othieno, 1988) but much lower than those in literature (Kebeney *et al*., 2010; Owuor *et al*., 1990b; Kwach *et al*., 2014). Though levels of Mg in the leaf were above what is considered deficiency limit of 0.10 % (Tolhurst, 1976), high rates of NPKS fertilizer application appear to introduce magnesium deficiency to tea.

The concentrations of magnesium in mature leaf tissues of tea did not change due to intervals of nitrogen application in the two locations unlike in the previous experiment (Kebeney *et al*., 2010). Though significant differences between fertilizer application intervals were not observed, interestingly, seedling tea at Timbilil tended to accumulate more magnesium in mature leaves when nitrogen application was done biennially. In contrast, clone 12/12 at Kangaita accumulated more Mg in the leaf when fertilizer application was done annually.

Table 4.38: Variations in mature leaf magnesium levels (%) due to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings Removed	12	0.11	0.10	0.09	0.10	0.10	0.10
		24	0.12	0.12	0.09	0.10	0.11	
		Mean rates	0.11	0.11	0.09	0.10		
		CV (%)			31.3			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	0.13	0.13	0.14	0.13	0.13	0.12
		24	0.12	0.12	0.09	0.12	0.11	
		Mean rates	0.13	0.12	0.12	0.12		
		CV (%)			26.5			
		LSD (p≤0.05)			NS		NS	
	Overall	12	0.12	0.11	0.12	0.11	0.12	
		24	0.12	0.12	0.09	0.11	0.11	
		Mean rates	0.12	0.12	0.10	0.11		
		CV (%)			28.7			
		LSD (p≤0.05)			NS		NS	NS
Timbilil	Prunings Removed	12	0.13	0.13	0.10	0.08	0.11	0.12
		24	0.14	0.12	0.13	0.14	0.13	
		Mean rates	0.14	0.13	0.12	0.11		
		CV (%)			29.3			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	0.14	0.13	0.13	0.08	0.12	0.13
		24	0.18	0.13	0.12	0.15	0.14	
		Mean rates	0.16	0.13	0.12	0.11		
		CV (%)			38.3			
		LSD (p≤0.05)			NS		NS	
	Overall	12	0.14	0.13	0.12	0.08	0.12	
		24	0.16	0.13	0.12	0.14	0.14	
		Mean rates	0.15	0.13	0.12	0.11		
		CV (%)			34.4			
		LSD (p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

These results were similar to what had been observed earlier, for seedling tea at Michimikuru and clone 12/12 at Kangaita (Kebeney *et al.*, 2010). These responses could be due to difference in location and soil type. The results suggest that the two sites may require different intervals of NPKS fertilizer application on tea. The observed pattern in leaf magnesium contents followed that observed in soil chemical analysis (Tables 4.16-4.18), suggesting that NPKS fertilizer applications at 24 months intervals increase availability of Mg and its uptake by tea. In general, leaf magnesium levels obtained in both intervals of fertilizer application were above the deficient limit (0.10%) for seedling tea within East Africa (Tolhurst, 1976; Othieno, 1988) region.

With retention of prunings *in situ*, soil available magnesium increased in surface soils of Kangaita (Table 4.16). Mature leaf magnesium levels also appeared higher with prunings left *in situ* but the effects were not significant. The results imply that soil chemical analysis may not be giving a true reflection of available magnesium levels in these soils.

4.3.6 Leaf Manganese

Manganese is an essential element during photosynthesis and several enzymatic processes in tea plants (Roy *et al*., 2006). Table 4.39 shows the variations in leaf manganese levels from the experimental sites. In both locations, increasing rates of nitrogenous fertilizer increased levels of manganese in the mature leaf of tea plants. However, the N effects on leaf Mn contents were not significant. The rise in manganese uptake was similar to findings in past studies (Wanyoko *et al*., 1990, 1992a, 1997; Owuor *et al*., 1990b; Kebeney *et al*., 2010; Kwach *et al*., 2014). The increase in levels of Mn in the mature leaves was similar to patterns observed on soils, especially at Timbilil where increasing nitrogen rates caused an increase in manganese levels. This was a reflection of the abundant supply of Mn in acid soils which had also been reported (Bonheure and Willson, 1992). Both soil and leaf data have shown that increasing rates of NPKS fertilizer application increased availability of manganese in soils leading to increased uptake of the nutrient. Excess levels of Mn in soils reduce availability of bases (Kamau *et al*., 1998, 2008) and phosphorus through fixation (Owuor *et al*., 1990b, 2011b; Kebeney *et al*., 2010) while increasing exchangeable Al (Ruan *et al*., 2006). In the current study, leaf manganese contents obtained were quite low as compared to literature data (Kebeney *et al*., 2010; Kwach *et al*., 2012, 2014), suggesting that tea plants just extract levels of manganese that are adequate for their growth.

Thus, with the current NPKS fertilizer rates of between 100 and 250 kg/ha/year, manganese toxicities are unlikely.

Increasing rates of nitrogenous fertilizers increased mature leaf manganese (Table 4.39) in a quadratic manner in both intervals of fertilization at both sites. However, the observed increase was not significant, implying that intervals of NPKS fertilizer application do not influence mature leaf Mn contents. The results agree with earlier observations in a similar study (Kebeney *et al*., 2010). In both intervals of fertilizer application, clonal tea at Kangaita appeared to extract and partition higher levels of Mn in their mature leaves than seedling tea at Timbilil. This shows that different tea varieties have varying abilities to extract nutrients from soils and partition them differently in their leaves. The results also demonstrate that availability of this nutrient in soils and its uptake by tea plants differ with soil types. Similar responses to intervals of nitrogen application were also noted in soils (Tables 4.19-4.21). This confirmed that availability of manganese in soils and its absorption by tea plants is not influenced by interval of fertilizer application.

Table 4.39: Variations in mature leaf manganese levels (%) due to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings Removed	12	0.074	0.081	0.112	0.067	0.083	0.085
		24	0.083	0.110	0.066	0.086	0.086	
		Mean rates	0.078	0.095	0.089	0.077		
		CV (%)			51.2			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	0.099	0.109	0.182	0.111	0.125	0.119
		24	0.119	0.135	0.086	0.113	0.113	
		Mean rates	0.109	0.122	0.134	0.112		
		CV (%)			55.5			
		LSD (p≤0.05)			NS		NS	
	Overall	12	0.087	0.095	0.147	0.089	0.104	
		24	0.101	0.122	0.076	0.100	0.100	
		Mean rates	0.094	0.108	0.112	0.094		
		CV (%)			54.8			
		LSD (p≤0.05)			NS		NS	0.033
Timbilil	Prunings Removed	12	0.054	0.065	0.094	0.066	0.070	0.069
		24	0.068	0.076	0.063	0.064	0.068	
		Mean rates	0.061	0.070	0.079	0.065		
		CV (%)			51.4			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	0.057	0.068	0.089	0.062	0.069	0.066
		24	0.053	0.087	0.051	0.064	0.064	
		Mean rates	0.055	0.078	0.070	0.063		
		CV (%)			56.0			
		LSD (p≤0.05)			NS		NS	
	Overall	12	0.055	0.067	0.091	0.064	0.069	
		24	0.060	0.082	0.057	0.064	0.066	
		Mean rates	0.058	0.074	0.074	0.064		
		CV (%)			53.7			
		LSD (p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

One reason for retaining prunings in tea fields is to supply nutrients to tea bushes, that is, after decomposition and mineralization (Dogo, 1994).

Retention of tea prunings *in situ* significantly increased (p≤0.05) levels of manganese in the mature leaves of tea plants at Kangaita but had no significant effect on leaf Mn contents at Timbilil. The observed trends were also noted in soils (Tables 4.19-4.21), suggesting that leaf analysis gives a fair estimate of nutrients extracted from soils by tea plants as reported earlier (Kamau *et al*., 2005; Kwach *et al*., 2011, 2012). Tea prunings contain reasonable levels of manganese as MnO (Dogo, 1994) and upon mineralization of plant tissues; this nutrient becomes more available in soils. This study has shown that with prunings left *in situ*, manganese levels increase in soils. However, this may not be beneficial as high Mn levels in soils create nutrients imbalances leading to reduced tea yields.

4.3.7 Leaf Aluminium

Levels of aluminium in mature leaves of tea plants from the experimental sites are presented in Table 4.40. The leaf aluminium contents seemed not to change with increasing rates of NPKS fertilizer application at Timbilil. However, increasing rates of nitrogenous fertilizers caused a marginal increase in mature leaf Al contents but this was followed by a decline, especially at higher NPKS rates at Kangaita. The overall effect was decline in mature leaf Al levels at this site. Results in other studies (Owuor and Cheruiyot, 1989; Owuor *et al*., 1990b; Ruan *et al*., 2006) had also shown decrease in mature leaf aluminium at higher rates of nitrogenous fertilizers. Increasing rates of applied nitrogen usually acidify soils and increase soil extractable aluminium contents (Owuor and Cheruiyot, 1989; Ruan *et al*., 2006), which is expected to increase its uptake by tea plants. The results herein show no significant change in leaf Al contents even with an increase in soil extractable aluminium (Tables 4.22-4.24), especially at Kangaita. This observation indicates that high rates of nitrogenous fertilizers reduce the uptake of aluminium by tea plants. As the nitrogenous fertilizers rates increase, more ammonium ions become available to tea plants and are probably absorbed in preference to aluminium (Ruan *et al*., 2006). Thus, one way of reducing aluminium uptake by tea plants is by using high rates of nitrogenous fertilizers as had been reported earlier (Owuor and Cheruiyot, 1989).

In an earlier study (Owuor *et al*., 1990b), splitting annual fertilizer applications reduced aluminium uptake by tea plants. However, in this study, application intervals had no significant effects on levels of aluminium in mature leaves of the tea bushes. This was also noted in soil aluminium contents (Tables 4.22-4.24), showing that aluminium availability in these soils and consequently, its uptake, does not depend on frequency of fertilizer application.

The concentrations of aluminium in mature leaves were not influenced by the pruning management applied. This occurred despite an increase in soil extractable aluminium (Table 4.22) with prunings left *in situ* at Timbilil. The inconsistent results on soil and leaf aluminium indicate that soil analysis may not be giving a fair estimate of what the plant can actually absorb. The results also show that tea prunings returned reasonable amounts of aluminium in soils. The high CVs obtained may imply existence of other factors that influenced uptake of this nutrient by tea plants but this requires investigation.

4.3.8 Leaf Iron

Table 4.41 shows variations in levels of iron in mature leaves of tea plants. Increasing rates of nitrogenous fertilizers increased levels of iron in mature leaves of tea at Timbilil but did not show regular patterns in leaf iron contents at Kangaita. The observed increase was similar to earlier observations made in Kericho (Kwach *et al*., 2012, 2014). Leaf iron contents in clone 12/12 at Kangaita were quite high as compared to those in seedling tea at Timbilil.

Table 4.40: Variations in mature leaf aluminium levels (%) due to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings Removed	12	0.15	0.17	0.18	0.12	0.16	0.16
		24	0.17	0.17	0.13	0.15	0.16	
		Mean rates	0.16	0.17	0.16	0.14		
		CV (%)			39.9			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	0.16	0.16	0.21	0.14	0.17	0.16
		24	0.17	0.19	0.13	0.16	0.16	
		Mean rates	0.17	0.17	0.17	0.15		
		CV (%)			40.2			
		LSD (p≤0.05)			NS		NS	
	Overall	12	0.16	0.16	0.20	0.13	0.16	
		24	0.17	0.18	0.13	0.16	0.16	
		Mean rates	0.16	0.17	0.17	0.14		
		CV (%)			40.1			
		LSD (p≤0.05)			NS		NS	NS
Timbilil	Prunings Removed	12	0.23	0.09	0.10	0.19	0.15	0.14
		24	0.08	0.09	0.17	0.17	0.13	
		Mean rates	0.15	0.09	0.13	0.18		
		CV (%)			105.3			
		LSD(p≤0.05)			NS		NS	
	Prunings *in situ*	12	0.08	0.07	0.07	0.11	0.09	0.10
		24	0.09	0.11	0.17	0.07	0.11	
		Mean rates	0.09	0.09	0.12	0.09		
		CV (%)			84.7			
		LSD(p≤0.05)			NS		NS	
	Overall	12	0.16	0.08	0.08	0.15	0.12	
		24	0.08	0.10	0.17	0.12	0.12	
		Mean rates	0.12	0.09	0.13	0.13		
		CV (%)			100.6			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

This implied that either clone 12/12 had higher ability to extract Fe from soils or the Kangaita soils were inherently richer in this nutrient than soils at Timbilil.

This observation supports earlier findings (Wanyoko, 1981; Yemane *et al*., 2008; Kwach *et al*., 2012; Omwoyo *et al*., 2013) that different tea cultivars have varied abilities to extract micronutrients from soils leading to variations in mature leaf nutrients levels (Wanyoko and

Njuguna, 1983; Kwach *et al*., 2014). The high iron levels observed in soils (Tables 4.25-4.27) may account for the higher levels of iron observed in mature leaves. Both soil and leaf analyses showed that higher N rates increased levels of iron in soils and mature leaves of tea. This may be detrimental as high levels of iron in tea plants suppress growth rates and reduce tea yields (Kuzhandaivel and Venkatesan, 2011).

Mature leaf iron levels were not significantly influenced by fertilizer application intervals at both sites. Similar observations were also recorded for soil available iron (Tables 4.25-4.27). The levels of iron in these soils and its uptake by tea plants under the influence of different intervals of NPKS fertilizer applications are being reported for the first time. Generally, leaf iron levels were quite high. This was expected as low pH in soils (Tables 4.1-4.3) favours availability and uptake of this micronutrient by tea plants (Yemane *et al*., 2008; Nath, 2013). This study has confirmed that interval of N fertilization is not a contributing factor towards availability and uptake of iron by tea plants. Pruning management types did not affect levels of iron in mature leaf of the tea plants as well as its availability in soils.

4.3.9 Leaf Copper

The diagnostic limit for copper in the mature leaf of tea has not been set but this nutrient is essential for fermentation during manufacture of black tea (Harler, 1971). The changes in mature leaf copper levels are presented in Table 4.42. Increase in rates of NPKS fertilizer application insignificantly increased levels of copper in mature leaves of tea at both locations.

Table 4.41: Variations in mature leaf iron levels (ppm) due to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings Removed	12	230	381	223	201	259	283
		24	349	286	212	384	308	
		Mean rates	289	334	218	293		
		CV (%)			49.2			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	235	259	222	223	235	254
		24	258	339	220	275	273	
		Mean rates	246	299	221	249		
		CV (%)			28.6			
		LSD (p≤0.05)			NS		NS	
	Overall	12	232	320	223	212	247	
		24	303	312	216	329	290	
		Mean rates	268	316	220	271		
		CV (%)			41.4			
		LSD (p≤0.05)			NS		NS	NS
Timbilil	Prunings Removed	12	77	90	110	105	96	92
		24	85	114	77	81	89	
		Mean rates	81	102	93	93		
		CV (%)			57.7			
		LSD(p≤0.05)			NS		NS	
	Prunings *in situ*	12	79	87	114	84	91	94
		24	91	109	111	79	98	
		Mean rates	85	98	113	82		
		CV (%)			63.7			
		LSD(p≤0.05)			NS		NS	
	Overall	12	78	89	112	95	93	
		24	88	111	94	80	93	
		Mean rates	83	100	103	87		
		CV (%)			60.9			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Similar increase in levels of copper in mature leaves of tea had been reported in earlier works (Kwach *et al*., 2011, 2012, 2014). Decreasing soil pH increase the uptake of micronutrients Fe, Cu, Zn and Mn by tea plants (Nath, 2013). In this study, there was reduction in soil pH (Tables 1-3) due to increasing rates of NPKS fertilizer application. Consequently, soil available Cu increased (Tables 28-30), except at the topmost soil depth at Timbilil. Soil analysis data (Tables 4.28-4.30) showed that extractable levels of Cu in these soils were within permissible limits (2-

250ppm) (Nath, 2013). Thus the Cu levels in mature leaf may not cause negative effects on growth and yields of tea. The current rates of 100-250 kg N/ha/year of NPKS fertilizers on tea can therefore be continued.

There were no significant differences between mature leaf copper levels obtained using 12 and 24 months intervals at both sites. It was thought that longer intervals of nitrogen application would reduce copper levels in soils and affect their uptake by tea plants. However, data on soil chemical analysis (Tables 4.28-4.30) indicated that extractable Cu levels in soils were not influenced by interval of fertilizer application. Leaf chemical analysis confirmed this finding. This implied that NPKS 25:5:5:5 fertilizers can be applied annually or biennially depending on other factors such as fertilizer costs, availability of funds, etc, without affecting copper levels in soils as well as in tea plants. Pruning management did not alter levels of copper in both soil and mature leaves of tea plants.

4.3.10 Leaf Zinc

Effects of different rates and intervals of NPKS fertilizer application and pruning managements on mature leaf zinc levels are summarized in Table 4.43. Increasing rates of nitrogenous fertilizers increased mature leaf zinc levels at both sites but the changes were not statistically different. The observed patterns were similar to those reported previously (Owuor *et al*., 1993b; Kwach *et al*., 2011, 2012, 2014). Zinc levels were generally above 10 ppm, the critical level for tea growing within the East African region (Owuor and Wanyoko, 1983; Othieno, 1988).

Bioavailabilities of micronutrients like Zn are usually high in strongly acidic soils (Gabisoniya and Gabisoniya, 1973; Yemane *et al*., 2008; Nath, 2013; Meliyo *et al*., 2015).

Table 4.42: Variations in mature leaf copper levels (ppm) due to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	14.0	13.3	17.0	12.7	14.3	14.3
		24	16.0	13.7	13.7	13.7	14.3	
		Mean rates	15.0	13.5	15.3	13.2		
		CV (%)			27.8			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	12.7	15.0	14.7	12.7	13.8	13.7
		24	12.7	14.0	14.7	13.3	13.7	
		Mean rates	12.7	14.5	14.7	13.0		
		CV (%)			20.5			
		LSD (p≤0.05)			NS		NS	
	Overall	12	13.3	14.2	15.8	12.7	14.0	
		24	14.3	13.8	14.2	13.5	14.0	
		Mean rates	13.8	14.0	15.0	13.1		
		CV (%)			24.6			
		LSD (p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	7.7	8.0	8.7	7.7	8.0	7.9
		24	8.0	8.0	7.0	8.0	7.8	
		Mean rates	7.8	8.0	7.8	7.8		
		CV (%)			18.0			
		LSD(p≤0.05)			NS		NS	
	Prunings *in situ*	12	8.0	7.7	9.3	7.7	8.2	8.0
		24	8.3	8.0	8.0	7.3	7.9	
		Mean rates	8.2	7.8	8.7	7.5		
		CV (%)			21.8			
		LSD(p≤0.05)			NS		NS	
	Overall	12	7.8	7.8	9.0	7.7	8.1	
		24	8.2	8.0	7.5	7.7	7.8	
		Mean rates	8.0	7.9	8.3	7.7		
		CV (%)			20.0			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Soils in the study areas were strongly acidic (Tables 4.1-4.3), probably explaining the high levels of zinc in mature leaves. Increase in levels of zinc in mature tea leaves at Kangaita reflected what was observed in soils. This showed that increasing nitrogen application rates increased uptake of zinc. At Timbilil, the effects of nitrogen application rates on soil and leaf zinc contents were quite different. While mature leaf Zn contents increased with increasing rates of fertilizer application, zinc levels in soils decreased. This implied that nitrogenous fertilizers increased zinc requirements by tea plants, possibly through increased growth rates that may induce zinc deficiencies in the long run.

There were no significant differences in mature leaf zinc levels due to intervals of fertilizer application at both locations. Similarly, soil extractable zinc levels (Tables 4.31-4.33) were not statistically different for the two intervals of NPKS fertilizer application. At both intervals of applied nitrogen, zinc contents in the mature leaf were high and above the minimum limit for tea in East Africa (Tolhurst, 1976; Owuor and Wanyoko, 1983; Othieno, 1988). Thus nitrogen can be applied on tea using either 12 or 24 months intervals without limiting availability and uptake of zinc by tea plants. Prunings *in situ* seemed to improve levels of Zn in soils but this was not reflected in the leaf. Therefore, mature leaf zinc levels were not influenced by pruning managements.

Table 4.43: Variations in mature leaf zinc levels (ppm) due to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	42.3	44.7	48.3	54.0	47.3	48.4
		24	46.3	58.3	43.3	49.7	49.4	
		Mean rates	44.3	51.5	45.8	51.8		
		CV (%)			28.6			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	43.3	51.3	52.7	40.3	46.9	48.1
		24	47.0	61.3	42.7	46.3	49.3	
		Mean rates	45.2	56.3	47.7	43.3		
		CV (%)			26.8			
		LSD (p≤0.05)			NS		NS	
	Overall	12	42.8	48.0	50.5	47.2	47.1	
		24	46.7	59.8	43.0	48.0	49.4	
		Mean rates	44.8	53.9	46.8	47.6		
		CV (%)			27.7			
		LSD (p≤0.05)			NS		NS	NS
Timbilil	Prunings removed	12	24.0	24.7	26.0	22.3	24.2	24.0
		24	25.3	24.7	22.3	23.0	23.8	
		Mean rates	24.7	24.7	24.2	22.7		
		CV (%)			21.1			
		LSD(p≤0.05)			NS		NS	
	Prunings *in situ*	12	23.7	24.3	-	24.7	36.0	30.0
		24	24.7	25.7	22.3	23..7	24.1	
		Mean rates	24.2	25.0	46.8	24.2		
		CV (%)			100.7			
		LSD(p≤0.05)			NS		NS	
	Overall	12	23.8	24.5	48.7	23.5	30.1	
		24	25.0	25.2	22.3	23.3	24.0	
		Mean rates	24.4	24..8	35.5	23.4		
		CV (%)			80.2			
		LSD(p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

4.4 Variations in Tea Yields Due to Different Rates and Intervals of NPKS 25:5:5:5 Fertilizer Application and Pruning Managements

Responses in tea yields during the two years of experimentation are summarized in Tables 4.44-4.46. Yield data recorded in 2013 (Table 4.44) showed that increasing rates of NPKS fertilizer application significantly increased (p≤0.05) tea yields at Kangaita. In the same year, tea yields at Timbilil increased with increasing fertilizer rates but the nitrogen effects were not significant. In

2014 (Table 4.45), increasing rates of NPKS fertilizer significantly increased ($p \leq 0.05$) tea yields at the two sites. This finding was in agreement with earlier results (Venkatesan *et al*., 2004; Owuor *et al*., 2008b). The control plots which never received fertilizer treatments produced significantly lower ($p \leq 0.05$) tea yields than NPKS fertilizer treated plots at the two sites. Mean data (Table 4.46) for the whole experimentation period also corroborated this finding. The results confirmed that increasing rates of NPKS fertilizers increased tea yields as reported in other studies (Venkatesan *et al*., 2004; Owuor *et al*., 2008b, 2010, 2013). During the two years of experimentation, tea yields responded quadratically to increasing rates of NPKS fertilizer application at the two sites. The highest tea yields were obtained when fertilizer was applied at 120 kg N/ha/year. However, there were no significant yield responses when the fertilizer was applied above this rate. Instead, yields of tea declined by 112 and 316 kg mt/ha/year (Table 4.46) at Kangaita and Timbilil, respectively. This trend supports earlier findings (Venkatesan *et al*., 2004; Owuor *et al*., 2008b, 2010, 2013). The results demonstrated that applying NPKS 25:5:5:5 fertilizers beyond this rate (120 kg N/ha/year) may not be economical for these teas. Optimal rates of nitrogenous fertilizers are usually lower than the point at which maximum yields are recorded (Kamau *et al*., 1998).

Table 4.44: Tea yields responses (kg mt/ha/year) to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements at the two sites, 2013

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	1552	1445	1926	1903	1706	1710
		24	1352	1995	1772	1739	1714	
		Mean rates	1452	1720	1849	1821		
		CV (%)			22.9			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	1755	1885	2502	2452	2148	2102
		24	1464	2185	2408	2170	2057	
		Mean rates	1610	2035	2455	2311		
		CV (%)			18.6			
		LSD (p≤0.05)			478		NS	
	Overall	12	1654	1665	2214	2177	1927	
		24	1408	2090	2090	1954	1885	
		Mean rates	1531	1877	2152	2066		
		CV (%)			20.5			
		LSD (p≤0.05)			325		NS	230
Timbilil	Prunings removed	12	2551	2559	2813	2596	2630	2667
		24	2374	2775	2997	2669	2704	
		Mean rates	2462	2667	2905	2633		
		CV (%)			16.6			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	2904	2805	3047	2927	2921	2859
		24	2515	2764	3123	2788	2798	
		Mean rates	2709	2785	3085	2858		
		CV (%)			12.3			
		LSD (p≤0.05)			NS		NS	
	Overall	12	2727	2682	2930	2762	2775	
		24	2444	2770	3060	2729	2751	
		Mean rates	2586	2726	2995	2745		
		CV (%)			14.4			
		LSD (p≤0.05)			NS		NS	NS

Insignificant interactions are not shown, NS means not significant

Table 4.45: Tea yields responses (kg mt/ha/year) to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements at the two sites, 2014

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean Interval	Mean PM
			0	60	120	180		
Kangaita	Prunings removed	12	2216	2575	3232	3138	2790	2520
		24	1670	2484	2505	2342	2250	
		Mean rates	1943	2530	2869	2740		
		CV (%)			20.1			
		LSD ($p \le 0.05$)			621		439	
	Prunings *in situ*	12	1862	2909	3292	3235	2824	2690
		24	1788	2442	3118	2875	2556	
		Mean rates	1825	2675	3205	3055		
		CV (%)			14.2			
		LSD ($p \le 0.05$)			468		NS	
	Overall	12	2039	2742	3262	3186	2807	
		24	1729	2463	2812	2609	2403	
		Mean rates	1884	2602	3037	2898		
		CV (%)			17.2			
		LSD ($p \le 0.05$)			374		264	NS
Timbilil	Prunings removed	12	2417	2855	2983	2591	2712	2633
		24	2247	2837	2749	2381	2554	
		Mean rates	2332	2846	2866	2486		
		CV (%)			10.9			
		LSD ($p \le 0.05$)			350		NS	
	Prunings *in situ*	12	2640	2878	2971	2717	2801	2747
		24	2147	2938	3101	2583	2692	
		Mean rates	2393	2908	3036	2650		
		CV (%)			11.3			
		LSD ($p \le 0.05$)			382		NS	
	Overall	12	2529	2866	2977	2654	2756	
		24	2197	2888	2925	2482	2623	
		Mean rates	2363	2877	2951	2568		
		CV (%)			11.1			
		LSD ($p \le 0.05$)			249		NS	NS

Insignificant interactions are not shown, NS means not significant

Thus, application of NPKS fertilizers upto 100 kg N/ha/year could be adequate for these teas. Similar tea yields responses to same rates of NPKS fertilizer in different sites implied that fertilizer recommendations for tea in the western highlands are valid for tea growing in the eastern highlands of Kenya.

In the year 2013, tea yields obtained were higher when NPKS fertilizer was applied annually at both sites than when fertilizer application was biennial (Table 4.44). However, the effects of fertilizer application intervals on yields were not significant. In the subsequent year (Tables 4.45), annual application of NPKS fertilizer resulted into significantly higher ($p \leq 0.05$) tea yields at Kangaita than yields obtained when the fertilizer was applied biennially at this site. Though not significantly different, overall means of tea yields for the entire experimentation period (Table 46) also showed that tea yields at both sites were higher when fertilizer application was done annually. Previous research (Kamau *et al*., 2000; Owuor *et al*., 1991, 1992, 2008b) demonstrated that splitting annual application of nitrogenous fertilizers did not affect tea yields. Consequently, it was speculated that NPKS fertilizer application annually may not be economical and high tea yields could be obtained when fertilizer application was biennial. Results herein show that application of NPKS fertilizer annually produced more yields than biennial fertilization. This has demonstrated that biennial application of NPKS fertilizers maybe too long for production of high tea yields. Lack of significant yield response to intervals of NPKS fertilization has an implication that biennial application of NPKS fertilizers could be done for other reasons such as soil conservation as excess nitrogenous fertilizers degrade soil quality (Venkatesan *et al*., 2004; Bonheure and Willson, 1992).

Tea yields obtained when prunings were left *in situ* were generally higher as compared to those obtained when prunings were removed. In 2013, tea yields obtained with prunings left in *situ* were significantly higher ($p \leq 0.05$) than yields obtained with prunings removed at Kangaita (Table 4.44). Similar trend was also observed at Timbilil but pruning management effects on yields were not significant.

Table 4.46: Mean yields responses (kg mt/ha/year) to different rates and intervals of NPKS 25:5:5:5 fertilizer application and pruning managements, 2013 and 2014.

Site	Pruning Management (PM)	Application Intervals (AI) (months)	Nitrogen rates in kg N /ha/year				Mean interval	Mean PM
			0	60	120	180		
Kangaita	Prunings Removed	12	1884	2010	2579	2520	2248	2115
		24	1511	2239	2139	2041	1982	
		Mean rates	1697	2125	2359	2280		
		CV (%)			20.3			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	1808	2397	2897	2843	2486	2396
		24	1626	2313	2763	2523	2306	
		Mean rates	1717	2355	2830	2683		
		CV (%)			15.0			
		LSD (p≤0.05)			439		NS	
	Overall	12	1846	2203	2738	2682	2367	
		24	1568	2276	2451	2282	2144	
		Mean rates	1707	2240	2594	2482		
		CV (%)			17.5			
		LSD (p≤0.05)			329		NS	233
Timbilil	Prunings Removed	12	2484	2707	2898	2594	2671	2650
		24	2311	2806	2873	2525	2629	
		Mean rates	2397	2757	2886	2560		
		CV (%)			12.4			
		LSD (p≤0.05)			NS		NS	
	Prunings *in situ*	12	2772	2842	3009	2822	2861	2803
		24	2331	2851	3112	2686	2745	
		Mean rates	2551	2846	3060	2754		
		CV (%)			10.9			
		LSD (p≤0.05)			NS		NS	
	Overall	12	2628	2774	2954	2708	2766	
		24	2321	2829	2992	2606	2687	
		Mean rates	2474	2802	2973	2657		
		CV (%)			11.6			
		LSD (p≤0.05)			264		NS	NS

Insignificant interactions are not shown, NS means not significant

In the year 2014, tea yields obtained with prunings left *in situ* in plantations appeared higher than those recorded when prunings were removed (Table 4.45). However, at both locations, pruning management effects on yields were not significant. When data for the entire experimental period (Table 4.46) was considered, tea yields were significantly higher ($p \leq 0.05$) when tea prunings were retained *in situ* at Kangaita. On average, tea yields recorded at this site from plots with prunings retained *in situ* were 2396 kg mt/ha/year as compared to 2115 kg mt/ha/year obtained from plots with prunings removed. This represented a 12% drop for plots with prunings removed. This showed that removal of prunings from tea plantations reduced tea yields. These results support findings in previous studies (De Silva, 2007; Othieno, 1980). The observed increase in tea yields could imply that nutrients demands of tea were partly satisfied following mineralization of prunings in soils. Thus, leaving prunings *in situ* in plantations increase tea yields.

4.5 Relationships (r) between Soil pH/available Nutrients and Mature Leaf Nutrients and Tea Yields

The relationships between soil pH and leaf nutrients/yields, soil available nutrients and leaf nutrients/yields were computed using Tables 4.1-4.3, 4.4-4.33, 4.34-4.43 and 4.44-4.46 for soil pH, soil available nutrients, mature leaf nutrients and yields, respectively. The results obtained are presented in Tables 4.47-4.52.

4.5.1 Relationships between Soil pH and Leaf Nutrients/yields and Available Soil Nutrients and Leaf Nutrients/yields at Timbilil

Soil available potassium showed a positive significant ($p \leq 0.05$, $r \geq 0,950$) correlation with mature leaf nitrogen but was negatively and significantly ($p \leq 0.05$, $r \geq 0,950$) correlated to leaf potassium and magnesium levels at surface soils (Table 4.47). Soil pH was positively and significantly ($p \leq 0.05$, $r \geq 0,950$) associated to leaf magnesium at depth 0-15 cm (Table 4.47) and leaf K in the other two lower depths (Tables 4.48 and 4.49). The positive association implied that decrease in soil pH (Tables 4.1-4.3) with increasing rates of NPKS fertilizer reduced uptake and consequently, the levels of potassium in mature leaves of tea plants. Decrease in mature leaf K levels with increasing rates of nitrogenous fertilizers had also been reported before (Owuor *et al*., 2011; Sitienei *et al*., 2013; Kwach *et al*., 2014). Results in current study confirmed that uptake of potassium is reduced with higher rates of NPKS fertilizers, probably due to leaching (Kamau *et* *al*., 1998; Kebeney *et al*., 2010). Soil available N levels were positively and significantly ($p \leq 0.05$, $r \geq 0,950$) related to leaf Ca at all depths (Tables 4.47-4.49) and Mg at depths 0-15 and 15-30 cm (Tables 4.48-4.49). Soil available calcium was significantly and positively related to leaf Ca at surface soils (Table 4.47), Mg at depths 0-15 and 15-30 cm (Tables 4.47-4.48) and K at soil depth of 15-30 cm (Table 4.48) but negatively correlated to mature leaf N at depth 15-30 cm (Table 4.48). At soil depths 0-15 cm (Table 4.47), 15-30 cm (Table 4.48) and 40-60 cm (Table 4.49), soil available magnesium was positively correlated to mature leaf zinc, potassium and aluminium, respectively. Negative significant associations were also observed between soil available zinc and leaf manganese at the two lower depths (Tables 4.48-4.49). Soil extractable Al had negative significant associations with leaf Zn (Table 4.48) and Cu (Table 4.49).

Mature leaf potassium contents were negatively related to soil extractable manganese levels (Table 4.49), similar to findings in previous works (Dogo *et al*., 1994; Kamau *et al*., 1998; Kebeney *et al*., 2010). Significant relationships between some soil and leaf nutrients had also been reported previously (Chowdhury *et al*., 2005; Özyazici *et al*., 2011). Both positive and negative associations between some soil and leaf nutrients demonstrated that some soil and leaf nutrients levels are related. However, for most nutrients, except Ca and K (Table 4.47), specific nutrient levels in soils were not related to their levels in mature leaves of tea.

Table 4.47: Correlation coefficients (r) between soil pH/nutrients and leaf nutrients and soil pH/nutrients and yields at Timbilil (soil depth; 0-15 cm)

	Leaf	N	P	K	Ca	Mg	Mn	Al	Zn	Cu	Fe	Yields
Soil	N	-0.899	0.495	0.902	**0.952**	**0.963**	-0.579	-0.393	-0.476	-0.055	-0.521	-0.728
	P	0.301	0.342	-0.521	0.122	-0.162	0.830	-0.814	0.088	0.037	0.761	0.596
	K	**0.998**	-0.652	**-0.973**	-0.818	**-0.966**	0.531	0.088	0.075	-0.343	0.398	0.550
	Ca	-0.924	0.683	0.859	**0.984**	**0.985**	-0.384	-0.490	-0.307	0.126	-0.307	-0.545
	Mg	-0.130	0.449	0.005	-0.297	-0.056	0.349	0.491	**0.964**	0.937	0.504	0.591
	Mn	0.715	-0.135	-0.841	-0.296	-0.586	0.798	-0.558	0.006	-0.235	0.669	0.624
	Al	-0.633	-0.055	0.793	0.658	0.690	-0.896	-0.080	-0.760	-0.466	-0.896	**-0.985**
	Zn	-0.744	0.035	0.901	0.593	0.732	-0.941	0.158	-0.526	-0.218	-0.887	-0.935
	Cu	-0.053	-0.101	0.080	0.546	0.265	-0.165	-0.770	-0.868	-0.744	-0.294	-0.477
	Fe	0.777	-0.199	-0.890	-0.389	-0.663	0.800	-0.472	0.045	-0.231	0.671	0.655
	pH	-0.897	0.428	0.927	0.916	**0.950**	-0.659	-0.307	-0.498	-0.086	-0.600	-0.785

(p≤0.05, r≥0.950)

Table 4.48: Correlation coefficients (r) between soil pH/nutrients and leaf nutrients and soil pH/nutrients and yields at Timbilil (soil depth; 15-30 cm)

	Leaf	**N**	**P**	**K**	**Ca**	**Mg**	**Mn**	**Al**	**Zn**	**Cu**	**Fe**	**Yields**
Soil	N	-0.891	0.717	0.804	**0.993**	**0.966**	-0.299	-0.568	-0.294	0.133	-0.228	-0.482
	P	0.349	-0.385	-0.301	0.173	-0.142	0.020	-0.652	-0.798	-0.852	-0.154	-0.255
	K	0.878	-0.459	-0.890	-0.948	-0.949	0.594	0.403	0.518	0.104	0.545	0.751
	Ca	**-0.966**	0.507	**0.987**	0.860	**0.968**	-0.661	-0.143	-0.306	0.112	-0.562	-0.719
	Mg	-0.921	0.471	**0.957**	0.588	0.828	-0.657	0.249	0.025	0.377	-0.508	-0.568
	Mn	0.641	-0.240	-0.713	-0.134	-0.466	0.577	-0.662	-0.312	-0.502	0.417	0.342
	Al	-0.078	-0.332	0.207	0.460	0.256	-0.485	-0.488	**-0.990**	-0.877	-0.611	-0.725
	Zn	-0.627	-0.127	0.822	0.458	0.606	**-0.984**	0.269	-0.557	-0.306	-0.947	**-0.951**
	Cu	-0.348	0.917	0.066	0.390	0.351	0.652	0.503	0.580	0.748	0.749	0.567
	Fe	0.502	0.151	-0.691	-0.081	-0.369	0.862	-0.706	0.093	-0.050	0.769	0.657
	pH	-0.926	0.409	**0.975**	0.852	0.943	-0.725	-0.149	-0.417	-0.010	-0.646	-0.797

(p≤0.05, r≥0.950)

Table 4.49: Correlation coefficients (r) between soil pH/nutrients and leaf nutrients and soil pH/nutrients and yields at Timbilil (soil depth 40-60 cm)

	Leaf	**N**	**P**	**K**	**Ca**	**Mg**	**Mn**	**Al**	**Zn**	**Cu**	**Fe**	**Yields**
Soil	N	-0.772	0.440	0.761	0.967	0.888	-0.471	-0.589	-0.605	-0.213	-0.456	-0.693
	P	0.156	0.397	-0.366	0.306	0.008	0.706	-0.915	-0.060	-0.037	0.636	0.430
	K	0.707	-0.192	-0.781	-0.860	-0.812	0.689	0.404	0.749	0.396	0.691	0.871
	Ca	-0.487	-0.056	0.640	-0.003	0.321	-0.732	0.781	0.126	0.249	-0.611	-0.483
	Mg	-0.134	-0.229	0.278	-0.399	-0.067	-0.480	**0.961**	0.367	0.321	-0.375	-0.160
	Mn	0.882	-0.280	**-0.974**	-0.753	-0.878	0.826	-0.002	0.435	0.059	0.748	0.856
	Al	0.448	-0.878	-0.216	-0.229	-0.352	-0.460	0.068	-0.805	**-0.964**	-0.618	-0.526
	Zn	-0.691	-0.040	0.869	0.477	0.653	**-0.966**	0.300	-0.463	-0.192	-0.906	-0.913
	Cu	-0.303	0.914	0.106	0.523	0.430	0.607	-0.665	0.400	0.603	0.681	0.456
	Fe	0.521	0.071	-0.686	-0.059	-0.370	0.794	-0.736	-0.033	-0.176	0.681	0.567
	pH	-0.867	0.243	**0.972**	0.697	0.847	-0.853	0.088	-0.400	-0.040	-0.770	-0.855

(p≤0.05, r≥0.950)

Therefore, it is difficult to use soil analysis in predicting levels of a particular nutrient in mature leaves of tea. Similarly, levels of a given nutrient in mature leaves of tea can not be used to estimate nutrient levels in soils.

Tea yields were negatively and significantly correlated to soil extractable aluminium levels at surface soils (Table 4.47) at Timbilil, demonstrating that reduced levels of soil exchangeable aluminium would increase yields at this site. This observation supports earlier findings (Ahsan, 1994). Aluminium regulates uptake of phosphorus, nitrogen, potassium, calcium and magnesium by tea plants (Kinoshi *et al*., 1985). Tea yields are usually low at high concentration of Al in soils as phosphorus fixation (Wanyoko *et al*., 1992a; Kebeney *et al*., 2010) and leaching of bases (Kamau *et al*, 1998; Kebeney *et al*., 2010) increases, leading to reduced growth rates and yields. Negative significant relationship was also observed between yields and soil extractable Zn at soil depth 15-30 cm (Table 4.48). This implied that tea yields increased despite a decrease in levels of zinc in these soils. The inverse correlation supports past findings (Wanyoko *et al*., 1992b; Chikondi, 2012) that application of zinc does not give significant yields responses, unless its levels in soils are limiting.

4.5.2 Relationships between Soil pH and Leaf Nutrients/yields and Available Soil Nutrients and Leaf Nutrients/yields at Kangaita

Various soil and leaf nutrients levels showed both positive and negative significant associations at given soil depths. Extractable aluminium levels in the soils were significantly and negatively related to mature leaf Mg at soil depth 0-15 cm (Table 4.50), P at depth 15-30 and 40-60 cm (Tables 4.51 and 4.52) and K (Table 4.52). Increased aluminium in soils (Tables 4.22-4.24) caused a decrease in levels of these nutrients in the leaves of tea. Previous studies (Wanyoko *et al*., 1992a; Owuor *et al*., 1990f, 2011b) had also reported that high levels of extractable Al in soils reduced leaf P (Wanyoko *et al*., 1992a; Kebeney *et al*., 2010) through fixation and Mg and

K through leaching (Kamau *et al*., 1998; Kebeney *et al*., 2010). Soil available N was negatively and significantly correlated to mature leaf P (Table 50) and Al (Table 4.51). This meant that increased levels of soil N reduced the levels of leaf phosphorus and aluminium. These results are in agreement with earlier findings on leaf P (Kebeney *et al*., 2010; Owuor *et al*., 2011b) and Al (Owuor and Cheruiyot, 1989; Owuor *et al*., 1990b; Ruan *et al*., 2006). Other negative significant associations were observed between soil Fe and leaf K (Table 4.50) and soil Zn and leaf Mg (Table 4.51). In such strongly acidic soils (Tables 4.1-4.3), levels of micronutrients iron and zinc are usually high (Nath, 2013).

Such low pH levels in soils reduce availability and uptake of magnesium by tea plants (Kebeney *et al*., 2010). Positive significant correlations were observed between levels of soil extractable P and leaf Zn (Table 50) and soil available Mg and leaf Fe (Tables 4.50 and 4.51). Previous studies (Chowdhury *et al*., 2005; Özyazici *et al*., 2011) had also reported relationships between some soil and leaf nutrients. Current results also agree with the past findings. However, no individual soil nutrient levels were related to its levels in mature leaves of tea plants at this site (Kangaita). This observation further implied that soil analysis cannot be sufficient to predict leaf nutrients levels and *vice versa*.

At the lowest soil depth (40-60 cm), tea yields at this site were positively and significantly related to soil extractable zinc and copper levels. This indicated that increased levels of these soil micronutrients increased tea yields. This observation supports earlier findings on zinc nutrition in tea (Barua and Dutta, 1972; Malenga *et al*., 1982; Wanyoko *et al*., 1992a). Positive significant ($p \leq 0.05$, $r \geq 0.950$) associations between tea yields and these micronutrients demonstrated that levels of Cu and Zn in soils directly affect tea yields; the lower the levels of these micronutrients in soils, the lower the tea yields and *vice versa*. This conformed to past results (Sharma and Sharma, 1995; Salukvadze, 1980; Venkatesan *et al*., 2004) where yields of tea were related to some soil nutrients levels.

4.5.3 Summary on relationships between soil and leaf nutrients at the two sites

In both locations, positive and negative significant associations between various soil and leaf nutrients were observed. However, the responses for individual nutrients varied in different sites. For example, whereas soil extractable Al was negatively related to mature leaf magnesium, phosphorus and potassium at Kangaita, levels of these leaf nutrients were not significantly related to soil aluminium levels at Timbilil.

Table 4.50: Correlation coefficients (r) between soil pH/ nutrients and leaf nutrients and soil pH/nutrients and yields at Kangaita (soil depth; 0-15 cm)

	Leaf	**N**	**P**	**K**	**Ca**	**Mg**	**Mn**	**Al**	**Zn**	**Cu**	**Fe**	**Yields**
Soil	N	0.926	**-0.992**	-0.880	-0.208	-0.539	-0.122	-0.688	0.032	-0.368	-0.172	0.774
	P	0.126	-0.060	0.275	0.233	0.365	0.284	0.101	**0.972**	-0.239	0.798	0.257
	K	-0.865	0.817	0.841	-0.047	0.922	-0.095	0.386	0.435	-0.158	0.773	-0.757
	Ca	0.174	-0.251	0.016	-0.139	0.444	-0.078	-0.270	0.812	-0.582	0.840	0.179
	Mg	-0.221	0.120	0.327	-0.184	0.745	-0.155	-0.103	0.790	-0.570	**0.985**	-0.191
	Mn	-0.257	0.274	0.537	0.125	0.671	0.145	0.203	0.915	-0.282	0.940	-0.123
	Al	0.802	-0.633	-0.616	0.360	**-0.998**	0.395	-0.060	-0.344	0.470	-0.844	0.798
	Zn	0.765	-0.463	-0.253	0.738	-0.853	0.783	0.289	0.208	0.624	-0.500	0.918
	Cu	0.777	-0.777	-0.508	0.005	-0.236	0.096	-0.436	0.551	-0.370	0.278	0.743
	Fe	0.707	-0.867	**-0.988**	-0.479	-0.589	-0.431	-0.797	-0.570	-0.344	-0.540	0.451
	pH	-0.764	0.712	0.410	-0.140	0.253	-0.230	0.305	-0.634	0.257	-0.286	-0.776

(p≤0.05, r≥0.950)

Table 4.51: Correlation coefficients (r) between soil pH/nutrients and leaf nutrients and soil pH/nutrients and yields at Kangaita (soil depth; 15-30 cm)

	Leaf	**N**	**P**	**K**	**Ca**	**Mg**	**Mn**	**Al**	**Zn**	**Cu**	**Fe**	**Yields**
Soil	N	0.518	-0.796	-0.927	-0.758	-0.230	-0.710	**-0.970**	-0.468	-0.683	-0.204	0.209
	P	0.774	-0.514	-0.199	0.659	-0.603	0.726	0.189	0.557	0.361	-0.103	0.930
	K	0.642	-0.772	-0.580	-0.327	-0.024	-0.240	-0.673	0.426	-0.661	0.398	0.514
	Ca	0.197	-0.289	-0.032	-0.182	0.433	-0.119	-0.321	0.781	-0.617	0.826	0.185
	Mg	-0.007	0.120	0.327	-0.184	0.745	-0.155	-0.103	0.790	-0.570	**0.985**	-0.321
	Mn	0.276	-0.009	0.359	0.726	-0.061	0.767	0.495	0.913	0.323	0.392	0.530
	Al	0.893	**-0.982**	-0.866	-0.262	-0.460	-0.175	-0.724	0.070	-0.444	-0.089	0.730
	Zn	0.819	-0.579	-0.470	0.557	**-0.973**	0.598	0.104	-0.096	0.565	-0.718	0.890
	Cu	0.607	-0.280	-0.144	0.795	-0.881	0.816	0.436	0.025	0.799	-0.662	0.778
	Fe	0.861	-0.829	-0.863	0.003	-0.905	0.051	-0.425	-0.453	0.118	-0.763	0.738
	pH	-0.823	0.630	0.310	-0.490	0.522	-0.569	-	-0.589	-0.149	-0.013	-0.927

(p≤0.05, r≥0.950)

Table 5.52: Correlation coefficients (r) between soil pH/nutrients and leaf nutrients and soil pH/nutrients and yields at Kangaita (soil depth; 40-60 cm)

	Leaf	**N**	**P**	**K**	**Ca**	**Mg**	**Mn**	**Al**	**Zn**	**Cu**	**Fe**	**Yields**
Soil	N	-0.419	0.144	-0.225	-0.734	0.204	-0.784	-0.431	-0.857	-0.341	-0.281	-0.656
	P	0.796	-0.525	-0.233	0.678	-0.680	0.742	0.200	0.473	0.421	-0.207	0.949
	K	0.810	-0.938	-0.811	-0.347	-0.300	-0.259	-0.767	0.154	-0.570	0.076	0.639
	Ca	0.735	-0.498	-0.159	0.609	-0.482	0.680	0.156	0.662	0.258	0.046	0.889
	Mg	-0.407	0.075	0.008	-0.805	0.827	-0.802	-0.560	0.118	-0.908	0.742	-0.590
	Mn	-0.293	0.441	0.726	0.456	0.521	0.461	0.537	0.934	0.084	0.774	-0.058
	Al	0.852	**-0.963**	**-0.991**	-0.347	-0.641	-0.281	-0.759	-0.358	-0.321	-0.455	0.636
	Zn	0.878	-0.630	-0.424	0.595	-0.870	0.654	0.094	0.181	0.463	-0.482	**0.976**
	Cu	0.829	-0.561	-0.292	0.661	-0.744	0.724	0.171	0.391	0.438	-0.291	**0.966**
	Fe	**0.985**	-0.918	-0.823	0.112	-0.851	0.184	-0.406	-0.112	0.054	-0.528	0.909
	pH	-0.791	0.703	0.391	-0.229	0.324	-0.317	0.234	-0.633	0.161	-0.223	-0.826

($p \leq 0.05$, $r \geq 0.950$)

Instead, soil aluminium was negatively related to leaf Cu and Zn contents at this site. Soil N was positively related to leaf calcium and magnesium levels at Timbilil but this soil nutrient had no significant relationship with these leaf nutrients at Kangaita. Instead, it was negatively related to leaf phosphorus and aluminium contents. Similarly, soil zinc related negatively to leaf magnesium at Kangaita but in Timbilil, this soil nutrient had a negative association with leaf manganese. These results implied that the soils were quite heterogenous with high variability in nutrients levels. It is therefore difficult to use soil analysis in predicting nutrients levels in tea plants. Thus, mature leaf analysis which is more precise be used in establishing nutritional status in tea plants.

4.6 Relationship (r) between Yields and Mature Leaf Nutrients Levels

Correlation results for leaf nutrients levels and tea yields are presented in Table 4.53. Yields were positively and significantly ($p \leq 0.05$, $r \geq 0.950$) related to mature leaf Fe contents at Timbilil, showing that yields increased with increased uptake of iron. Indeed, leaf iron levels increased with increasing fertilizer application rates (Table 4.41) leading to an increase in tea yields (Table

46). Increased tea yields as a result of increased iron in tea plants had also been reported in India (Kuzhandaivel and Venkatesan, 2011). Though tea yields were negatively and positively associated to some other leaf nutrients levels, the associations were insignificant. The results herein have indicated that tea yields are influenced by leaf iron levels at Timbilil. Therefore, adequate levels of iron must be maintained in soils to sustain high yields of tea.

Table 1: Correlation coefficients (r) between yields of tea and leaf nutrients levels

		Yields/mature leaf nutrients									
Site		N	P	K	Ca	Mg	Mn	Al	Zn	Cu	Fe
Kangaita	Yields	0.944	-0.753	-0.526	0.455	-0.797	0.528	-0.078	0.251	0.263	-0.351
Timbilil	Yields	0.517	0.218	-0.716	-0.519	-0.563	0.942	-0.041	0.784	0.548	0.957

($p \leq 0.05$, $r \geq 0.950$)

CHAPTER FIVE

SUMMARY, CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS FOR FUTURE STUDIES

5.1 Summary

1. Increasing rates of NPKS fertilizer application significantly decreased ($p \leq 0.05$) soil pH levels at Timbilil but had no significant effect on soil pH levels at Kangaita. While increasing rates of NPKS fertilizer application significantly ($p \leq 0.05$) increased levels of soil extractable N at Kangaita, it significantly ($p \leq 0.05$) decreased soil available N levels at Timbilil. However, levels of other soil nutrients at all soil depths studied responded sporadically to increasing rates of NPKS fertilizer application at both sites. No conclusive trends were established due to the high CVs recorded. Mature leaf N levels significantly ($p \leq 0.05$) increased due to progressive increase in rates of NPKS fertilizer application at both sites. However, above 120 kg/ha/year of applied NPKS fertilizer, the observed increase in leaf N was not significant. At both sites, increasing rates of NPKS fertilizer application significantly ($p \leq 0.05$) increased tea yields in a quadratic manner, with maximum yield being recorded at 120 kgN/ha/year.

2. Generally, biennial application of NPKS fertilizer did not affect soil pH and nutrients levels at both sites. However, the interval significantly ($p \leq 0.05$) increased levels of available soil N at two soil depths (0-15 and 40-60 cm) at Kangaita but significantly reduced ($p \leq 0.05$) levels of soil N at all depths in Timbilil. Additionally, levels of available phosphorus at soil depth 15-30 cm at Timbilil increased significantly ($p \leq 0.05$) during biennial NPKS application. Soil pH and all other soil nutrients levels were not affected by intervals of NPKS fertilizer application in both locations. Most mature leaf

nutrients levels at both sites were not influenced by interval of NPKS application. However, with biennial fertilizer application at Kangaita, mature leaf Ca levels significantly ($p \le 0.05$) increased while leaf N contents and tea yields reduced significantly ($p \le 0.05$).

3. At soil depth 0-15 cm, prunings left *in situ* significantly increased ($p \le 0.05$) levels of soil extractable N, Ca, Mg and Mn at Kangaita and soil Al levels at Timbilil. However, pruning managements did not affect soil pH and other soil nutrients at various depths in both sites. Mature leaf calcium and manganese levels significantly increased ($p \le 0.05$) with tea prunings left *in situ* at Kangaita. However, prunings managements did not affect levels of all other leaf nutrients at both sites. Tea yields significantly ($p \le 0.05$) increased due to leaving prunings in situ in tea farms.

4. In both locations, positive and negative significant ($p \le 0.05$, $r \ge 0.950$) associations between various soil and leaf nutrients were observed. However, except for mature leaf calcium and potassium and soil Ca and K levels at surface soils in Timbilil, no individual soil nutrients levels were related to their levels in leaves of tea plants. Tea yields were positively and significantly ($p \le 0.05$, $r \ge 0.950$) correlated to levels of zinc and copper at the lowest soil depth in Kangaita but negatively and significantly ($p \le 0.05$, $r \ge 0.950$) associated to levels of soil aluminium at surface layers and soil zinc at depth 15-30 cm at Timbilil. Mature leaf iron levels were positively and significantly ($p \le 0.05$, $r \ge 0.950$) related to tea yields.

5.2 Conclusions

1. Increasing rates of NPKS fertilizer application decreased ($p \le 0.05$) soil pH levels at Timbilil but did not have significant effect on soil pH at Kangaita. Increasing rates of

fertilizer application increased ($p \leq 0.05$) soil available N levels at Kangaita but significantly ($p \leq 0.05$) decreased soil available N levels at Timbilil. Other soil extractable nutrients levels responded sporadically to increasing rates of applied NPKS at both sites. No conclusive trends were established due to high CVs. Increasing rates of NPKS application significantly ($p \leq 0.05$) increased both mature leaf N levels and tea yields at the two sites. Tea yield responses to applied N were quadratic and peaks occurred at 120 kgN/ha/year.

2. Generally, biennial NPKS fertilizer application did not affect soil pH, most soil available and mature leaf nutrients levels at both sites. However, this interval of fertilizer application significantly ($p \leq 0.05$) decreased soil N levels at Timbilil but significantly ($p \leq 0.05$) increased soil N levels while reducing significantly ($p \leq 0.05$) levels of mature leaf N and tea yields at Kangaita.

3. Prunings left *in situ* significantly ($p \leq 0.05$) increased levels of soil available N, Ca, Mg and Mn at Kangaita and Al at Timbilil. However, the effect of leaving prunings *in situ* was restricted in upper soil depth of 0-15 cm at both sites. Soil pH and other available soil nutrients levels were not influenced by pruning managements. Leaving prunings *in situ* significantly ($p \leq 0.05$) improved levels of mature leaf calcium and manganese as well as tea yields at Kangaita.

4. There were positive and negative significant ($p \leq 0.05$, $r \geq 0.950$) associations between various soil and mature leaf nutrients levels at both sites. However, except Ca and K, individual soil nutrients levels were not related to their levels in mature leaves of tea plants.

5.3 Recommendations

1. Rates of NPKS 25:5:5:5 fertilizer applications to be reviewed downwards to rates between 100 and 120 kg per hectre per year for economic tea production.

2. NPKS 25:5:5:5 fertilizer applications to be done annually as currently recommended for sustained high yields of tea.

3. Tea prunings to be left *in situ* after pruning to improve soil quality and tea yields in the long run.

4. Mature leaf diagnosis tool which is more precise can be used in assessing nutrients demands of tea plants.

5.4 Significance of the Study

Data generated in this study has provided a knowledge base to tea growers on the current soil and leaf nutritional status. This can help them modify their fertilization programmes and minimize quantities of nitrogenous fertilizers applied on tea. This will help reduce costs of production and conserve the environment as excess nitrogen degrades soil quality. Policy makers can also use these results in setting management policies geared towards improved production and sustainability in the tea industry.

5.5 Suggestions for Future Studies

1. Tea is a perennial crop and annual responses are quite variable hence yield data for only two years may not be sufficient enough for conclusive trends. Longer experimentation is required in order to establish if observed trends can be stable over time.

2. Detailed study is required to assess quality/quantity of tea prunings at different sites and determine their decomposition rates to establish the release time of nutrients from prunings.

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APPENDICES

APPENDIX 1

Randomized plot/treatment allocation

Replicate 1		Replicate 2		Replicate 3	
Plot No.	Treatment	Plot No.	Treatment	Plot No.	Treatment
1A	R2F1(-)	9A	R2F1(+)	17A	R2F1(-)
1B	R2F1(+)	9B	R2F1(-)	17B	R2F1(+)
2A	R1F2(+)	10A	R1F2(-)	18A	R1F2(-)
2B	R1F2(-)	10B	R1F2(+)	18B	R1F2(+)
3A	R0F2(-)	11A	R1F1(-)	19A	R3F2(+)
3B	R0F2(+)	11B	R1F1(+)	19B	R3F2(-)
4A	R1F1(+)	12A	R3F2(-)	20A	R2F2(-)
4B	R1F1(-)	12B	R3F2(+)	20B	R2F2(+)
5A	R3F2(-)	13A	R0F1(-)	21A	R0F2(+)
5B	R3F2(+)	13B	R0F1(+)	21B	R0F2(-)
6A	R0F1(+)	14A	R2F2(+)	22A	R1F1(+)
6B	R0F1(-)	14B	R2F2(-)	22B	R1F1(-)
7A	R2F2(+)	15A	R0F2(+)	23A	R0F1(-)
7B	R2F2(-)	15B	R0F2(-)	23B	R0F1(+)
8A	R3F1(-)	16A	R3F1(+)	24A	R3F1(+)
8B	R3F1(+)	16B	R3F1(-)	24B	R3F1(-)

KEY: R0, R1, R2 and R3 were NPK(S) 25:5:5:5 fertilizer rates of 0, 60, 120 and 180 kg N/ha/year respectively. F1 and F2 were fertilizer application intervals of 12 and 24 months respectively. (+) –Tea prunings left *in situ*, (-) – Removal of tea prunings,

NB: R0F1 (+), R0F1 (-), R0F2 (+) and R0F2 (-) were the control plots.