EFFECTS AND THE RELATIONSHIP BETWEEN NITROGENOUS FERTILIZER APPLICATION RATES AND PLUCKING INTERVALS ON SOME SOIL QUALITY INDICATORS AND YIELD OF TEA (*Camellia sinensis* (L.) IN EASTERN AFRICA TEA GROWING REGIONS

BY

ROBERT ONDIEKI OMBORI

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DECLARATION

This thesis has been submitted in partial fulfillment for the award of Master of Science (Chemistry) degree of Maseno University. The thesis has not been submitted in any other university for a degree award and the work herein is my original work. All cited work has been acknowledged.

By:

Robert Ondieki Ombori

Adm. No. PG/MSC/00062/2012

Sign…………………………….. Date…………………………

SUPERVISORS

Prof. P. Okinda Owuor

Department of Chemistry

School of Physical and Biological Sciences

Maseno University

P.O. Box 333, Maseno, Kenya.

Sign…………………………….. Date…………………………

Dr. David M. Kamau

Environment & Natural Resource Systems Unit

KALRO Secretariate,

P. O. Box 57811, Nairobi, Kenya

Sign………. ……….. Date…………………………

Dr. Bowa O. Kwach

Department of Chemistry

School of Physical and Biological Sciences

Maseno University

P. O. Box 333, Maseno, Kenya.

Sign…………………………….. Date…………………………

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This work is dedicated to my beloved sons Reuben Isaiah Ombori and Ryan Isaac Ong’oa.

ABSTRACT

Eastern Africa tea is grown in high rainfall areas causing high nutrients depletion through leaching and surface run-off. Nutrients are also removed with harvested crop. The depletion requires nutrients replenishment through fertilizer applications. But inappropriate nitrogen rates cause nutrients imbalance, reduce soil pH, and influence soil organic carbon contents. Plucking intervals cause variations in tea productivity. Despite environmental factors vary in Eastern Africa, recommended fertilizer formulation, NPKS, 25:5:5:5, rates and harvesting intervals are similar in all regions. It is not documented if the NPKS fertilizer rates and plucking intervals influence soil chemical parameters within Eastern Africa tea growing regions. This study determined effects of NPKS 25:5:5:5 as fertilizer rates and plucking intervals on soil organic carbon, pH, and nutrients levels and the relationship between soil organic carbon, pH, nutrients levels and tea yields in Eastern Africa. Soil samples were collected from fertilizer trials on clone TRFK 6/8 at Timbilil, Changoi, Arroket (Kenya), Maruku, Katoke (Tanzania), Kitabi and Mulindi (Rwanda), trials were laid out as 5x3 factorial with five nitrogen fertilizer rates (0, 75, 150, 225 and 300KgN/ha/year) and three plucking intervals (7, 14 and 21 days) as treatments at each site. Soil samples were obtained at depths of 0-10, 10-20, 20-30, 40-60 cm. Soil organic carbon (SOC) was determined using colorimetric methods; pH using pH meter; nitrogen by Kjeldhal method and the other nutrients using ICPAES. Yields were obtained from the field trials. Soil organic carbon contents ranged from 4.16 to 17.61% and were sufficient. Increasing nitrogen rates increased ($p \leq 0.05$) soil organic carbon, N, P, Al, Mn, Fe, Cu levels but lowered ($p \leq 0.05$) soil pH, K, Ca, Mg, and Zn. The soil pH values ranged between 3.22 and 4.84 and were in optimal range. There was decrease in soil pH with nitrogen application rates suggesting that long term application could increase soil acidity to levels detrimental for tea production. It is necessary to periodically monitor soil pH to invoke mitigation activities if the pH levels decrease below 4.0. Plucking intervals had no influence on SOC, pH and nutrients levels at all sites. Soil organic carbon, pH, and nutrients levels varied significantly ($p \leq 0.05$) from location to location. However, levels were optimal for most of the parameters and therefore were not constraining tea production. Soil organic carbon directly correlated ($p \leq 0.05$) with yields, N, P, Al, Fe, Cu, and Mn and inversely with pH, K, Ca, Mg, and Zn. The correlation between SOC, the nutrients and yields suggest that tea production management must ensure these parameters are optimal for realization of high yields.

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LIST OF ABBREVIATIONS AND ACRONYMS

CV	Coefficient of variation
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectrophotometer (ICP- AES)
LSD	Least significant difference
N rates	Nitrogenous fertilizer rates
ppm	Parts per million
SOC	Soil Organic Carbon
TRFK	Tea Research Foundation of Kenya
TRIT	Tea Research Institute of Tanzania
TRI	Tea Research Institute (Kenya)
KgN/ha/yr	Kilogram nitrogen fertilizer per hectare per year

DEFINITIONS OF TERMS

Genotype (Clones/Cultivars): Plants/varieties that are derived from one mother bush by a method of vegetative propagation and maintained through cultivation. They have the same genetic constitution.

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CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Tea (*Camellia sinensis*, (L) O. Kuntze) is an evergreen plant in the *Theaceae* family (Bokuchava and Skobeleva, 1969; Hara *et al.*, 1995). There were about 4.12 million ha of land under tea cultivation with a total production of about 5 million tons in the world in 2015 (ITC 2016). Primarily, three main varieties: the China type (*C. sinensis* variety), the Assamese type (*C. sinensis* variety *Assamica*) and hybrid type (*Cinensis* variety *Assamica ssp lasiocalyx*) are exploited commercially (Barnejee, 1992). The beverages of tea are the second most consumed fluids in the world after water (Agarwal, 1989; Sharma *et al*. 2007) with consumption far outstriping that of coffee, beer, wine and carbonated drinks (Cabrera *et al*., 2006; Monirul *et al*., 2012). The tea plant is one of the major foreign exchange earners in many production regions of the world (Harler, 1971; Eden, 1976; Mbadi and Owuor, 2008).
Tea is grown in a wide range of latitudes, ranging from 45^{o}N (Russia) to 30^{o}S (South Africa), and longitudes from 150^{o}E (New Guinea) to 60^{o}W (Argentina) (Shoubo, 1989), at altitudes ranging from sea level in Japan and Sri Lanka (Anandacoomaraswamy *et al*., 2000) to about 2,700 m above mean sea level (amsl) in Olenguruone, Kenya and Gisovu, Rwanda (Owuor *et al*., 2008a). The favourable growing conditions for tea in the East African highlands include a suitable temperature (15-25^{0}C), relatively high humidity (80-90%), medium to high well distributed annual rainfall (1200-2000mm) and acidic soils (pH 4.5-5.6) (Anon, 2002). The crop is therefore adaptable to various geographical and environmental factors which usually influence growth, soil quality and nutrients supply (Shoubo, 1989; Anandacoomaraswamy *et al*., 2000; Anon, 2002). As tea plant can tolerate large deviations in normal nutrients requirements before the first visible signs of deficiency begin to appear in the foliage, carrying out regular soil quality analysis to detect nutrients deficiency which affect tea crop yields (Thu and Nguyen, 2011; Thu *et al*., 2013; Msomba *et al*., 2011: Anon, 2002; Owuor *et al*., 2008b), is necessary to facilitate applying corrective measures.

In Eastern Africa, clone TRFK 6/8 is widely grown and constitutes about 80% of Rwanda tea, 60% of Kenya clonal tea and 35-40% of Tanzania tea (Msomba *et al*., 2011; Owuor *et al*., 2011a). The agronomic recommendations in use in the Eastern Africa tea growing regions are largely uniform and have been adopted from the recommendations made in Kenya (Othieno, 1988; Anon, 2002), sometimes without re-testing in new growing areas. Nutrients diagnosis in this region is based on mature leaf nutrients and the recommended nitrogenous fertilizer rates set vary between 100 and 250 kg N/ha/year (Anon, 2002). However, farmers have failed to replicate yields (Msomba *et al*., 2014) in different locations within Eastern Africa. The uniform agronomic recommendations used in tea production in East Africa may be inappropriate in some regions. Indeed it is not documented how the different agronomic inputs influence soil nutrients levels and if the variations in soil nutrients are related to yields in the different regions.

Plants absorb nutrients mainly from the soil. But the nutrients are lost from the soil through soil erosion (Fagerström *et al*., 2002; Lobo *et. al*. 2005), leaching (Ramos and Varela, 1990; Owuor *et al.*, 1997) and surface run-offs (Othieno, 1975). Soil nutrients also get depleted through continuous tea cropping (Dang, 2002; Baruah, 2013). Soil organic matter acts as a revolving nutrient fund among other functions (Alexandra and Jose, 2005). Leaf drop and prunings left in field return organic matter to the soil which improves soil organic carbon (SOC) (Dutta *et al*., 1971; Sandanam *et al*., 1982a; Phukan *et al*., 2011). Soil organic carbon is simultaneously a source and a sink for nutrients and plays a vital role in soil fertility maintenance (Vanlauwe, 2004; Bationo *et al*., 2005). The management practices adopted in tea plantations including soil organic matter (SOM) management plays important roles in improvement of SOC and nutrients availability (Iori *et al*., 2014). Increasing nitrogenous fertilizer application rates leads to increased SOC (Venkatesan *et al*., 2004; Chandravanshi *et al*., 2008; Franzluebbers, 2005).

In the absence of nitrogen fertilization, plants absorb nutrients from the mineralized organic matter in the soil (Venkatesan *et* al., 2004; Thenmozhi *et al*., 2012) causing decline in SOC. Soil organic matter is influenced by other factors including climate and soil management practices (Oades, 1995). In highly weathered tea soils of the tropics, high organic matter decomposition rates (Gillman and Sumpter, 1986) lead to decrease in soil fertility (Sandanam *et al*., 1978; Lee and Pankhurst, 1992), soil nutrients loses (Lee and Pankhurst, 1992) and decline in productivity (Dalal and Mayer, 1987). The previous work (Venkatesan *et al*., 2004; Thenmozhi *et al*., 2012; Chandravanshi *et al*., 2008) investigated patterns of SOC at single sites with similar climatic patterns. It is not known whether SOC varies with nitrogen fertilizer rates at different sites and if the levels are region specific. And also the relationship between SOC, pH and yields in different parts of Eastern Africa is not documented.

Tea grows well in acidic soils (Ranganathan, 1977; Natesan *et al.*, 1984; Anandacumaraswamy *et al.*, 1989; Barua, 2000; Banerjee, 1993; Othieno, 1992). An important soil condition for tea growth is moderate to low pH (ranging from 3 to 5.6) and the optimum pH for good growth and optimum nutrient utilization (especially nitrogen) is between pH 4 and 5 (Ranganathan and Natesan, 1985). Soil pH is a critical factor for economic tea plant growth since it influences the availability of other plant nutrients and microbial activities (Plaster, 1992). At low soil pH, base cations K, Ca, and Mg are prone to leaching (Ruan *et al.*, 2006; Kamau *et al.*, 2008; Owuor and Wanyoko, 1996) and fixation of phosphorus by sorption or precipitation with aluminium and iron oxides is increased (Ruan *et al.*, 2004; Chong, 2008). Long-term tea cultivation causes soil acidification with pH reducing below 4.0 as a consequence of high nitrogen fertilizer application rates (Oh *et al.*, 2006; Dang, 2002; Owuor *et al.*, 2012). Nitrogen fertilizer application is the main cause of soil acidification (Tachibana *et al.*, 1995; Bonheure and Willson, 1992; Venkatesan *et al.*, 2004; Dogo *et al.*, 1994; Kamau *et al.*, 2008; Owuor and Wanyoko, 1996). Indeed soil pH in a tea field decreased to as low as 2.9 due to application of high nitrogen fertilizers rates (Tachibana *et al.*, 1995).

Tea plantations soils in Russia that received 50 to 300 kg ammonium sulfate annually for 35 years, showed decreased soil pH while the content of mobile Fe and Al level increased (Gabisoniya *et al.*, 1973). In Acrisols of Vietnam, 10 years of continuous application of nitrogen fertilizers on tea crop increased both H^+ and Al^{3+} concentrations in the soil while Ca^{2+} and Mg^{2+} levels decreased (Do *et al.*, 1980) with a decline in plant yield. The magnitude of any change in soil pH and exchangeable aluminium and iron in the soil, however, varies depending on management practices (Minh, 2002). Indeed, in Kenya, high rates of application of nitrogenous fertilizers reduced soil pH and extractable nutrients such as phosphorus and potassium (Dogo *et al.*, 1994; Owuor *et al.*, 2011b). Several studies have demonstrated that soil pH varies due to nitrogenous fertilizer application rates (Tachibana *et al.*, 1995; Gabisoniya *et al.*, 1973; Do *et al.*, 1980; Minh, 2002; Dogo *et al.*, 1994) and this affects yield (Venkatesan *et al.*, 2004; Kamau *et al.*, 2008). However, it is not established if the magnitude of the changes in the soil pH and other nutrients vary at different extents with variations in rates of nitrogen fertilizer application in different locations in East Africa. Nutrient requirements for commercial tea production are particularly high because harvestable portions of tea contain nutrients (Do *et al.*, 1980; Ranganathan and Natesan, 1985). The nutrients play varied functions in the tea plant that affect development of plant tissues and yields (Roy *et al*., 2006; Wickramasinghe and Krishnapillai, 1986; Bonheure and Willson, 1992; Willson, 1975a). The nutrients are classified as macro (nitrogen, phosphorus, potassium, calcium, magnesium) or micro (aluminium, iron, zinc, copper and manganese) elements (Bonheure and Willson, 1992). Nitrogen is the major nutrient for tea thus; fertilizer use in tea cultivation is usually based on nitrogenous fertilizers (Verma, 1993; Verma *et al*., 2001). The nutrient accounts for about 2- 4% of the dry weight of harvested shoots (Ranganathan and Natesan, 1985; Wanyoko and Njuguna, 1988). Use of nitrogen fertilizers varies with tea growing countries, the lowest rate being in Vietnam at 36-40 kg N/ha/year and the highest in Japan at 800 Kg N/ha/year (Bonheure and Willson, 1992; Owuor and Wanyoko, 1996). Currently, the recommended fertilizer application rates in East Africa ranges from 100-250 Kg N/ha/year depending on production level (Othieno, 1988: Owuor *et al*., 2011a). Yields of tea (Owuor *et al*., 2009; 2010; Msomba *et al*., 2014) and mature leaf nutrients (Kwach *et al*., 2014) have been demonstrated to vary with nitrogenous fertilizer application rates in East Africa. The previous studies in Eastern Africa have demonstrated that nitrogen rates increased tea yields but decreased some of the mature leaf nutrients like phosphorus, potassium, calcium and magnesium. It is not known if these variations are related to soil nutrients levels at different sites. And indeed the relationship between soil nutrients levels and soil organic carbon is not established in different locations of production within Eastern Africa.

Plucking of tea is the periodic harvesting of the young shoots, normally a bud and two to three leaves, above the plucking table and is either done by hand or mechanically (Kamau, 2008). This aims at striking a balance between yield and quality of resultant tea (Owuor *et al*., 2000). Longer plucking intervals decreased yields (Owuor *et al*., 1993, 1997, 2000; Barua *et al*, 1986), black tea quality (Owuor *et al*., 1994, 1997; Barua *et al*., 1986) but increased fatty acids levels (Okal *et* al., 2012). However, mature leaf nutrients (Kwach, 2013; Kwach *et al*., 2014) were not influenced by plucking intervals. Earlier studies did not investigate the effects of plucking intervals on soil nutrients levels and soil organic carbon contents. There is no data to establish if plucking interval causes variations in soil organic carbon and nutrients levels of tea soils in Eastern Africa and if such variations are specific to geographical area of production.

1.2 Statement of the Problem

Management practices, without periodical checks and balances, adopted in tea plantations could be the cause of soil quality degradation and decline in tea yields in East Africa. The uniform agronomic recommendations in East Africa adopted from Kenya could be inappropriate in other regions, and contributing factor to the decline in tea yields. Indeed different agronomic inputs could be influencing soil nutrients levels and the variations in soil nutrients maybe related to yields in the different regions. Nitrogenous fertilizer application rates and plucking intervals cause variations in tea productivity. However, it has not been established if nitrogen fertilizer as NPKS 25:5:5:5 rates and plucking intervals also influence soil organic carbon and soil nutrients (nitrogen, phosphorus, potassium, calcium, magnesium, aluminium, iron, zinc, copper and manganese) contents and if such influences vary with geographical area of production. Also it has not been documented if the variations in SOC are related to yields, soil pH and soil nutrients levels within East Africa tea growing regions. Soil pH is a critical factor for tea production and it is influenced by climatic patterns, location of production and agronomic inputs. However, there is no data showing the variations in the magnitude of the changes in soil pH with rates of nitrogenous fertilizer and plucking intervals in different locations in East Africa and if the extents of the changes are specific to geographical area of production.

1.3 Broad Objectives of the Study

The broad objective of this study was to establish the effects of nitrogenous fertilizer application rates and plucking intervals on soil chemical parameters and yields of tea and relationships between yields and soil chemical parameters in Eastern Africa tea growing regions.

1.4 Specific Objectives

The specific objectives were:

i. To determine the influence of nitrogenous fertilizer application rates and plucking intervals on soil organic carbon content, pH and nutrients (nitrogen, phosphorus, potassium, calcium, magnesium, aluminium, iron, zinc, copper and manganese) levels in Eastern Africa tea growing regions.

ii. To determine the interaction effects between site, nitrogen fertilizer rates and plucking intervals for some soil quality indicators

iii. To determine the relationship between soil nutrient levels, organic carbon contents with yields of tea in East Africa tea growing regions.

iv. To establish the relationship between soil organic carbon contents and nutrients levels and pH levels in different locations of production.

1.5 Null Hypotheses (H_o)

i. Soil organic carbon, pH and nutrients (nitrogen, phosphorus, potassium, calcium, magnesium, aluminium, iron, zinc, copper and manganese) levels do not vary with nitrogen fertilizer rates and plucking intervals in Eastern Africa.

ii. There are no interaction effects between site, nitrogen fertilizer rates and plucking intervals for some soil quality indicators

iii. Soil nutrients levels are not related with soil organic carbon and yields in Eastern Africa tea growing regions.

iv. There is no relationship between soil organic carbon, pH and nutrients levels in different locations of production.

NB: If the Null hypotheses do not hold, then alternative hypotheses shall be accepted.

1.6 Justification of the Study

Inapropriate management of soil quality parameters result in its degradation and variations in tea productivity. If the factors causing these variations are not well understood the soil will in the long run attain moribund state and make tea productivity unsustainable.

1.7 Significance of the Study

This study is helping in the development of soil management practices that improve crop productivity and make tea production sustainable in Eastern Africa tea growing regions.

CHAPTER TWO

REVIEW OF LITERATURE

2.1 Origin and Distribution of Tea

Tea (*Camellia sinensis,* (L) O. Kuntze) is an evergreen plant in the *Theaceae* family (Bokuchava and Skobeleva, 1969; Hara *et al.*, 1995). The plant originated from China and India (Elliot and Whitehead, 1996; Mondal, 2007). Primarily, three main varieties; the China type (*C. sinensis*), the Assamese type (*C. sinensis* variety *Assamica*) and hybrid type (*C. sinensis* variety *Assamica* ssp *Lasiocalyx*) are exploited commercially (Barnejee, 1992). The perennial tree plant is now commercially grown in many parts of the world for production of various tea beverages (Sharma *et al.*, 2007; Monirul *et al.*, 2012). Tea beverages are the second most consumed fluids in the world after water (Agarwal, 1989; Sharma *et al*. 2007; Gardener *et al.*, 2007). Its global consumption far outstrips that of coffee, beer, wine and carbonated drinks (Cabrera *et al*., 2006; Monirul *et al*., 2012). The tea plant is one of the major foreign exchange earners in producing regions of the world (Harler, 1971; Eden, 1976; Mbadi and Owuor, 2008). There were about 4.12 million hectares of land under tea cultivation with a total production of over 5 million tons per year in the world in 2015 (ITC 2016).

The tea plant is grown in a wide range of latitudes, from 45^{o}N (Russia) to 30^{o}S (South Africa), and longitudes from 150^{o}E (New Guinea) to 60^{o}W (Argentina) (Shoubo, 1989) and altitudes ranging from sea level in Japan to 2,700 m above mean sea level (amsl) in Olenguruone, Kenya and Gisovu, Rwanda (Owuor *et al.*, 2008a). In Kenya, tea is grown on the foothills of the Aberdare ranges and Mt. Kenya in the east of the Great Rift Valley and Mau ranges, Nandi, Kisii and Kakamega hills in the west of the Great Rift Valley. In Tanzania, tea is grown in the Southern Highland areas covering Tukuyu, Mufindi, and Njombe and in the Northern Tanzania in East and West Usambaras and Bukoba region on Lake Victoria (TRIT, 2006). Tea in Uganda is grown on the ridges of Rowenzories Mountain in the areas of Kigezi, Ankole, Toro, Bugama, Mubende and Zeu, and around Lake Victoria in Mityana, Lugazi and Masaka areas. In Rwanda, tea is planted in the provinces of Byumba, Cyangugu, Gikomgoro, Gisenyi and Kibaye. The total area occupied by tea in 2015 in Kenya, Uganda, Tanzania and Rwanda highlands was over 225,000 hectares with a production of about 117,000 metric tons (ICT, 2016). The differences in the growing areas are accompanied by variations in biotic and abiotic factors that affect growth, soil quality and nutrients supply to tea (Anon, 2002). The favourable tea growing conditions in the East African highlands include suitable temperature (15-25^{0}C), relatively high humidity (80-90%), medium to high well distributed annual rainfall (1200-2000mm) and acidic soils (pH 4.5-5.6) (Anon, 2002 ; Uddin *et al.*, 2005). However, it is not documented if due to variations in biotic and abiotic factors in the different regions, the soil quality varies.

2.2 Agronomic Inputs in Eastern Africa

In Eastern Africa, tea growing areas fall in several agro-ecological regions, differing widely in elevation and climatic factors but with favourable soil conditions. Despite these differences, agronomic inputs are largely uniform throughout the region (Owuor *et al*., 2011a). The agronomic recommendations in use in the Eastern Africa tea growing regions have largely been adopted from Kenya (Othieno, 1988; Anon, 2002) sometimes without re-testing in new growing areas. The recommended nitrogenous fertilizer rates set vary between 100 and 250 Kg N/ ha/year and plucking intervals between 7 and 15 days (Anon, 2002; Othieno, 1988). Clone TRFK 6/8 is widely grown in the region and constitutes 80% of Rwanda tea, 60% of Kenya clonal tea and 35-40% of Tanzania tea (Msomba *et al*., 2011; Owuor *et al*., 2011a). The uniform agronomic recommendations currently used in tea production in East Africa may be inappropriate in some regions since farmers have not managed to replicate yields (Msomba *et al*., 2014), quality (Babu *et al*. 2007; Owuor *et al*. 2008a; Fung *et al*. 2003; Jin *et al*. 2008; Li *et al*. 2007) and leaf nutrients levels (Kwach *et al*., 2014) in the different production areas. Indeed it is not documented how the different agronomic inputs influence soil nutrients levels and if the variations in the soil nutrients are related to yields in the different regions.

2.3 Soil Organic Carbon and Nitrogenous Fertilizer Rates in Tea

Tea plant can attain a height of 20-30m (Purseglove, 1987) when allowed to grow freely. Some trees more than 1500 year old are still thriving in their original forests of Yunnan Province in south-western China (Hara *et al.*, 1995). However, the plant is maintained as an evergreen shrub by regular pruning and harvesting (Hara *et al.*, 1995). Closer to the equator, tea leaves are harvested all year round while further away from the equator, harvesting is seasonal (Hara *et al.*, 1995). The variations in the environment and growing conditions cause large differences in growth rates and patterns that are reflected in yields (Uddin *et al.*, 2005). Tea growing soils of the world are of different origin, and composition ranging from the lightest of sand to heavily silt loam or even silt clay loam types (Othieno, 1992). However, medium or light textured soils of acidic character are also suitable for growth of tea (Harler, 1971). Soil organic carbon, the organic fraction of the soil, is a complex mixture of plant and animal products in various stages of decomposition (Chan *et al*., 2001). Successive decomposition of dead material and modified organic matter results in the formation of a more complex organic matter called humus (Juma, 1998). Humus contains a high percentage of soil organic carbon in humic substances such as humic acids, fulvic acids among others (Nath, 2014). When these organic components dissociate in the soil they form negative charges (Brady, 1990) which attract and store cations for plant absorption. Several studies have given credence to the role of soil organic carbon (SOC) in improving soil physical, chemical and biological properties (Dick *et al*., 1998, Karlen *et al*., 1994; Smith *et al.* 1993; Post *et al*., 2000). Soil organic carbon (SOC) serves as a nutrient revolving fund, enhances cation exchange capacity, improves soil aggregation and water retention capacity, supports biological activity (Dudal and Deckers, 1993; Karlen *et al*., 1997; Adanu and Aliyu, 2012), maintains tilts and minimizes erosion (Soane *et al*., 1972; Alexandra and Jose, 2005). Due to positive influence on several soil processes, environmental qualities and crop productivity, SOC is considered the single most important indicator of soil quality in sustainable land management (Dick, 1992). SOC is influenced by several factors including climate, clay content and mineralogy, and soil management practices (Oades, 1995; Šimanský *et al*., 2009; Polláková and Konôpková, 2012). For soils of the tropical regions, SOC may constitute an important source of potential acidity in the soil (Meragalge, 2007). However, in Brazil (Iori, *et al*., 2014), SOC played an important role in nutrient recycling and the potential soil acidity ($H^+ + Al^{3+}$) followed the pattern of the organic matter (OM). In tea soils, soil organic carbon (SOC) content less than 0.50 % is considered as low and SOC more than 0.75 %, the soil is considered very rich in carbon (Baruah and Borthakur, 1997; Eyüpoğlu, 1999; Adiloğlu and Adiloğlu, 2006; Nath and Bhattacharyya, 2014). Comparative studies on the SOC levels of East African tea soils are lacking. And the relationship between SOC and soil pH is not well established in the tropical regions.

Soil organic carbon is an index of sustainable land management (Woomer *et al*., 1994; Nandwa, 2001) and is critical in determining responses to nitrogen and phosporus fertilizations. Long-term fertilizer experiments established relationships between soil organic carbon and soil fertility (Macedo *et al*., 2008). Positive relationship between increased nitrogen fertilizer rates and SOC in tea soils has been revealed (Thenmozhi *et al*., 2012). Increasing nitrogen fertilizer application rates improved soil organic carbon (Venkatesan *et* *al*., 2004). Organic carbon reserves of tea soil are lost due to lack or inadequate supply of nitrogen since tea plants tend to mineralize and absorb nutrients from organic matter in the soil under nutrient stress conditions (Venkatesan *et al*., 2004). Similarly, SOC contents increase with addition of nitrogenous fertilizers to tea sub-surface soils due to high microbial activity brought about by the addition of fertilizers (McAndrew and Malhi, 1992; Neff *et al.,* 2002; Chandravanshi *et al*., 2008). Good nitrogen fertilization program helps in sequestering atmospheric CO_2 into soil organic carbon by increased plant growth and subsequently, the return of organic carbon to the soil for storage as soil organic matter in a no-till system (Halvorson *et al*., 1999). However, it is not known if there are variations in SOC contents due to nitrogen fertilizer rates under different locations within Eastern Africa tea growing regions. Residues from tea leaf fall-off and prunings and their decomposition alters soil organic matter and SOC and affect the release of nitrogen, phosphorus, and sulphur through microbial activity (Smith *et al*., 1993). When the carbon content of the residues is high compared to their nitrogen, phosphorus and sulphur contents, then the residues cause significant immobilization of nutrients that would otherwise be available for plant uptake (Paul and Clark, 1989; Smith *et al*., 1993). Decomposition of plant litter and humus are fundamental ecosystem processes which maintain continuous supply of essential nutrients to plants (Pansombat *et al*., 1997). Well decomposed tea mulch, and soil collected beneath the layer of mulch, released high amount of ammonium or nitrate ions within six weeks (Krishnapillai, 1984). Exchangeable potassium, magnesium and phosphorus released during the period were equally high. The total nitrogen in the soil is influenced by addition of fertilizers, mineralization of organic compounds derived from the soil and mulching materials, de-nitrification and leaching processes (Meragalge, 2007). Although tea prunings have relatively high amounts of nitrogen (3.5-4.0%) and low C/N ratios, their decomposition and release of nitrogen to plants are affected by other factors such as polyphenol contents (Palm and Sanchez, 1991) and pH which may induce leaching of nitrogen as nitrate ions (Meragalge, 2007). High polyphenol contents decrease the decomposition rate and consequently the release of nitrogen (Sivapalan, 1986; Forrest and Bendall, 1969; Kamau, *et al*., 2012). Although tea prunings have high amounts of polyphenols, they readily dissolve in water hence do not inhibit the nitrification process (Sivapalan, 1986).

Dead branches and fallen leaves produce high amounts of organic substances per hectare each year in productive tea gardens (Li and Ding, 1992). However, erosion and mineralization causes loss of the organic substances in the soil. The increase in SOM and consequently SOC status has been attributed to the accumulation of fallen leaves, prunings left in the field and microbial residues in tea plantations (Pansombat *et al*., 1997; Wang *et al*., 1997). Removal of pruning from tea fields deplete SOM and SOC, leading to significant loss of plant nutrients and reduced tea production (Weeraratna, 1981). In India, if the pruning litter is not retained in the field, loss of nitrogen, phosphorus and potassium at 100, 20 and 40 kg/ha respectively takes place (Singh and Misra, 2009). Indeed, decline in SOC leads to significant decrease in the availability of micro-nutrients such as zinc, copper, manganese and iron (Katyal *et al*., 2001). Most of the previous work has been conducted far away from the tropics where the temperatures are relatively low compared to those experienced within Eastern Africa. This may influence SOC contents differently within eastern Africa tea growing regions. It is therefore not known if there are variations in SOC contents due to nitrogen fertilizer rates and plucking intervals under different locations within Eastern Africa tea growing regions and if magnitudes of such changes vary with the locations. It is also not documented if the possible variations cause changes in the levels of the micronutrients.

2.4 Soil pH and Nitrogen Fertilizer Rates in Tea

Soils of tea fields in different countries differ widely in parent materials and morphological characteristics, but the most important requirement is soil pH, generally 3-6 values (Somaratne, 1986; Ranganathan and Netasan, 1985; Othieno, 1992). Soil acidity is one of the most important soil properties influencing tea growth (Sandanam *et al*., 1978) and nutrients utilization especially nitrogen (Natesan, 1999). While most tea varieties yield best in the optimal soil pH range of 4.5-5.6 (Saikh, 2001; Othieno,1992; Ranganathan and Netasan, 1985), certain tolerant varieties can flourish at high pH of 6.0-6.5 (Natesan, 1999). Low soil pH reduces the populations of microbes in the soil (Hayatsu, 1991 and 1993b) interfering with nitrification process. Increased acidity cause deficiency in base ions (Hasegawa, 1993), and low phosphorus levels (Bhattacharya and Dey, 1983) causing a decline in tea production. Low pH influences accumulation of aluminium ions (Al^{3+}) (Marschner, 1986; Ahsan, 1994) to high levels which may be toxic and limit plant growth and cause decline in yields. As pH increases above 5 (Bohn *et al*., 2001), nutrients such as zinc, iron and manganese become unavailable. Long-term application of nitrogenous fertilizers to tea fields for high yields eventually causes a reduction in soil pH, with an associated decline in soil fertility (Wickramasinghe *et al*., 1981; Nioh *et al*., 1995; Othieno *et al*., 2000; Venkatesan *et al*., 2004; Owuor *et al*., 2012).

Although tea grows on acidic soils, the growth and productivity of tea plants can be negatively affected by the acidification due to reduced nutrient availabilities (Jianyun *et al*., 2004). Under acidified conditions, base cations potassium, calcium, and magnesium are prone to leaching and fixation of phosphorus by sorption or precipitation with aluminium and iron oxides is increased. These observations are in line with other findings (Tisdale and Nelson 1975, Willson and Clifford 1992), which explain that ionic forms of phosphorus (H_2PO^{4-}) readily react with oxides (hydroxide), iron and aluminium which are abundant in acid soil, to form insoluble compounds that are not easily extracted from soil. High levels of Al^{3+} ion at low pH improves the phosphorus uptake (Konishi *et al.,* 1985) but reduces potassium (Ishigaki *et al.,* 1972) and calcium uptake by the tea plant (Konishi *et al.,* 1985). Excessive use of nitrogenous fertilizers increases soil acidity (Bonheure and Willson, 1992; Venkatesan *et al*., 2004; Owuor *et al*., 2012), decreases soil fertility (Othieno *et al*., 2000), thus creating of nutrient imbalances in the soil (Venkatesan *et al*., 2004). This may lead to a reduction in the productive life of the soil. In Pakistan (Hamid, 2006), increased nitrogen fertilizer rates reduced sub-surface soil pH and yields. Indeed, availability of nitrogen, phosphorus, calcium, and magnesium decreased with the high nitrogen fertilizer rates (Dang, 2002; Kamau *et al*. 2008a).

The acidic nature of soil and availability of micronutrients to plants (Baruah *et al*., 2013) vary with climate (Khattak and Hussain, 2007). Different tea growing regions have soils that differ in physical and chemical properties as a result of different parent materials, weathering patterns and agronomic inputs (Baruah *et al*., 2013; Bhattak and Hussain, 2007; Anon, 2002). Such differences may lead to variations in soil pH that affects soil quality and yields of tea (Bhattak and Hussain, 2007). Though it has been demonstrated that environmental factors and agronomic inputs influence soil pH and other nutrients in the tropics, it is not known if the magnitude of the changes in soil pH and other nutrients vary to different extents with variations in rates of nitrogenous fertilizer in different locations of East Africa.

2.5 Soil Nutrients, Nitrogen Fertilizer Rates and Yield in Tea.

The plant nutrients are supplied by the soil in varying quantities either from the reserves (Mengel and Kirkby, 1987; Hamid, 2006) or through application of organic or inorganic fertilizers (Willson, 1969; Bonheure and Willson, 1992; Kamau *et al.*, 2005). Tea, like any crop, requires many nutrients for its growth. The nutrients are classified as either macro- or micro-elements (Bonheure and Willson, 1992; Owuor and Wanyoko, 1996; Owuor and

Othieno, 1996) depending on the quantities required. The nutrients have a variety of functions in the tea plant (Wickremasinghe and Krishnapillai, 1986; Roy *et al*., 2006) that affect either yields (Godziashvili and Peterburgsky, 1985; Sharma and Sharma, 1995) or quality (Bonheure and Willson, 1992). The nutrients in tea soils get depleted due to continuous cropping (Dang, 2002; Baruah, 2013), harvesting (Ranganathan and Natesan, 1985; Owuor *et al*., 2011b,), leaching (Ramos and Varela, 1990; Owuor *et al*., 1997) and surface run-offs (Lobo *et al*., 2005; Othieno, 1975) in high rainfall areas. Nutrients availability in tea soils is also influenced by nitrogen fertilizer rates (Willson, 1975c; Dang 2002; Kamau *et al*. 2008a).

Nitrogen, phosphorus and potassium are macro-nutrients and the most critical nutrients in the fertilization programmes of tea (Cloughley, 1983; Bonheure and Willson, 1992; Kamau *et al*., 2008; Owuor *et al*., 2008b). Nitrogen constitutes 2–4 percent dry matter of plants (Roy *et al*., 2006) and the highest content is in young harvestable tea shoots (Dang, 2005). Plants absorb nitrogen either as the nitrate ion (NO_3^-) or the ammonium ion (NH_4^+) (Roy *et al*., 2006). Nitrogen is part of chlorophyll (the green pigment in leaves) and is an essential constituent of all proteins, nucleotide, hormones, protoplasm, vitamins, etc (Wickremasinghe and Krishnapillai, 1986; Roy *et al*., 2006). The nutrient promotes rapid sprouting and growth of tea shoots and when applied to the tea plants, yields increase (Wickremasinghe and Krishnapillai, 1986; Bonheure and Willson, 1992). In tea soils, the amount of nitrogen in available form is small, while the quantity withdrawn annually by crop is comparatively large (Banerjee, 1993). Availability of nitrogen to tea plants is affected by a number of factors, among them; levels of other nutrients in the soil, genotypes or clones (Wanyoko and Njuguna, 1983) and location of production (Kwach, *et al*., 2011: Kwach *et al*., 2014). Tea soil nitrogen replenishment is usually through application of inorganic nitrogenous fertilizers. The recommended rates of nitrogen fertilizer application for mature tea vary from country to country (Bonheure and Willson, 1992). The lowest annual application rates per hectare in Vietnam is at 36 to 40 kg N, while the highest one in Japan at 800 kg N (Bonheure and Willson, 1992). In Sri Lanka, the recommended rate is 160 kg N/ha/year, while in Central Africa; it is 165 kg N/ha/year for high yielding areas (Kemmler, 1986). In Kenya, the recommended fertilizers are NPK(S) 25:5:5:5 or NPK 20:10:10 at annual rates of 100-250 kg N/ha depending on yields (Anon, 2002; Othieno, 1988). A rate of 150 kg N/ha/year is however, considered the most appropriate (Othieno, 1988) for Kenya and other East African countries (Kwach *et al*., 2014). In tea plantations, excessive amounts of nitrogenous fertilizers are usually applied to ensure nitrogen is available for tea crop use (Oh *et. al.*, 2006). However, increased rates of nitrogen fertilizer application are uneconomical and may reduce yields (Wanyoko, 1983; Bonheure and Willson, 1992; Kamau *et al*., 2005). Excessive supply of nitrogen in soil may also lead to nitrogen toxicity to plant (Salisbury and Ross, 1992) and inhibits plant growth and development and cause decline in yields (Caicedo *et al*., 2000). High nitrogen fertilizer application rates decreased soil pH (Tachibana *et al*., 1995) and led to leaching of extractable base ions (Kamau *et al*., 2008). Variations in nitrogen response in different tea soils may be related to the characteristics of soil particularly the mineralization process and rapid conversion of nitrate by nitrification (Banerjee, 1993). Increase in nitrogen fertilizer application increases the levels of nitrogen in the leaf tissues (Kwach *et al*., 2014), and decreases black tea quality (Cloughley, 1985; Owuor *et al*., 1990; Owuor *et al*., 2010, 2009, 2008a) within Eastern Africa regions. Results from the previous work considered only the influence of nitrogen rates on tea yields and quality but not on soil nitrogen levels. It is not documented how soil nitrogen varies with nitrogenous fertilizer application rates and plucking intervals in different locations of tea production within Eastern Africa. It is also not known how the levels of soil nitrogen relate to tea yield in different locations of tea production.

Potassium is the second major nutrient for tea after nitrogen and makes up 1.5-2% of the dry matter in tea leaves (Verma, 1997, 1993; Wu Xun *et al*., 1997). Potassium takes part in a number of enzymatic reactions which are involved in processes like photosynthesis, carbohydrate metabolism, translocation and protein synthesis (Do *et al*., 1980) in the tea plant. The nutrient triggers growth of young tissues maintains optimum turgor needed for cell elongation and division (Ranganathan and Natesan, 1985) and regulates water usage by the plant during absorption and transpiration (Lacaille, 1966). Potassium increases the plant’s resistance to pests and diseases, tolerance to drought and improves yields (Malakouti, 1996; Kumar and Kumar, 2010). In areas that suffer potash deficiencies, continuous tea cropping without application of potash fertilizers lowers yields and ultimately causes death of tea plants (Willson, 1975c). Tea yield responses to applied potash fertilizers have been widely reported in various countries (Godziashvili and Peterburgsky, 1985; Rahman and Jain, 1985; Krishnapillai and Ediriweera, 1986; Malenga and Grice, 1991; Wibowo, 1994; Rahman and Jain, 1985; Venkatesan *et al*., 2003). In addition to yield responses, the quality of tea (Ruan *et al*., 1998; 1999; Venkatesan and Ganapathy, 2004) improved due to potassium fertilizer application. In Kenya (Owuor *et al*., 1998), potassium did not affect black tea quality and yields (Owuor *et al*., 1988; Kamau *et al*. 1999). Exchangeable potassium levels in the soil decrease with increasing nitrogen fertilizer rates. In India, (Venkatesan *et al*. 2004) high nitrogen fertilizer application rates decreased potassium levels in tea soils. The results are in agreement with recent research findings from (Baruah *et al*., 2013; Kebeney *et al*., 2010). The low levels of potassium in tea soils were as a result of leaching caused by excess ammonium ions in the fertilizers. The previous trials were set at same locations and this may not determine if results vary at different locations. The levels of soil potassium may be influenced by area of production. It is not known how tea soil potassium levels vary with nitrogenous fertilizer application rates in different locations of production within Eastern Africa.

Phosphorus is less abundant in plants compared to nitrogen and potassium, having a concentration of about one-fifth to one-tenth that of nitrogen in plant dry matter (Roy *et al*., 2006). The nutrient plays a number of roles in the tea plant including; formation of new shoots and roots, transformation of energy that takes part in metabolism of fats, respiration and utilization of nitrogen (Bonheure and Willson, 1992). It is an important constituent of nucleic acids, phospholipids and enzymes. Phosphorus deficiency results in stunted growth of the plants and the mature tea plants show a characteristic bluish colouration (Mudau, 2006). Application of phosphatic fertilizers have had mixed responses to phosphorus in tea productivity. In Sri-Lanka, (Zoysa *et al*., 1999), the nutrient uptake was influenced by genotype. Plain black tea quality (Sharma *et al*., 2005; Mudau, 2006) improved by increased phosphorus application. Increase in phosphate fertilizer application rate increased tea yield and improved black tea quality in Japan (Salukvadze, 1980). But in Kenya, there were no responses to plain black tea quality (Owuor *et al*., 1998) and soil phosphorus (Owuor *et al*., 2012) to phosphatic fertilizer application. With these varied responses, possible deficiencies of phosphorus in tea plants are guarded against by its inclusion in the fertilizer formulations; NPK(S) or NPK. Phosphorus availability in the soil is highest at soil pH levels between 5.5 and 7.0 and lowest when pH falls below 5.5 or above 7.0 (Bhattacharya and Dey, 1983). At low pH, which characterizes most tea soils, phosphorus is strongly fixed as insoluble phosphates of aluminium, iron or calcium and remains unavailable to the tea plants (Bhattacharya and Dey, 1983). Increasing nitrogen fertilizer application rates to tea reduces soil available phosphorus (Wang *et al*., 1997; Zhang *et al*., 1997; Owuor *et al*., 2012). Several studies in Kenya indicated that increasing nitrogen fertilizer application rates to tea causes decrease in the soil available phosphorus especially in the lower soil depths due to its low mobility (Kamau *et al.*, 1998; Kamau, 2003; Kebeney *et al.*, 2010; Owuor *et al.*, 2012). Phosphorus uptake by tea plants is influenced by genotype (Zoysa *et al.*, 1999). High rates of nitrogenous fertilizer reduce mature leaf phosphorus (Owuor *et al.*, 1990; Owuor *et al.*, 2012; Wanyoko *et al.*, 1992). Increase in soil phosphorus increased tea yield and improved black tea quality in Japan (Salukvadze, 1980). Highest plain black tea quality with respect to total colour and percent brightness were obtained with annual phosphorus rate of 60 kg P_20_5 /ha (Sharma *et al.*, 2005) in India. However, in Kenya phosphorus application had no effect on black tea quality (Owuor *et al.*, 1998). Most of the previous work trials were conducted at a single location with similar environmental conditions. Therefore, their results may not explain variations for similar trials in different locations. Changes in tea soil phosphorus levels due to nitrogenous fertilizer rates and plucking intervals in different locations of production within East Africa and the relationships between soil phosphorus and yield and SOC have not been reported.

The other essential macronutrients for tea are calcium (Willson, 1975a) and magnesium (Willson, 1975b). Calcium ranks with magnesium, phosphorus and sulphur in the group of least abundant macronutrients in plants. Calcium is one of the constituents of plant cell wall and plays an important role in cell division and activation of shoot growing points (Kler, 1995). The element is also known for protein synthesis, neutralization of acids and absorption of nitrogen (Willson, 1975a). Calcium deficiency may cause shoot malformation and terminal die back (Wachira and Ng'etich, 1999; Roy *et al.*, 2006). Calcium deficiency is characterized by brittle old leaves covered with discoloured areas at the edge of the lamina, which then become dark brown in colour (Willson, 1975a; Roy *et al.*, 2006). Calcium uptake by tea plant is third after nitrogen and potassium (Othieno, 1992). A considerable amount of calcium is therefore required by tea plant. On the average, between 10 to 20 kg calcium is removed annually through harvesting fields yielding 2000 kg made tea /ha/year (Othieno, 1992). High levels of calcium lower quality of plain black tea by decreasing solubility of polyphenols and increasing cream formation (Jobstl *et al.*, 2005). The availability of calcium to tea plants depends on the soil pH levels. Low levels of calcium in tea soils is due to increased acidity (Dogo *et al.*, 1994; Kamau *et al.*, 2008; Kebeney *et al.*, 2010) resulting from the use of high nitrogen fertilizers application rates. At low soil pH levels, the base calcium ions leach to depths that cannot be reached by the roots of plants hence becomes unavailable (Kebeney *et al.*, 2010). The trials for earlier results did not take into account the location of production. Due to varying climatic conditions soil calcium levels and requirements might vary with location of production. It is not documented how tea soil calcium levels varies with nitrogenous fertilizer application rates and harvesting intervals in different locations of production within Eastern Africa and if such variations are related to yields.

Magnesium occupies up to 0.30% of the leaves dry matter in the fresh leaves (Wu Xun *et al*., 1997). It regulates photosynthesis process and is involved in enzymatic metabolism of carbohydrates, synthesis of nucleic acids and translocation of sugars (Willson, 1975c; Bonheure and Willson, 1992). High levels of potassium and nitrogen in fertilizers caused magnesium deficiency in South Indian tea soils (Jayaganesh *et al*., 2011). The deficiency of magnesium in tea plant is detected when old leaves turn yellow and premature falling of younger leaves from the affected plants (Othieno, 1992). Application of magnesium sulphate was recommended for high yielding tea fields in South India where the magnesium levels in most tea soils were inadequate to sustain high production (Venkatesan, 2006). Indeed, Jayaganesh *et al*. (2011) observed increase in yield and quality of tea when magnesium sulphate was applied together with nitrogen and potassium fertilizers. Generally, the levels of magnesium in tea soils are low when high rates of nitrogen fertilizers are used (Wanyoko *et al*., 1997; Kebeney *et al*., 2010). The previous studies did not consider the influence of location and plucking intervals on soil magnesium levels. The variations in soil magnesium levels due to harvesting intervals and location of production within Eastern African tea growing regions and the relationships with yield are not documented.

The essential micronutrients in tea production include aluminium, manganese, iron, copper and zinc (Bonheure and Willson, 1992). The tea plant grows best in acidic soils which usually have high levels of extractable aluminium (Ruan *et al*., 2006; Owuor and Cheruiyot, 1989). Tea can accumulate large amounts of the micronutrient, especially in old leaves where quantities above 30,000 ppm have been reported (Matsumoto *et al*., 1976). Addition of aluminium to the soils is beneficial in accelerating growth of tea plants (Matsumoto *et al*., 1976) that may improve yields of tea. Excess aluminium in soils improves phosphorus uptake (Sivasubramanium and Talibudeen, 1972; Bhattachavya and Dey, 1983; Konishi *et al*., 1985) but reduces potassium (Ishigaki *et al*., 1972) and calcium (Memon *et al*., 1981; Konishi *et al*., 1985) uptake by tea plants. High levels of aluminium in the fermenting “dhool” improve the appearance and value of the resultant black tea (Edmonds and Gudnason, 1979; Chang and Gudnason, 1982). Use of high rates of nitrogen fertilizers increases availability of aluminium to plants. Application of ammonium nitrogen fertilizers increased aluminium uptake by tea plants compared to nitrate nitrogen fertilizers (Ishigaki, 1974b). Increasing rates of nitrogen fertilizer caused increase in soil extractable aluminium but decreased the amounts of aluminium in the mature leaf (Owuor and Cheruiyot, 1989) and black tea (Owuor *et al*., 1989). From the earlier results trials did not consider the influence of nitrogen, location and plucking intervals on variations of soil aluminium. These factors might influence soil aluminium levels. The influence of nitrogen fertilizer application rates and location of production on aluminium levels in tea soils in different locations of East Africa tea growing regions have not been compared.

Manganese is essential in splitting water molecules during photosynthesis and activating several enzymes as it functions as an auto-catalyst (Roy *et al*., 2006). High levels of manganese in tea inhibit tea polyphenol levels and increase total amino acids levels while low levels have beneficial effects on tea yields (Gohain *et al*., 2001). This implies that low levels of manganese in the soils may help improve yields and quality of processed tea. However, high rates of nitrogenous fertilizer application increase soil acidity (Dogo *et al*., 1994; Kamau *et al*., 2008) which favours high accumulation of manganese in tea soils (Kamau *et al*., 2008; Kebeney *et al*., 2010),while low manganese levels increase yield of tea leaves (Gohain *et al*., 2001). Trials from previous work did not consider the influence of nitrogen, location and plucking intervals on soil manganese levels. Due to variations in climatic conditions in tea growing regions, location and plucking intervals might influence soil manganese levels. It is not documented how soil manganese levels change with nitrogenous fertilizer application rates, plucking intervals in different locations of production in the Eastern Africa tea growing regions.

The content of iron in the tea plant is limited though it plays a significant role, being part of the enzyme peroxidase which is involved in oxido-reductive processes (Bokuchava and Skobeleva, 1969). Iron plays a role in the synthesis of chlorophyll, carbohydrate production, cell respiration, and in nitrogen assimilation (Roy *et al*., 2006), hence influencing nutritional yields and quality of made tea. The tea plants showed some responses to the addition of iron in some Indian soils (Kuzhandaivel and Venkatesan, 2011). The addition of small amounts of iron increased polyphenol contents of tea whereas high doses caused a drastic decline. In China (Fung *et al*. 2008) uptake of iron was severely restricted by higher aluminium concentrations. On Russian tea soils, the content of mobile iron increased with increasing nitrogen fertilizer application rates (Gabisoniya *et al*., 1973). Decrease in soil pH and increase in the exchangeable iron directly influences soil quality and productivity (Dang, 2002). Mature leaf iron (Kwach *et al*., 2014) increased with rise in nitrogenous fertilizer rates and varied with location of production. However, plucking intervals (Kwach *et al*., 2014) did not influence mature leaf iron levels. The previous results give varying influences of nitrogen rates and location on soil iron levels. Further the trials did not consider influence of locality and plucking intervals on soil iron levels. The influence of nitrogenous fertilizer application rates, plucking intervals and location on soil iron levels within Eastern Africa is not known.

Copper is an important part of the enzyme polyphenol oxidase, which is responsible for the fermentation process in black tea production (Bonheure and Willson, 1992). It also takes part in formation of the chlorophyll molecule and is a major component of several enzymes (Roy *et al*., 2006). Tea grown in copper deficient soils does not ferment (Harler, 1971). Copper deficient plants exhibit an alteration in the expression of some morphological features such as root and leaf pose (Loustalot *et al*., 1945). Excess copper inhibits important processes such as photosynthesis and enzyme activities which suppress tea growth (Yruela, 2005) thus lowering yields. Soil pH controls the uptake of copper by plants (Alva *et al*., 2000). Increased nitrogen fertilizer rates lower soil pH, solubilizing copper from solid phase of soils (Mozaffari *et al*., 1996) accumulating it in the soil. In China copper uptake by plants was highest at soil pH levels below 3.58 (Chong *et al*., 2008). Copper levels in mature leaves of the tea plant increased with high rates of nitrogen fertilizers (Kwach, 2013), an indicator that copper uptake is greatly enhanced by low pH levels in the soil. However, mature leaf copper levels (Kwach *et al*., 2014) were not influenced by plucking intervals. Previous work did not consider influence of nitrogenous fertilizer application rates, plucking intervals and location on levels of soil copper at different areas of production for similar trials. While it has been shown that increased rates of nitrogenous fertilizer lower soil pH in tea soils and may lead to high levels of copper, the effect of nitrogen fertilizer, plucking intervals and location on soil copper levels in Eastern Africa tea growing regions is not documented.

Zinc is required directly or indirectly by auxins and several enzymes in tea plants (Iwasa, 1977). Zinc deficiency reduces the growth of tea (Tolhurst, 1973) leading to decline in yields. Its deficiency is corrected by foliar application of zinc oxide (Othieno, 1992). Zinc application increases the yield of mature and semi-mature tea (Barua and Dutta, 1972; Dootson, 1974; Malenga *et al*., 1982). Zinc application on young tea improves both yield and quality of made tea (Wang *et al*., 1993). In Kenya, annual tea yields increased with frequency of foliar application of zinc oxide (Wanyoko *et al*., 1992). There were significant ($P \leq 0.05$)

differences in mature leaf zinc levels with location of production (Kwach *et al*., 2014), possibly demonstrating the zinc reserves in the soils were widely varying with locations. Increasing rates of nitrogenous fertilizer application (Kwach *et al*., 2014) increased ($p \leq 0.05$) the mature leaf zinc levels. Similar responses were recorded in Kericho (Owuor *et al*., 1993). However, plucking intervals had no significant influence on mature leaf zinc level. While it has been demonstrated that nitrogen rates influence mature leaf zinc levels, it has not been established how nitrogen rates, plucking intervals and location of production influence tea soil zinc levels in Eastern Africa.

2.6 Plucking Intervals, Soil Organic Carbon, pH and Nutrients

Tea is an evergreen perennial crop whose tender shoots are plucked (harvested) at regular rounds (6-25 days) (Verma, 1997) for processing various tea beverages. Plucking of the young shoots, normally a bud and two to three leaves, above the plucking table is either done by hand or mechanically (Kamau,2008). The plucking rounds vary among tea growing countries in the eastern Africa region. In Kenya, plucking rounds range from 7 to 15 days (Anon, 2002), while, in Rwanda it ranges from 9 to 14 days (Uwimana, personal communication) and in Southern Tanzania, the practice is to pluck after 13–14 and 27–30 days under normal long rain season and adverse conditions, respectively (Burgess, 1992), in clone TRFK 6/8. Previous studies demonstrated that plucking intervals affect tea yield and black tea quality. Short plucking intervals improved both yields (Odhiambo, 1989; Owuor *et al*., 2009, Owuor *et al*., 2013a; Owuor and Kwach, 2012) and black tea quality (Barua *et al*., 1986; Owuor *et al*., 1990, 1997, 2000, 2009; Owuor and Odhiambo, 1993, 1994). Short plucking intervals increased fatty acid levels (Okal *et al*., 2012a, Owuor and Kwach 2012), while long plucking intervals decreased yields (Owuor *et al*., 1997) and leaf nutrients (Kwach, 2013).The variations in yields, quality parameters and leaf nutrients with plucking intervals imply that, the amounts of macro and micronutrients removed from the soil may vary with variations in plucking intervals. The previous studies did not consider the influence of plucking intervals on soil nutrients and soil organic carbon contents. It is not established if plucking intervals cause variations in soil organic carbon, pH and nutrients levels of tea soils in Eastern Africa and if the variation is specific to geographical area of production.

CHAPTER THREE

METHODOLOGY

3.1 Experimental Sites and Materials

3.1.1 Experimental Sites

This study was superimposed on nitrogenous fertilizer trials on clone TRFK 6/8 in seven different locations within the Eastern Africa tea growing regions. The trial on clone TRFK 6/8 was set up by the Chemistry Divisions of Tea Reseasrch Foundation of Kenya (TRFK), Tea Research Institute of Tanzania (TRIT) and Office Des Cultures Industrielles du Rwanda The’ (OCIR The’) in 2002 . The clone was subjected to five different nitrogenous fertilizer rates in eight different locations within the Eastern Africa tea growing growing regions. The locations were: Timbilil Estate (TRI), Changoi Tea Estate and Sotik-Arroket in Kenya, Maruku Estate and Katoke Estate in Tanzania, and Kitabi Estate and Mulindi Estate in Rwanda. The study sites coordinates are shown in the table1.

Table 1-a: The Study Sites with their Coordinates

					Mean annual (2012-2014)	
Country	**Site**	**Latitude**	**Longitude**	**Altitude (amsl)**	**Rainfall**	**Temperature**
Kenya	Timbilil Estate (TRI)	0^{o} 22’S	35^{o} 21’E	2180m	2175mm^{a}	19.5^{o}C^{a}
	Changoi Tea Estate	0^{0}30’S	35^{0}13’E	1860m	2130mm^{a}	19.0^{o}C^{a}
	Sotik-Arroket Estate	0^{o} 36’S	35^{o} 04’E	1800m	2000mm^{a}	20.5^{o}C^{a}
Tanzania	Maruku Tea Estate	1^{o}23’ S	31^{o} 45’E	1488m	21000mm^{b}	19.5^{o}C^{b}
	Katoke Tea Estate	1^{o} 36’S	31^{o} 41’E	1217m	1950mm^{b}	21.5^{o}C^{b}
Rwanda	Kitabi	2^{0}32’S	29^{0}26’E	2231m	1500mm^{c}	23.5^{o}C^{c}
	Mulindi	1^{0}27’S	30^{0}01’E	1800m	1400mm^{c}	18.5^{o}C^{c}

[a]TRFK (2014), [b]TRIT (2014), [c]Nyirahabimana and Uwimana (2017)

amsl = above mean sea level

Table 1-b: The Study Sites with their Soil Characteristics

Location	Depth cm	CEC cmols/kg	sand %	clay %	silt %	porosity %	Textural class	Soil description
[a]Timbilil	0-10		41.37	49.75	10.96	37.56	C	Volcanic dark red, deep
	10-20	25.64	41.37	49.75	10.96	37.56	C	friable clays, a dusky red
	20-30		42.15	44.13	13.28	45.22	C	top soil, with kaolinite
	40-60	16.27	38.08	48.36	15.57	47.00	C	classed humic nitosols
[a]Changoi	0-10		23.75	70.79	11.52	43.33	C	Volcanic derived, deep,
	10-20	25.42	23.75	70.79	11.52	43.33	C	free draining, dark red
	20-30		22.28	72.08	11.67	31.67	C	with dark redish top soil,
	40-60	17.34	23.07	70.32	12.86	31.67	C	classified as nitosols
[a]Arroket	0-10		29.84	48.59	21.57	51.33	C	Dark reddish brown,
	10-20	25.75	29.84	48.59	21.57	51.33	C	moderately deep, firm clay
	20-30		27.84	49.59	22.57	42.00	C	loam humic top soil classed
	40-60	18.13	28.20	50.23	21.57	44.00	C	as chromoluvic phaeozems
[b]Kitabi	0-10		35.93	31.22	17.47	59.86	SC	Dark brown, reddish-
	10-20	36.09	35.93	31.22	17.47	59.86	SC	brown top soil, clay-
	20-30		41.77	44.54	13.16	44.81	SC	rich, classed as
	40-60	17.96	42.03	43.82	17.18	51.87	SC	nitosols
[b]Mulindi	0-10		35.13	51.75	46.40	58.97	C	Dark, metasedimentary,
	10-20	22.85	35.13	51.75	46.41	59.04	C	deep dark clay-
	20-30		39.53	33.66	32.26	51.12	C	rich top soil, with loam
	40-60	18.24	42.44	29.57	28.68	37.52	SC	feel classed as peat
[b]Katoke	0-10		47.44	43.39	12.57	43.07	SC	Volcanic dark red,
	10-20	25.96	47.45	43.31	12.31	42.17	SC	friable clay with dusk
	20-30		40.10	36.39	12.63	43.02	SC	top soil, classed as
	40-60	16.93	39.61	34.49	16.19	48.89	SC	nitosols
[b]Maruku	0-10		45.61	19.49	27.98	49.88	SCL	Volcanic dark red,
	10-20	34.80	45.92	19.43	28.06	56.15	SCL	moderately deep
	20-30		60.44	18.51	31.65	52.76	SC	clay loam humic top
	40-60	25.85	60.49	18.44	24.73	47.67	SC	soil classed as nitosols

CEC =Cation Exchange Capacity C = Clay, SC = Sandy Clay, SCL = Sandy Clay Loam
[a] Nyabundi *et al.*, (2017), [b] TRFK,(2014)

3.2 Methodology and Research Design

The sites for the trial were carefully selected such that although the plants were at different ages, all the sites had mature tea of clone TRFK 6/8. At each site, the trial was laid out as 5x3 factorial two experiment in randomized complete block design and replicated 3 times (Appendix I). The treatments were the seven sites with five nitrogen rates (0, 75, 150, 225 and 300 kg N/ ha /year) as NPKS 25:5:5:5 and three plucking intervals (7, 14 and 21 days) (Appendix I). A plot comprised of 50 bushes of clone TRFK 6/8 with spacing given in appendix I according to (Msomba *et al*., 2011; Owuor *et al*., 2011a: Msomba *et al*., 2014:

Kwach *et al*., 2014) methods. Tea at each site was pruned between April and August 2008 so that all plants were in same pruning cycle life. First experimental treatments commenced in September/October 2008, depending on when there was adequate soil moisture at different sites in the respective countries. In subsequent years, the trials received fertilisers in September/October in single annual dose. Soil was sampled in October 2014.

3.3 Sampling and Sample Preparation

3.3.1 Yields

Yields data was obtained from secondary sources (Msomba *et al*., 2014) which were recorded after every plucking, as scheduled per plot and the green leaf yields converted to Kg/ha using a conversion factor of 0.225.

3.3.2 Soil Sampling

Soil was obtained from 3 points within a plot using calibrated steel auger then mixed at depths of 0-10cm, 10-20cm, 20-30cm, 40-60cm from all the trials. The samples of about half a kilogram of soil were placed in labelled polythene bags and transported to the laboratory at Tea Research Institute (TRI) of Kenya in Kericho where they were air-dried, ground into fine powder (< 2mm) using a ceramic mortar and pestle before processing and chemical analysis.

3.4 Soil Analysis

3.4.1 Soil pH Determination

Twenty five grams of freshly sampled soil were weighed into 100 ml plastic beakers and twenty five ml distilled water added to give a final soil: water ratio of 1:1 (Othieno, 1988). The mixtures were then left to stand for 30 minutes after which they were stirred to form a thin paste. Glass electrodes of pH meter were inserted in a water-saturated soil for pH reading using a Jenway 3305 digital pH meter.

3.4.2 Soil Organic Carbon

Soil organic carbon (SOC) was determined by potassium dichromate oxidation-reduction titration method (Walkley and Black, 1934). Briefly, 0.5g air-dried and ground soil sample were weighed and transferred into a 500mL Erlenmeyer flask. Ten millilitres (10mL) of 1N potassium dichromate ($K_2Cr_2O_7$) reagent was added and the flask swirled to mix the contents. To it, 20mL of concentrated sulpuric acid H_2SO_4) was added and the contents gently mixed for one minute and allowed to cool for 30 minutes. The contents were diluted with 150ml distilled water and 5mL of 85% phosphoric acid added. One millilitre (10 drops) of diphenylamine indicator was added to the contents and titrated with 0.5N ammonium ferrous sulphate ($Fe(NH_4)_2(SO_4)_2.6H_2O$) until a sharp green end-point was reached.

Two blank determinations on potassium dichromate were run and titrated against ammonium ferrous sulphate the same way. Carbon in the soil sample is oxidized as shown in the chemical equations below:

$\{K_2Cr_2O_7 + 4\,H_2SO_4 \rightarrow K_2SO_4 + Cr_2(SO_4)_3 + 4H_2O + 3[O]\}\times 2$

$\{C(\text{organic carbon}) + 2[O] \rightarrow CO_2\}\times 3$

$2K_2Cr_2O_7 + 6H_2SO_4 + 3C \rightarrow 2K_2SO_4 + 2Cr_2(SO_4)_3 + 8H_2O + 3CO_2$

The percentage of SOC was then calculated using the formula:

$$\% C = \frac{(B-T) \times 0.3 \times V}{W \times B}$$

Where B = Blank titre

T = Sample titre

W = Weight of oven-dry soil in grams

V = Volume of $K_2Cr_2O_7$

0.3 = (1mL, 1 N $K_2Cr_2O_7$ = 0.003g C) x 100

3.5 Soil Nutrient Extraction and Determination

Nitrogen- Kjeldhal Method

Total nitrogen concentrations in the soils were determined by extraction of 10 grams of the samples using 50 mL of 2M potassium chloride (KCl) solution (Bremner and Mulveney, 1982). After shaking in a reciprocal shaker for one hour, the extracts were filtered through whatman No.2 filter paper and the filtrates used for the analysis of ammonium and nitrate-N. The distillates of NH_4-N were generated by digesting 10 mL of the soil sample filtrates using magnesium oxide and NH_3-N after addition of devarda's alloy. The distillates were collected in 50 mL conical flasks before being titrated using 0.005M sulphuric (VI) acid (H_2SO_4). The percentage of nitrogen was calculated using the formula.

$$\% \text{ N in soil sample} = \frac{V \times N \times 14}{10 \times wt}$$

Where V= titre value, N= Normality of H_2SO_4, Wt= weight of the soil sample

Phosphorus, Potassium, Aluminium, Copper, Zinc, Iron, Calcium, Magnesium, Manganese

Mehlich-3 extracting solution (Mehlich, 1984), a mixture of 0.2 N CH_3COOH, 0.25N NH_4NO_3, 0.015N NH_4F, 0.013N HNO_3 and 0.001 M EDTA at pH of 2.50 was used. This solution was made by dissolving 40.03 g ammonium nitrate (NH_4NO_3) in about 1,000 mL of deionized water. This was followed by addition of 8.0 mL of 3.75M ammonium fluoride (NH_4F)-0.25M Ethylenediamine tetraacetic acid (EDTA) stock solution and mixed well. Then 23 mL of concentrated glacial acetic acid (CH_3COOH) and 2 mL of concentrated nitric acid (HNO_3) were added to this mixture and the final volume brought to 2,000 mL with a pH of 2.50.

For calibration standards, 1 L of standards in Mehlich- 3 extracting solution containing the highest concentrations of each element were prepared from a standard solution containing 1,000 mg/Litre of the analyte. Then 250 mL of other calibration standards were prepared from diluting the most concentrated one.

Exactly 5.0g of the powdered and dry soil sample was accurately weighed on a digital analytical balance (Mettler Toledo, Switzerland) with ±0.0001g precision and transferred into a 200mL plastic shaking bottles. Fifty (50) millilitres of the extractant solution (Mehlich3) (Mehlich, 1984) was added to the soil samples and put on a reciprocating mechanical shaker for 10 minutes. This mixture was then immediately filtered into 40 mL Teflon tubes through Whatman No.2 filter paper. Two blanks without soil samples were prepared in the same way. Samples with concentrations above the highest standard were diluted using dilution factors (Mehlich, 1984). Inductively Coupled Plasma Atomic Emission Spectrophotometer (ICP-AES 9000) was calibrated using multiple element standards. After instrument calibration and programming, samples were analyzed for phosphorus, potassium, calcium, magnesium, iron, manganese, zinc, aluminium and copper using ICP-AES 9000 in automated mode, displaying the nutrients levels on PC screen in ppm. The macronutrients were measured to 0.1ppm and micronutrients to 0.01ppm (Zhang *et al*., 2009; Schroder *et al*., 2010).

3.6 Statistical Analyses

The study had three independent variables (regions of production, nitrogenous fertilizer application rates and plucking intervals) and four dependent variables (soil organic carbon, pH, nutrients levels and tea yields). The data was analyzed using MSTATC, version 2.10 (1993) software package for ANOVAs. Student t-test was used and significant means were separated by LSDs ($p \leq 0.05$). This involved three factor randomized complete block design where factorial ANOVA for the factors were: replication (Var 1: sites (1= Timbilil, 2 = Changoi, 3 = Arroket, 4 = Kitabi, 5 = Mulindi, 6 = Katoke, 7 = Maruku) with values from 1 to 7, factor A (Var 2: replicates (1 to 3) with values from 1 to 3, factor B (Var 3: Nitrogen rates (1= 0, 2= 75, 3 = 150, 4 = 225, 5 = 300KgN/ha/year) with values from 1 to 5, factor C (Var 4: plucking intervals (1 = 7, 2 = 14, 3 = 21days) with values from 1 to 3, Variable 5: Soil parameters.Correlation coefficient (r) values ($p \leq 0.05$) were obtained using Pearson product moment on Excel. The trial was analyzed as 5x3 factorial design replicated for the 7 locations for soil organic carbon, pH, nutrients levels and yields

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Variations in Soil Organic Carbon under Clone TRFK 6/8 in Eastern Africa with Location of Production, Nitrogenous Fertilizer Rates and Plucking Frequencies

The effects of nitrogenous fertilizer rates and plucking frequencies on soil organic carbon contents at the seven sites are shown in Tables 2, 3, 4, and 5 according to the four depths of (0-10), (10-20), (20-30) and (40-60) cm respectively. The soil organic carbon contents for depth one (0-10cm) ranged from 4.16% to 17.61%, depth two (10-20cm) 3.50% to 14.82%, depth three (20-30cm) 3.26% to 12.45% and depth four (40-60cm) 2.99% to 15.11%. Soil organic carbon decreased with increased soil depths as expected. The upper soil profile (0-10cm) (Tables 2-5), had higher soil organic carbon contents than the lower depths as had also been reported elsewhere (Nazrul *et al*., 2013; Nath, 2013; Kamau *et al*., 2008). However, reported values were relatively low (<3%) compared to the current study probably due to removal of tea prunings from the fields (Weeraratna, 1981), rapid decomposition caused by high rainfall and temperatures (Nazrul *et al*., 2013), and other climatic and geographical factors affecting the distribution of soil organic carbon. Also the high percentage clay contents (Table 1-b) at the upper soil profiles could have influenced soil organic carbon contents as observed earlier (Das *et al*., 2016; Zinn *et al*., 2005).

As a recommendation in tea management (Othieno, 1988), all prunings were left in the field. Indeed the fields had thick layers of organic mulch from the prunings and leaf drops. The high soil organic carbon contents at 0-10 cm depth could be due to leaf drop and tea prunings left in the fields, nitrogen fertilization (Ruan *et al*., 2006; Venkatesane *et al*., 2004; Kamau *et al*., 2008) and microbial decomposion of fallen plant foliage (Hamid, 2006). Leaf fall and prunings left in the fields every four years help to sustain tea production through nutrients recycling (Othieno, 1980). The decomposition and mineralization of these prunings provide nutrients to the tea plant as feeder roots are concentrated at this region and enhance crop productivity. The high cation exchange capacity values, CEC, (Table 1b) observed in the regions, can be attributed to high soil organic carbon contents (Tables 2-5) as recognized by other reseachers (Liyanage *et al*., 2012). CEC levels give the overall nutrient capacity as well as soil texture. CEC in the range of 25 cmols/kg soils and above, represent clay dominated or fine soils as is the case with all the sites especially at 0-20 cm soil profile. The tea farmers are therefore encouraged to leave tea prunings in the fields as this will improve soil organic carbon contents which in the long run increase crop productivity.

Table 2: Responses of Tea Clone 6/8 Soil Organic carbon contents (%) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 0 – 10 cm)

Site	Plucking Frq(dys)	Nitrogen Rates (KgN/ha/year)					Mean Pl frq	Mean site	C.V. %
		0	75	150	225	300			
	7	3.05	4.12	4.62	4.90	4.88	4.31		
	14	3.47	3.63	3.73	4.51	4.66	4.00	4.16	9.07
	21	3.26	3.88	4.17	4.70	4.77	4.16		
Timbilil	MeanN rates	3.26	3.88	4.17	4.70	4.77			
	LSD, p≤0.05			0.60			NS		
	7	3.56	4.36	4.72	5.06	7.14	4.97		
	14	3.86	3.62	4.23	4.99	6.23	4.59		
Changoi	21	3.71	3.99	4.48	5.02	6.69	4.78	4.67	19.63
	Mean N rates	3.71	3.99	4.48	5.02	6.69			
	LSD, p≤0.05			1.47			NS		
	7	4.01	3.39	3.98	4.31	4.50	4.04		
	14	4.54	5.20	5.72	5.80	5.84	5.42		
	21	4.27	4.30	4.85	5.05	5.17	4.73	4.73	6.38
Arroket	Mean N rates	4.27	4.30	4.85	5.05	5.17			
	LSD, p≤0.05			0.48			NS		
	NxPl frq			0.68					
	7	5.52	5.79	6.49	6.56	7.45	6.36		
	14	4.82	5.25	6.82	8.76	8.83	6.90		
	21	5.17	5.52	6.65	7.66	8.14	6.63	6.63	4.99
Kitabi	Mean N rates	5.17	5.52	6.65	7.66	8.14			
	LSD, p≤0.05			0.53			NS		
	NxPl frq			0.75					
	7	13.23	15.77	18.32	19.09	18.19	16.92		
	14	16.45	18.79	17.92	18.67	19.62	18.29		
	21	14.85	17.29	18.12	18.88	18.90	17.61	17.61	6.32
Mulindi	Mean N rates	14.85	17.29	18.12	8.88	18.90			
	LSD, p≤0.05			1.78			NS		
	NxPl frq			2.52					
	7	3.35	4.17	4.62	5.56	6.62	4.87		
	14	4.69	3.82	4.23	4.93	5.69	4.63		
	21	4.02	4.00	4.42	5.25	6.16	4.77	4.77	6.19
Katoke	Mean N rates	4.02	4.00	4.42	5.25	6.16			
	LSD, p≤0.05			0.47			NS		
	7	8.53	8.25	11.10	11.61	11.25	10.15		
	14	10.03	11.49	10.89	10.73	12.26	11.08		
	21	9.28	9.87	10.99	11.17	11.76	10.61	10.62	10.89
Maruku	Mean N rates	9.28	9.87	10.99	11.17	11.76			
	LSD, p≤0.05			1.85			NS		
Mean for	7	6.00	7.34	7.66	7.48	8.00	7.30		
all	14	7.44	7.75	7.76	8.25	8.04	7.85		10.00
7 Sites	21	6.72	7.55	7.71	7.86	8.02	7.57		
	N rates	6.72	7.55	7.71	7.86	8.02			
LSD,p≤0.05				0.32			NS	0.76	
		Site x Nrates=0.64, N rates x Pl frq =0.46, Site x N rates x pl frq=0.90							

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[*] Insignificant interactions are not shown

Table 3: Responses of Tea Clone 6/8 Soil Organic Carbon contents (%) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 10 – 20 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Plucking frq**	**Mean site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
	7	2.11	2.79	3.58	3.59	4.16	3.25		
	14	2.51	3.35	3.69	4.47	4.74	3.75		
	21	2.31	3.07	3.64	4.03	4.45	3.50	3.50	9.71
Timbilil	MeanN rates	2.31	3.07	3.64	4.03	4.45			
	LSD, p≤0.05			0.55			NS		
	7	3.06	3.03	3.75	4.39	5.30	3.90		
	14	3.39	4.00	4.74	4.54	5.02	4.34		
	21	3.22	3.52	4.24	4.46	5.16	4.12	4.12	6.60
Changoi	Mean N rates	3.22	3.52	4.24	4.46	5.16			
	LSD, p≤0.05			0.44			NS		
	NxPl frq			0.62					
	7	2.82	3.30	3.87	4.89	5.54	4.08		
	14	2.06	3.24	4.54	4.56	4.52	3.79		
	21	2.44	3.27	4.20	4.73	5.03	3.93		
Arroket	Mean N rates	2.44	3.27	4.20	4.73	5.03		3.93	9.95
	LSD, p≤0.05			0.63			NS		
	NxPl frq			0.89					
	7	2.76	3.12	3.15	3.42	3.66	3.22		
	14	4.32	4.42	5.32	5.22	5.06	4.87		
	21	3.54	3.77	4.24	4.32	4.36	4.05		
Kitabi	Mean N rates	3.54	3.77	4.24	4.32	4.36		4.04	5.07
	LSD, p≤0.05			0.33			NS		
	NxPl frq			0.47					
	7	11.80	14.51	16.04	17.16	17.60	15.42		
	14	13.68	13.73	14.23	14.52	14.90	14.21		
	21	12.74	14.12	15.14	15.84	16.25	14.82		
Mulindi	Mean N rates	12.74	14.12	15.14	15.84	16.25		14.82	4.82
	LSD, p≤0.05			1.15			NS		
	NxPl frq			1.62					
	7	2.63	3.09	4.03	5.01	5.18	3.99		
	14	2.95	3.05	4.01	4.56	4.81	3.88		
	21	2.79	3.07	4.02	4.78	4.99	3.93		
Katoke	Mean N rates	2.79	3.07	4.02	4.78	4.99		3.93	9.20
	LSD≤0.05			0.58			NS		
	7	5.51	7.72	6.46	8.64	9.07	7.48		
	14	6.04	9.19	9.38	8.91	8.71	8.45		
Maruku	21	5.78	7.92	8.45	8.78	8.89	7.96		
	Mean N rates	5.78	7.92	8.45	8.78	8.89			
	LSD, p≤0.05			1.98			NS	8.96	13.76
Mean for all 7 Sites	7	5.49	5.98	5.84	6.73	7.22	6.05		
	14	5.71	5.85	6.56	6.68	6.82	6.33		
	21	5.60	5.92	6.20	6.71	7.02	6.29		10.26
	N rates	5.60	5.92	6.20	6.71	7.02			
LSD,p≤0.05				0.32			NS	1.04	

Site x Nrates=0.53, N rates x Pl frq =0.38, Site x N rates x pl frq=0.76

*Insignificant interactions are not shown, pl- plucking intervals, frq- frequency, N rates- nitrogenous fertilizer rates

Table 4: Responses of Tea Clone 6/8 Soil Organic Carbon contents (%) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 20 – 30 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Plucking frq**	**Mean site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
	7	2.30	2.65	3.26	3.40	3.44	3.01		
	14	2.77	3.73	3.66	3.70	4.00	3.57		
	21	2.53	3.19	3.46	3.55	3.72	3.29	3.29	3.77
Timbilil	MeanN rates	2.53	3.19	3.46	3.55	3.72			
	LSD, p≤0.05			0.20			NS		
	NxPl frq			0.28					
	7	2.94	2.60	3.54	3.44	3.75	3.25		
	14	2.78	3.30	3.67	3.71	3.75	3.44		
	21	2.86	2.95	3.60	3.57	3.75	3.35	4.35	6.56
Changoi	Mean N rates	2.86	2.95	3.60	3.57	3.75			
	LSD, p≤0.05			0.35			NS		
	NxPl frq			0.50					
	7	3.05	2.66	3.51	3.46	3.75	3.29		
	14	3.08	3.50	3.50	3.55	3.67	3.46		
	21	3.07	3.08	3.50	3.51	3.71	3.37		
Arroket	Mean N rates	3.07	3.08	3.50	3.51	3.71		3.37	9.53
	LSD, p≤0.05			0.52			NS		
	7	2.62	3.56	3.56	3.75	4.32	3.56		
	14	1.69	2.32	2.89	3.85	4.02	2.96		
	21	2.16	2.94	3.23	3.80	4.17	3.26	3.26	9.88
Kitabi	Mean N rates	2.16	2.94	3.23	3.80	4.17			
	LSD, p≤0.05			0.52			NS		
	NxPl frq			0.73					
	7	10.83	11.14	11.78	16.15	13.00	12.58		
	14	11.51	12.46	13.35	10.54	13.70	12.31		
	21	11.17	11.80	12.56	13.34	13.35	12.44		
Mulindi	Mean N rates	11.17	11.80	12.56	13.34	13.35			
	LSD, p≤0.05			1.12			NS	12.45	5.63
	7	1.79	3.27	3.36	3.45	3.72	3.12		
	14	1.65	2.64	3.41	3.61	4.38	3.14		
	21	1.72	2.96	3.39	3.53	4.05	3.13		
Katoke	Mean N rates	1.72	2.96	3.39	3.53	4.05			
	LSD, p≤0.05			0.54			NS	3.13	10.75
	NxPl frq			0.76					
	7	7.23	8.40	8.08	9.34	10.32	8.67		
	14	5.78	5.52	7.40	7.50	8.79	7.00		
	21	6.51	6.96	7.74	8.42	9.55	7.84		
Maruku	Mean N rates	6.51	6.96	7.74	8.42	9.55			
	LSD, p≤0.05			0.80			NS	7.84	6.34
	NxPl frq			1.13					
Mean for all	7	5.27	4.84	5.20	5.52	5.94	5.35		
7 Sites	14	4.06	4.71	5.29	5.60	5.96	5.13		
	21	4.66	4.78	5.25	5.56	5.95	5.24		7.61
	N rates	4.66	4.78	5.25	5.56	5.95			
LSD,p≤0.05				0.17			NS	0.82	

Site x Nrates=0.34, Site x N rates x pl frq=0.48

[*] Insignificant interactions are not shown,
pl- plucking intervals, frq- frequency, N rates- nitrogenous fertilizer rates

Table 5: Responses of Tea Clone 6/8 Soil Organic Carbon contents (%) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 40 – 60 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Plucking frq**	**Mean site**	**C.V. %**
		0	**75**	**150**	**225**	**300**			
	7	2.28	2.74	2.81	3.01	3.58	2.88		
	14	2.16	3.15	3.41	3.28	3.51	3.10		
	21	2.22	2.95	3.11	3.16	3.55	3.00		
Timbilil	MeanN rates	2.22	2.95	3.11	3.16	3.55			
	LSD, p≤0.05			0.50			NS	2.99	10.45
	7	2.81	3.16	3.18	3.61	3.72	3.30		
	14	2.22	2.80	2.95	3.68	3.66	3.06		
Changoi	21	2.51	2.98	3.07	3.65	3.69	3.18		
	Mean N rates	2.51	2.98	3.07	3.65	3.69			
	LSD, p≤0.05			0.39			NS	3.18	7.69
	7	2.57	3.07	3.60	3.65	3.66	3.31		
	14	2.09	3.15	3.78	3.75	4.00	3.35		
Arroket	21	2.33	3.11	3.69	3.70	3.83	3.33		
	Mean N rates	2.33	3.11	3.69	3.70	3.83			
	LSD, p≤0.05			0.62			NS	3.33	11.53
	7	1.99	3.22	3.49	3.69	4.19	3.32		
	14	2.42	2.89	3.69	3.59	3.82	3.28		
	21	2.21	3.05	3.59	3.64	4.00	3.30		
Kitabi	Mean N rates	2.21	3.05	3.59	3.64	4.00			6.63
	LSD, p≤0.05			0.35			NS	3.30	
	NxPl frq			0.42					
	7	10.19	11.78	13.24	13.54	13.86	12.52		
	14	15.35	17.59	18.28	18.73	18.87	17.77		
	21	12.77	14.69	15.76	16.13	16.37	15.14		
Mulindi	Mean N rates	12.77	14.69	15.76	16.13	16.37		15.11	2.90
	LSD, p≤0.05			0.70			NS		
	7	1.89	2.05	2.88	3.13	3.76	2.74		
	14	1.87	2.89	3.95	4.05	4.62	3.48		
	21	1.88	2.47	3.41	3.59	4.19	3.12		
Katoke	Mean N rates	1.88	2.47	3.41	3.59	4.19			
	LSD, p≤0.05			0.36			NS	3.11	7.23
	NxPl frq			0.51					
	7	4.63	4.82	5.11	5.35	5.49	5.08		
	14	2.56	3.71	4.55	5.49	5.79	4.42		
	21	3.59	4.26	4.83	5.42	5.64	4.75		
	Mean N rates	3.59	4.26	4.83	5.42	5.64			
	LSD, p≤0.05			0.38			NS	4.75	5.02
Maruku	NxPl frq			0.54					
Mean for all 7 Sites	7	3.77	4.41	4.98	5.16	5.42	4.75		
	14	4.10	5.17	5.90	6.01	6.30	5.49		
	21	3.93	4.79	5.44	5.58	5.86	5.12		6.44
	N rates	3.93	4.79	5.44	5.58	5.86			
LSD, p≤0.05				0.14			NS	NS	
	Site x N rates = 0.28, , N rates x Pl frq = 0.20, Site x N rates x pl frq = 0.39								

[*] Insignificant interactions are not shown

The values of organic carbon contents were high and above adequate range (0.75 %), (Nath and Bhattacharyya, 2014) at all the sites. Timbilil had the lowest soil organic carbon contents compared to the other six sites while Mulindi had exceptionally high levels. The Mulindi site had peat soils that are generally water logged with high contents of partially decomposed plant materials. The nature of soils in Mulindi was therefore expected to have very high SOC (Agus *et al*., 2011; Nath, 2013). However, the variations observed in other regions could be attributed to differences in environmental factors (Oades, 1995; Šimanský *et al*., 2009) and soil chemical properties (Polláková and Konôpková, 2012) in areas of production. Yields (Msomba *et al*., 2014) and mature leaf nutrients (Kwach *et al*., 2014) varied with location of production in the regions studied. These variations in organic carbon contents could be one of the causes in yield variations (Table 50) observed in the regions. Despite the differences in environmental condtions, the SOC contents were above the levels considered adequate (Baruah and Borthakur, 1997; Nath and Bhattacharyya, 2014). Soil organic carbon was therefore not a limiting factor at all sites.

Increasing rates of nitrogenous fertilizers significantly ($p \leq 0.05$) increased soil organic carbon in all the seven studied sites. That trend was repeated for the mean data for all locations.These results are similar in patterns to the previous studies (Venkatesan *et al*., 2004; Nazrul, *et al*., 2013). These results demonstrate that where soil organic carbon is low, application of nitrogen fertilizer is one way of increasing the levels of organic carbon. Nitrogen fertilization can significantly increase crop residue inputs to the soil, resulting in increases in soil organic matter. A good nitrogen fertilizer input program helps sequestering atmospheric CO_2 into soil organic carbon by increased plant growth and subsequently, the return of organic carbon to the soil for storage as soil organic matter in a no-till system (Halvorson *et al.*, 1999). These results demonstrate that in order to maintain high organic carbon status of tea soils and thereby improve soil fertility, an adequate supply of nitrogen fertilizers (75-150 KgN/ha/yr) should be applied to tea fields for sustainable crop production.
Intervals of harvesting did not influence ($p \leq 0.05$) soil organic carbon contents in all locations and soil depths. The results suggest that at every location, the return of organic matter to the soil through prunings and leaf drop was not influenced by the harvesting interval. Similarly, the promotive effect of applied nitrogen to generate organic carbon (Venkatesane *et al*., 2004; Chandravanshi *et al*., 2008) was observed at all sites. Thus provided management practices are uniform, plucking intervals may have little influence on soil organic carbon contents. Previous studies demonstrated that yields (Owuor *et al*., 1997, 1993) and black tea quality

(Owuor *et al.*, 1997; Baruah *et al.*, 1986) and levels of precursors of aroma quality parameters (Okal *et al.*, 2012a) declined with longer plucking intervals. However, in other studies plucking intervals did not have significant ($p \leq 0.05$) influence on mature leaf nutrients (Kwach *et al.*, 2014) and soil chemical properties (Kamau *et al.*, 2008). The current work showed lack of responses in soil organic carbon contents to intervals of harvesting in the sites studied.

However, significant interactions effects between nitrogen fertilizer rates and plucking intervals were sporadically observed at different sites and soil depths (Tables 2-5). These results demonstrate that the extent at which SOC was changing with plucking intervals varied with sites and soil depths. These sporadic patterns could be attributed to varied soil characteristics (Table 1-b) observed in the regions.

Overall there was significant interaction ($p \leq 0.05$) effect between sites and nitrogen rates at all soil depths, demonstrating that the extents of increase in SOC with nitrogen fertilizer rates varied with location of production. Indeed this was further demonstrated by significant interaction effects in SOC between sites, nitrogen fertilizer rates and plucking intervals. Similar non-uniform responses had been observed in the mature tea leaf nutrients (Kwach *et al.*, 2014), levels of precursors of aroma quality parameters (Okal *et al.*, 2012a) and plain quality parameters (Owuor *et al.*, 2010; Owuor *et al.*, 2009). There is need for carrying out more experiments, monitor them for a longer period to understand these interaction effects in order to improve soil organic carbon and hence realize sustainable tea productivity.

4.2 Variations in Soil pH with Location of Production, Nitrogenous Fertilizer Rates and Plucking Frequencies.

The soil pH data from samples analysed in different sites for four depths are presented in Tables 6 to 9. The acidity decreased down the soil profiles except at Arroket, Kitabi and Katoke where there was a slight increase in soil acidity at the lower depths. That could be probabily due to leaching effects caused by nitrogenous fertilizers. That trend was repeated for overall data for all locations. Nitrogen fertilizer application at the top soil profile reduces soil pH (Owuor *et al.*, 2011b; Thenmozhi *et al.*, 2012). The upper soil profiles in the regions had high clay (Table 1-b) and organic carbon (Tables 2-5) percentages. Hydrogen (H^+) and aluminium (Al^{+3}) ions on the cation exchange sites of negatively charged clay and organic matter fractions of the soil contribute to increased soil acidity (Schroeder, 1984) when exchanged to soil solutions and Al^{+3} ions get hydrolysed. Similarly more feeder tea roots are at the top soil depths (Othieno, 1980), thus enhancing absorption of nutrients cations over anions from soil solution and results in the efflux of H_3O^+ ions from plant roots into the rhizospheres. It is therefore possible that a combination of these factors is contributing to lower soil pH at the top soil level than at the lower depths. The reduction in soil pH at the top depths may influence leaching of base ions (Ruan *et al*., 2006; Kamau *et al*., 2008; Owuor and Wanyoko, 1996) and fixation of phosphorus (Owuor *et al*., 2011; Chong, 2008) affecting crop productivity. The decrease in soil pH is as a result of increased concentration of H^+ ions which have stong ability to bind to soil colloids than base ions (Ca^{+2}, Mg^{+2}, and K^+). Therefore, high concentrations of H^+ ions in the soil encourages leaching of the base ions. Soil pH should be monitored periodically to invoke mitigation activities if the pH decreases below the optimal values.

Soil pH varied significantly ($p \leq 0.05$) with the sites. These findings support early studies (Hamid, 2006; Eyüpoğlu, 1999) that pH vary with location of production. The variations observed in soil pHs for some sites, were as low as 3.10, much below the acceptable range (Othieno, 1992; Anon, 2002) for tea growing. Soil pH was therefore one of the constraining factors to tea growing in the sites. The results indicate that due to variations in environmental factors and soil characteristics (Table 1-b) at the sites, even with application of the same agronomic inputs, the pH levels will be different. And that the magnitude of the changes in soil pH varies at different extents in East Africa tea growing regions.There were sporadic significant ($p \leq 0.05$) decreases in soil pH due to increased nitrogenous fertilizer application rates at some sites. But generally, although increasing nitrogen fertilizer application tended to increase the soil acidity, this did not reach significant level in a number of sites. In previous studies, increasing rates of nitrogen reduced soil pH (Darusman *et al*., 1991; Owuor *et al*., 2011b; Hayatsu and Kosuge, 1989). The lowering of soil pH was more conspicuous above the 150 kg N/ha rate especially at the top 0-10 cm soil depth. And for means of all sites, there were significant ($p \leq 0.05$) decreases in soil pH with increased nitrogen application rates. These values were however, for some locations, below the acceptable optimum range for tea cultivation (Othieno, 1992; Anon, 2002). The decrease in soil pH with nitrogen application rates suggest that long term application of the NPKS 25:5:5:5 fertilizers could increase soil acidity to levels that may not be suitable for tea or crop production. It is therefore necessary to continuously monitor soil pH to invoke mitigation activities if the pH levels decrease below 4.0. Plucking frequencies did not have any influence on the soil pH levels at all sites and in the mean for all sites. Similar insignificant effect of plucking intervals on soil pH levels had been observed (Kamau *et al.*, 2008). In related study, plucking intervals had non-significant effect on mature tea leaf nutrients (Kwach *et al*., 2014). The results imply that plucking intervals are not a contributing factor to decrease in soil pH at tea farming. The plucking intervals below 10 days currently in use within the locations are appropriate for tea production and therefore can be continued as it has minimal affect on soil pH.

Table 6: Responses of Tea Clone 6/8 pH Levels to Nitrogen Rates, Plucking Frequencies and Location (Depth: 0- 10 cm)

Site	**Plucking Frq (dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Pl Frq**	**Mean Site**	**C.V%**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	3.24	3.18	3.17	3.19	3.26	3.21	3.22	3.62
	14	3.39	3.15	3.21	3.11	3.18	3.21		
	21	3.49	3.19	3.11	3.15	3.29	3.25		
	Mean N rates	3.37	3.17	3.16	3.15	3.24			
	LSD, p≤0.05			0.15			NS		
Changoi	7	3.65	3.29	3.10	3.15	3.17	3.27		
	14	3.75	3.38	3.22	3.28	3.13	3.35		
	21	3.41	3.33	3.31	3.24	3.14	3.29	3.30	5.01
	Mean N rates	3.36	3.34	3.21	3.22	3.14			
	LSD, p≤0.05			NS			NS		
Arroket	7	4.00	3.95	3.73	3.21	3.44	3.67		
	14	4.14	4.00	3.94	3.93	3.70	3.94		
	21	3.91	3.53	3.68	3.44	4.24	3.76	3.79	8.31
	Mean N rates	4.01	3.83	3.78	3.53	3.79			
	LSD, p≤0.05			0.41			NS		
Kitabi	7	4.43	4.40	4.00	3.89	3.81	4.11		
	14	4.43	4.42	4.15	4.00	4.08	4.22		
	21	4.28	4.15	3.75	3.69	3.47	3.87	4.06	3.05
	Mean N rates	4.38	4.32	3.97	3.86	3.79			
	LSD, p≤0.05			NS			NS		
Mulindi	7	4.52	4.26	4.19	3.89	4.12	4.20		
	14	4.42	4.44	3.96	3.98	3.91	4.14		
	21	4.75	4.14	4.07	4.02	3.97	4.19	4.18	4.51
	Mean N rates	4.56	4.28	4.07	3.96	3.99			
	LSD, p≤0.05			NS			NS		
Katoke	7	4.42	4.41	4.41	4.41	4.27	4.38		
	14	4.35	4.45	4.31	4.41	4.24	4.35		
	21	4.48	4.53	4.41	4.39	4.46	4.45	4.40	3.10
	Mean N rates	4.42	4.46	4.38	4.40	4.33			
	LSD, p≤0.05			NS			NS		
Maruku	7	4.97	4.75	4.86	4.74	4.54	4.77		
	14	4.96	4.85	4.64	4.61	4.46	4.71		
	21	4.86	4.84	4.82	4.67	4.34	4.71	4.73	2.98
	Mean N rates	4.93	4.81	4.77	4.68	4.45			
	LSD, p≤0.05			NS			NS		
Means For All 7 Sites	7	4.18	4.03	3.92	3.78	3.80	3.94		
	14	4.21	4.10	3.92	3.90	3.81	3.99		
	21	4.17	3.96	3.88	3.80	3.84	3.93		5.57
	Mean N rates	4.19	4.03	3.91	3.83	3.82			
LSD,p≤0.0			0.13				NS	0.07	
		Site x Nrates=0.21, Site x Pl frq = 0.18							

*Insignificant interactions are not shown

Table 7: Responses of Tea Clone 6/8 pH Levels to Nitrogen Rates, Plucking Frequencies and Location (Depth: 10- 20 cm)

Site	**Plucking Frq (dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean Site**	**C.V %**
		0	**75**	**150**	**225**	**300**			
	7	3.89	3.56	3.41	3.40	3.37	3.53		
	14	3.46	3.43	3.54	3.23	3.32	3.40	3.45	6.54
Timbilil	21	3.64	3.32	3.35	3.48	3.34	3.43		
	Mean N rates	3.67	3.44	3.43	3.37	3.34			
	LSD, p≤0.05			NS			NS		
	N x Pl frq			0.43					
	7	3.37	3.28	3.33	3.29	3.22	3.30		
	14	3.37	3.41	3.41	3.30	3.19	3.34	3.33	4.32
Changoi	21	3.49	3.38	3.35	3.33	3.24	3.36		
	Mean N rates	3.41	3.35	3.36	3.31	3.22			
	LSD, p≤0.05			0.19			NS		
	N x Pl frq			0.27					
	7	4.15	4.05	3.84	3.55	3.44	3.81		
	14	4.10	4.14	3.96	3.90	3.76	3.97	3.89	8.98
Arroket	21	4.28	4.08	3.91	3.72	3.49	3.90		
	Mean N rates	4.18	4.09	3.90	3.72	3.56			
	LSD, p≤0.05			NS			NS		
	N x Pl frq			0.66					
	7	4.46	4.41	4.13	4.25	4.14	4.27		
	14	4.45	4.29	4.07	4.08	4.17	4.21	4.23	3.70
Kitabi	21	4.35	4.30	3.90	4.21	4.21	4.19		
	Mean N rates	4.42	4.33	4.03	4.18	4.17			
	LSD, p≤0.05			NS			NS		
	N x Pl frq			0.25					
	7	4.64	4.54	4.35	4.38	4.18	4.42		
	14	4.74	4.48	4.27	4.13	4.13	4.35		
Mulindi	21	4.58	4.35	4.28	4.23	4.10	4.30	4.36	4.19
	Mean N rates	4.65	4.46	4.30	4.24	4.14			
	LSD, p≤0.05			NS			NS		
	N x Pl frq			0.54					
	7	4.35	4.41	4.38	4.33	4.31	4.35		
	14	4.44	4.41	4.41	4.41	4.33	4.40	4.37	3.29
Katoke	21	4.47	4.45	4.42	4.25	4.22	4.36		
	Mean N rates	4.42	4.42	4.40	4.33	4.29			
	LSD, p≤0.05			NS			NS		
	7	4.97	4.75	4.86	4.74	4.54	4.77		
	14	4.96	4.85	4.64	4.61	4.46	4.71		
Maruku	21	4.86	4.84	4.82	4.67	4.34	4.71	4.73	2.98
	Mean N rates	4.93	4.81	4.77	4.68	4.45			
	LSD, p≤0.05			NS			NS		
	N x Pl frq			0.27					
Mean for all 7 Sites	7	4.28	4.16	4.03	3.99	3.99	4.09		
	14	4.22	4.15	4.07	3.97	3.96	4.07		
	21	4.25	4.10	4.00	4.00	3.89	4.05		
	N rates	4.25	4.14	4.03	3.99	3.95			6.82
LSD,p≤0.05				0.14			NS	0.14	

*Insignificant interactions are not shown

Table 8: Responses of Tea Clone 6/8 pH Levels to Nitrogen Rates, Plucking Frequencies and Location (Depth: 20- 30 cm)

Site	PluckingFrq (dys)	Nitrogen Rates (KgN/ha/year)					Mean Plucking Frq	Mean Site	C.V.%
		0	75	150	225	300			
	7	3.86	3.58	3.41	3.44	3.42	3.54		
	14	3.49	3.51	3.43	3.36	3.37	3.43	3.48	6.31
Timbilil	21	3.72	3.42	3.36	3.26	3.52	3.45		
	MeanN rates	3.69	3.50	3.40	3.35	3.44			
	LSD,p≤0.05			NS			NS		
	N x Pl frq			0.41					
	7	3.38	3.23	3.32	3.31	3.28	3.30		
	14	3.53	3.42	3.42	3.33	3.23	3.39	3.35	4.39
Changoi	21	3.42	3.48	3.23	3.33	3.30	3.35		
	MeanN rates	3.45	3.38	3.32	3.32	3.27			
	LSD, p≤0.05			0.15			NS		
	N x Pl frq			0.28					
	7	4.42	4.23	4.15	4.09	4.07	4.19		
	14	4.90	4.72	4.49	3.79	4.09	4.40		
Arroket	21	4.91	4.74	4.62	4.47	3.79	4.51	4.37	9.66
	MeanN rates	4.74	4.56	4.42	4.12	3.99			
	LSD, p≤0.05			NS			NS		
	7	4.40	4.34	4.19	4.27	4.16	4.27		
	14	4.63	4.28	4.24	4.25	4.14	4.31		
Kitabi	21	4.42	4.35	4.19	4.08	4.05	4.22	4.27	3.48
	MeanN rates	4.49	4.32	4.21	4.20	4.12			
	LSD, p≤0.05			NS			NS		
	N x Pl frq			0.280					
	7	4.76	4.73	4.57	4.36	4.44	4.57		
	14	4.62	4.62	4.48	4.28	4.35	4.47		
Mulindi	21	4.69	4.53	4.59	4.42	4.20	4.49	4.51	4.85
	MeanN rates	4.69	4.63	4.55	4.35	4.33			
	LSD,p ≤0.05			NS			NS		
	7	4.35	4.43	4.43	4.37	4.37	4.39		
	14	4.33	4.37	4.36	4.33	4.27	4.33		
Katoke	21	4.53	4.51	4.45	4.44	4.40	4.47	4.40	2.99
	MeanN rates	4.40	4.44	4.41	4.38	4.35			
	LSD, p≤0.05			NS			NS		
	7	4.96	4.91	4.91	4.80	4.83	4.88		
	14	4.86	4.75	4.74	4.71	4.71	4.76		
Maruku	21	4.82	4.75	4.75	4.72	4.61	4.73	4.79	3.37
	MeanN rates	4.88	4.81	4.80	4.74	4.72			
	LSD, p≤0.05			NS			NS		
Means	7	4.31	4.21	4.14	4.09	4.08	4.17		
For all 7 sites	14	4.34	4.24	4.16	4.01	4.02	4.15		
	21	4.36	4.25	4.17	4.10	3.98	4.17		
	N rates	4.34	4.23	4.16	4.07	4.03			7.13
LSD,p≤0.05				0.14			NS	0.15	

Site x N rates = 0.29,

*Insignificant interactions are not shown

Table 9: Responses of Tea Clone 6/8 pH Levels to Nitrogen Rates, Plucking Frequencies and Location (Depth: 40 – 60 cm)

Site	**Plucking Frq (dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Pl Frq**	**Mean Site**	**C.V. %**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	3.99	3.58	3.46	3.48	3.47	3.59		
	14	3.58	3.56	3.43	3.41	3.41	3.48	3.54	6.88
	21	3.87	3.54	3.39	3.62	3.33	3.55		
	Mean N rates	3.81	3.56	3.43	3.50	3.40			
	LSD,p≤0.05			0.32			NS		
Changoi	7	3.53	3.36	3.35	3.24	3.13	3.32		
	14	3.57	3.45	3.32	3.30	3.30	3.39		
	21	3.63	3.43	3.22	3.26	3.31	3.37	3.36	3.46
	Mean N rates	3.58	3.41	3.30	3.27	3.25			
	LSD,p≤0.05			NS			NS		
Arroket	7	3.17	4.07	4.09	3.88	3.29	3.90		
	14	3.85	3.53	3.64	3.60	3.37	3.60	3.80	8.40
	21	3.94	3.91	3.93	3.92	3.74	3.89		
	Mean N rates	3.99	3.84	3.88	3.80	3.46			
	LSD,p≤0.05			0.42			NS		
Kitabi	7	4.46	4.16	4.16	4.07	3.97	4.16		
	14	4.54	4.33	4.33	4.37	4.18	4.35		
	21	4.57	4.34	4.14	4.00	4.01	4.21	4.24	2.37
	Mean N rates	4.52	4.28	4.21	4.14	4.05			
	LSD,p≤0.05			NS			NS		
Mulindi	7	4.76	4.79	4.73	4.40	4.73	4.69		
	14	4.82	4.88	4.42	4.32	4.49	4.59		
	21	4.78	4.63	4.83	4.71	4.70	4.73	4.67	4.21
	Mean N rates	4.79	4.77	4.66	4.47	4.64			
	LSD,p≤0.05			0.26			NS		
Katoke	7	4.49	4.48	4.41	4.40	4.37	4.43		
	14	4.52	4.50	4.44	4.40	4.30	4.43		
	21	4.47	4.34	4.33	4.26	4.21	4.33	4.40	3.27
	Mean N rates	4.49	4.44	4.39	4.35	4.30			
	LSD,p≤0.05			NS			NS		
Maruku	7	5.09	4.95	4.91	4.85	4.81	4.92		
	14	4.89	4.87	4.81	4.78	4.73	4.82		
	21	4.99	4.77	4.75	4.77	4.68	4.79	4.84	2.87
	Mea N rates	4.99	4.86	4.82	4.80	4.74			
	LSD,p≤0.05			0.16			NS		
Means for all 7 Sites	7	4.36	4.20	4.16	4.04	3.97	4.15		
	14	4.25	4.16	4.06	4.03	3.97	4.09		
	21	4.32	4.14	4.09	4.08	4.00	4.16		
	Mean N rates	4.31	4.17	4.10	4.05	3.98			5.77
LSD,p≤0.05			0.11				NS	0.12	

Site x Nrates=0.17, Site x Pl frq = 0.19

*Insignificant interactions are not shown

There were significant ($p \leq 0.05$) interactions between nitrogen and plucking intervals for soil pH at Arroket, Kitabi and Mulindi for depth 0-10cm, Timbilil, Changoi, Arroket, Kitabi, Mulindi and Maruku for depth 10-20cm, Timbilil, Changoi, and Kitabi at 20-30cm and Arroket at 40-60cm. Similar patterns were observed for all sites means between site and nitrogen rates and site and plucking intervals except at soil depth 10-20cm demonstrating that the responses varied from site to site, suggesting that factors influencing soil pH varied with location of production. These findings show that pH varied widely from site to site. These locational variations could be attributed to differences in geographical and climatic patterns and the differences in soil compositions (Table 1-b) in the regions. The significant interactions effects between sites, nitrogen rates and plucking intervals imply that at different sites the extent of variations due to the two variables did not always follow the same patterns. While nitrogen fertilizer rates reduced ($p \leq 0.05$) the soil pH at some sites, at other sites the responses were insignificant.

4.3 Variations in Soil Nutrients Levels of Clone TRFK 6/8 in Eastern Africa with Location of Production, Nitrogenous Fertilizer Rates and Plucking Frequencies

The effects of sites, NPK(S) fertilizer rates and plucking frequencies on the different soil nutrients levels are shown in Tables 10-50 for soil nitrogen, phosporus, potassium, calcium, magnesium, aluminium, iron, zinc, copper, and manganese.

4.3.1 Soil Nitrogen Levels

Soil nitrogen levels are presented in Tables 10-13. The values obtained were within the optimal (0.12 to 0.4%) range for tea soil nitrogen levels (Gilbert, 1983; Adiloğlu and Adiloğlu, 2006). The nitrogen levels were higher in the surface layer and decreased with the depths. These observations are similar with the previous results (Hamid, 2006; Hamid *et al*., 1993; Kebeney *et al*., 2010). Nitrogen content is closely related with soil organic carbon (Tables 2-5) and soil texture (Table 1b). And therefore, organic carbon may be a good indicator of nitrogen status of the soils (Hamid, 2006; Kamau *et al*., 2008). Clay soils have higher nitrate nitrogen (NO_3^--N) retention while high cation exchange capacity and organic matter contents hold more nitrogen-NH_4^+ (Zhou, 2017). However, Mulindi with exceptionally high levels of SOC and clay percentage did not show any significant difference in nitrogen levels with other sites. This is due to leaching and washing away of nitrogen nutrient in this waterlogged site. In well managed tea fields where prunings are left the tea fields, most of the feeder roots are within 0-10 cm soil depth. The decomposition and mineralization of the organic matter enhances percentage nitrogen in the tea surface soils. Even in the control plots, the prunings and leaf drops seemed to have been supplying nitrogen to the soil. The results therefore suggest that in the short term nitrogen nutrient may not be a limiting factor in tea production in this Eastern Africa for well managed tea plantations, provided there is adequate moisture in the soil.

Soil nitrogen contents varied ($p \leq 0.05$) with locations of production at all the seven sites and depths studied (Table 10-13). The extent of variations may be related to the characteristic of soil particularly the mineralization process and rapid conversion to nitrate by nitrification (Banerjee, 1993). The variations with location demonstrate that the uniform agronomic inputs in the Eastern Africa tea growing regions maybe inappropriate in some regions.The significant variations with locations could be one of the causes of yields differences (Msomba *et al*., 2014) observed in the regions. The results demonstrate that each site may require specific fertilizer norms for clone TRFK 6/8 to realize equitable yields, provided other factors are not limiting.

The levels of soil nitrogen increased ($p \leq 0.05$) linearly with nitrogen rates at all sites except at Maruku depth 20-30cm, Changoi, Arroket, and Maruku (40-60cm). For all sites means, increased nitrogen rates increased ($p \leq 0.05$) soil nitrogen levels at the four depths studied. These responses agree with previous studies (Hamid, *et al*., 1993; Hamid, 2006). The data showed similar responses to what has been shown in mature tea leaf nitrogen levels (Wanyoko *et al*., 1997; Kebeney *et al*., 2010; Kwach *et al*., 2014) indicating that tea soil nitrogen levels are in the same pattern with levels of nitrogen in mature leaf. In other studies (Owuor *et al*., 2011b); the yield responses and nitrogen uptake in mature leaf content seemed to follow similar patterns. Thus, application of nitrogenous fertilizer increases soil nitrogen levels. The results demonstrate that nitrogen nutrient difficiency in tea plants can be corrected by surface application of the nutrient in all tea growing regions in East Africa and the mature leaf analysis alone maybe adequate in predicting tea plants nitrogen requirements. The variations in responses of nitrogenous fertilizer rates demonstrate that each location may require specific fertilizer norms for clone TRFK 6/8 to realize optimal yields and quality.

Harvesting intervals did not influence soil nitrogen levels at all sites. The patterns observed were erratic and sporadic from site to site and factors causing them need more trials to be established. There were significant ($p \leq 0.05$) interactions between N x plucking intervals for soil nitrogen levels at Kitabi 0-10cm, Katoke 20-30cm and Mulindi 40-60cm soil depths, sit x

N rates for all sites overall values at all depths considered indicating that the observed responses were unique and did not follow the same pattern.

Table 10: Responses of Tea Clone 6/8 Soil Nitrogen Levels (%) to Location, Nitrogenous fertilizer Rates and Plucking Frequencies (Depth: 0 – 10 cm)

Site	**Plucking Frq (dys)**	**Nitrogen Rates (KgN/ha/year**					**Mean Plucking Frq**	**Mean Site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
	7	0.309	0.312	0.321	0.324	0.328	0.319		
	14	0.310	0.294	0.321	0.326	0.329	0.316		
	21	0.312	0.311	0.322	0.327	0.331	0.200	0.318	2.51
Timbilil	Mean N rates	0.310	0.306	0.321	0.326	0.329			
	LSD,p≤0.05			0.011			NS		
	7	0.268	0.271	0.277	0.289	0.266	0.274		
	14	0.272	0.271	0.281	0.294	0.247	0.273		
	21	0.277	0.273	0.286	0.293	0.258	0.277	0.275	8.81
Changoi	Mean N rates	0.272	0.272	0.281	0.292	0.257			
	LSD,p≤0.05			0.002			NS		
	7	0.246	0.250	0.254	0.256	0.261	0.253		
	14	0.242	0.243	0.250	0.259	0.263	0.251		
Arroket	21	0.252	0.254	0.260	0.263	0.232	0.252	0.252	5.91
	Mean N rates	0.247	0.249	0.255	0.259	0.252			
	LSD,p≤0.05			0.002			NS		
	7	0.260	0.270	0.281	0.289	0.300	0.280		
	14	0.278	0.282	0.292	0.299	0.309	0.292		
	21	0.280	0.292	0.302	0.309	0.319	0.301	0.291	0.82
Kitabi	Mean N rates	0.273	0.281	0.292	0.299	0.309			
	LSD,p≤0.05			0.003			NS		
	NxPl frq			0.005					
	7	0.214	0.224	0.234	0.244	0.264	0.236		
	14	0.224	0.233	0.243	0.254	0.238	0.238		
	21	0.252	0.254	0.262	0.238	0.293	0.260	0.245	8.18
Mulindi	Mean N rates	0.230	0.237	0.246	0.245	0.265			
	LSD,p≤0.05			0.026			0.017		
	7	0.280	0.292	0.297	0.302	0.310	0.296		
	14	0.293	0.300	0.308	0.312	0.319	0.307		
	21	0.283	0.292	0.303	0.312	0.320	0.302	0.302	0.39
Katoke	mean	0.285	0.295	0.303	0.309	0.316			
	LSD,p≤0.05			0.002			NS		
	7	0.180	0.186	0.193	0.202	0.205	0.193		
	14	0.193	0.197	0.202	0.204	0.214	0.202		
Maruku	21	0.206	0.213	0.215	0.222	0.226	0.217	0.204	0.43
	Mean N rates	0.193	0.198	0.204	0.210	0.215			
	LSD,p≤0.05			0.012			NS		
Means for all 7 Sites	7	0.256	0.263	0.270	0.277	0.286	0.270		
	14	0.268	0.267	0.276	0.283	0.293	0.277		
	21	0.271	0.275	0.283	0.290	0.297	0.283		
	N rates	0.265	0.268	0.276	0.283	0.292			
LSD,p≤0.05				0.016			0.019	0.016	11.33
				Site x Nrates = 0.031					

*Insignificant interactions are not shown

Table 11: Responses of Tea Clone 6/8 Soil Nitrogen Levels (%) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 10 – 20 cm)

Site	Plucking Frq (dys)	Nitrogen Rates (KgN/ha/year)					Mean PlFrq	Mean Site	C.V.%
		0	75	150	225	300			
	7	0.281	0.282	0.282	0.290	0.292	0.285		
	14	0.282	0.282	0.271	0.288	0.292	0.283		
	21	0.280	0.282	0.290	0.290	0.291	0.287		
Timbilil	MeanN rates	0.281	0.282	0.281	0.289	0.292		0.285	2.93
	LSD,p≤0.05			0.011			NS		
	7	0.200	0.217	0.219	0.224	0.229	0.218		
	14	0.203	0.220	0.224	0.230	0.234	0.222		
	21	0.218	0.232	0.233	0.232	0.236	0.230	0.223	4.70
Changoi	MeanN rates	0.207	0.223	0.226	0.229	0.233			
	LSD,p≤0.05			0.014			0.017		
	7	0.245	0.249	0.255	0.226	0.233	0.242		
	14	0.256	0.262	0.232	0.234	0.241	0.245		
	21	0.265	0.269	0.240	0.245	0.283	0.260	0.249	11.86
Arroket	MeanN rates	0.255	0.260	0.242	0.235	0.252			
	LSD,p≤0.05			0.004			NS		
	7	0.270	0.261	0.271	0.279	0.281	0.272		
	14	0.268	0.273	0.278	0.282	0.292	0.279		
	21	0.260	0.270	0.281	0.292	0.300	0.280	0.277	0.61
Kitabi	MeanN rates	0.266	0.268	0.277	0.284	0.291			
	LSD,p≤0.05			0.002			NS		
	7	0.194	0.204	0.206	0.222	0.224	0.210		
	14	0.204	0.214	0.215	0.227	0.231	0.218		
	21	0.204	0.215	0.225	0.231	0.235	0.222	0.217	2.37
Mulindi	MeanN rates	0.200	0.211	0.215	0.227	0.230			
	LSD,p≤0.05			0.007			NS		
	7	0.259	0.262	0.269	0.270	0.272	0.266		
	14	0.262	0.269	0.272	0.278	0.281	0.273		
	21	0.269	0.275	0.279	0.288	0.292	0.281	0.273	0.44
Katoke	MeanN rates	0.264	0.269	0.273	0.279	0.282			
	LSD,p≤0.05			0.002			NS		
	7	0.173	0.182	0.184	0.193	0.196	0.186		
	14	0.183	0.189	0.194	0.198	0.202	0.193		
	21	0.193	0.198	0.203	0.206	0.213	0.203	0.194	0.99
Maruku	Mean N rates	0.183	0.190	0.193	0.199	0.204			
	LSD,p≤0.05			0.002			NS		
Means for all 7 Sites	7	0.238	0.234	0.239	0.246	0.252	0.242		
	14	0.232	0.234	0.260	0.245	0.249	0.244		
	21	0.237	0.243	0.248	0.251	0.251	0.246		
	N rates	0.236	0.237	0.249	0.247	0.251			
LSD,p≤0.05				0.020			NS	0.021	16.16
			Site x Nrates= 0.039						

*Insignificant interactions are not shown

Table 12: Responses of Tea Clone 6/8 Soil Nitrogen Levels (%) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 20 – 30 cm)

Site	**Plucking Frq (dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Pl Frq**	**Mean Site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
	7	0.177	0.191	0.193	0.194	0.202	0.192		
	14	0.180	0.190	0.195	0.196	0.201	0.192		
	21	0.180	0.191	0.194	0.196	0.201	0.192	0.192	0.79
Timbilil	MeanN rates	0.179	0.191	0.194	0.195	0.201			
	LSD,p≤0.05			0.002			NS		
	7	0.143	0.153	0.162	0.132	0.170	0.152		
	14	0.150	0.156	0.132	0.177	0.178	0.151		
	21	0.154	0.159	0.136	0.178	0.158	0.157	0.153	20.04
Changoi	MeanN rates	0.149	0.156	0.144	0.149	0.169			
	LSD,p≤0.05			0.004			NS		
	7	0.186	0.195	0.179	0.184	0.188	0.186		
	14	0.171	0.181	0.188	0.192	0.195	0.185		
	21	0.192	0.196	0.201	0.213	0.225	0.205	0.192	10.97
Arroket	MeanN rates	0.183	0.191	0.189	0.196	0.203			
	LSD,p≤0.05			0.003			NS		
	7	0.157	0.168	0.171	0.178	0.190	0.173		
	14	0.175	0.180	0.190	0.202	0.200	0.189		
	21	0.183	0.190	0.192	0.202	0.210	0.195	0.186	0.80
Kitabi	MeanN rates	0.172	0.179	0.184	0.194	0.200			
	LSD,p≤0.05			0.002			NS		
	7	0.191	0.193	0.204	0.213	0.217	0.204		
	14	0.196	0.201	0.206	0.217	0.221	0.208		
	21	0.198	0.203	0.206	0.225	0.225	0.211	0.208	1.90
Mulindi	MeanN rates	0.195	0.199	0.205	0.219	0.221			
	LSD,p≤0.05			0.005			NS		
	7	0.158	0.163	0.170	0.175	0.179	0.169		
	14	0.165	0.170	0.175	0.179	0.183	0.174		
	21	0.173	0.178	0.183	0.188	0.192	0.183	0.175	0.50
Katoke	MeanN rates	0.165	0.170	0.176	0.181	0.184			
	LSD,p≤0.05			0.001			NS		
	NxPl frq			0.002					
	7	0.123	0.133	0.171	0.173	0.181	0.156		
	14	0.161	0.172	0.173	0.181	0.186	0.174		
Maruku	21	0.173	0.182	0.184	0.190	0.194	0.185	0.172	1.62
	MeanN rates	0.152	0.162	0.176	0.181	0.187			
	LSD,p≤0.05			NS			NS		
Means for	7	0.155	0.163	0.179	0.183	0.190	0.174		
	14	0.168	0.175	0.185	0.191	0.185	0.181		
all 7 Sites	21	0.175	0.186	0.191	0.198	0.191	0.188		
	N rates	0.166	0.175	0.185	0.191	0.189			18.87
LSD,p≤0.05				0.017			0.020	0.018	
			Site x Nrates= 0.033						

*Insignificant interactions are not shown

Table 13: Responses of Tea Clone 6/8 Soil Nitrogen Levels (%) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 40 – 60 cm)

Site	**Plucking Frq (dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Plucking Frq**	**Mean Site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
	7	0.199	0.181	0.185	0.192	0.196	0.191		
	14	0.168	0.181	0.187	0.190	0.197	0.185		
Timbilil	21	0.169	0.183	0.187	0.189	0.198	0.185	0.187	15.83
	Mean N rates	0.179	0.182	0.186	0.190	0.197			
	LSD,p≤0.05			0.030			NS		
	7	0.102	0.111	0.113	0.121	0.141	0.118		
	14	0.105	0.115	0.121	0.126	0.129	0.119		
Changoi	21	0.116	0.121	0.129	0.133	0.143	0.128	0.122	2.21
	MeanN rates	0.108	0.115	0.121	0.127	0.138			
	LSD,p≤0.05			NS			NS		
	7	0.152	0.142	0.162	0.171	0.183	0.162		
	14	0.152	0.163	0.172	0.191	0.194	0.174		
Arroket	21	0.172	0.193	0.196	0.197	0.202	0.192	0.176	1.51
	Mean N rates	0.158	0.166	0.176	0.186	0.193			
	LSD,p≤0.05			NS			NS		
	7	0.137	0.149	0.159	0.164	0.170	0.156		
	14	0.163	0.169	0.172	0.179	0.182	0.173		
Kitabi	21	0.172	0.181	0.183	0.188	0.158	0.176	0.168	8.88
	Mean N rates	0.157	0.166	0.172	0.177	0.170			
	LSD,p≤0.05			0.020			0.024		
	7	0.172	0.176	0.193	0.196	0.202	0.188		
	14	0.193	0.205	0.209	0.214	0.207	0.206		
Mulindi	21	0.210	0.213	0.216	0.222	0.225	0.217	0.203	2.08
	Mean N rates	0.192	0.198	0.206	0.211	0.211			
	LSD,p≤0.05			0.005			NS		
	NxPl frq			0.008					
	7	0.130	0.138	0.140	0.145	0.157	0.142		
	14	0.148	0.150	0.159	0.161	0.165	0.156		
Katoke	21	0.140	0.150	0.159	0.163	0.170	0.156	0.152	0.81
	Mean N rates	0.139	0.146	0.153	0.156	0.164			
	LSD,p≤0.05			0.002			NS		
	7	0.112	0.122	0.172	0.191	0.196	0.159		
	14	0.146	0.173	0.190	0.195	0.204	0.182		
	21	0.172	0.181	0.196	0.204	0.211	0.193		
Maruku	Mean N rates	0.143	0.158	0.186	0.197	0.204		0.178	1.77
	LSD,p≤0.05			NS			NS		
Means for	7	0.139	0.144	0.157	0.168	0.175	0.156		
	14	0.149	0.159	0.166	0.175	0.175	0.165		
all 7 Sites	21	0.153	0.163	0.168	0.175	0.166	0.165		
	Mean N rates	0.147	0.155	0.164	0.173	0.172			
LSD,p≤0.05				0.015			NS	0.016	19.24
	Site x Nrates=0.030, Site x Pl frq = 0.025								

*Insignificant interactions are not shown

4.3.2 Soil Phosphorus Levels

Tables 14-17 show the effects of NPK(S) fertilizer rates and plucking frequencies on the soil extractable phosphorus levels. Soil phosphorus levesl at the upper soil depths remained high (above optimal level, 10 ppm) (Nazrul *et al*., 2013) and decreased with depths. This result is in agreement with the early finding (Owuor *et al*., 2012; Wang *et al*., 1997). Decrease of phosphorus levels with depth (Tables 6-9) could be due to low availability of phosphorus following fixation of applied phosphorus in NPK fertilizers at 0-10cm. The fixation causes low or lack of availability of phosphorus to lower soil depths (Wanyoko *et al*., 1992; Kebeney *et al*., 2010). At low soil pH phosphate ($H_2PO_4^-$) ions react with manganese, iron and aluminium ions resulting in the formation of insoluble hydroxyl phosphates in acid soil (Brandy and Weil, 2002; Othieno, 1980). One way of increasing the availabity of phosphorus to tea plant could be through prunings left in the tea fields at the soil surface that encourage profuse growth of feeder roots within nutrient-rich zones. The decomposition results in the formation of organic chemicals (Othieno, 1980) which help solubilize insoluble hydroxyl phoshates and enhance uptake of phosphorus by the feeder roots within the prunings-soil interface, thus improving crop productivity.

The results obtained herein (Tables 14-17) show that soil phosphorus varied ($p \leq 0.05$) with site. From the data, all sites at the upper soil profiles (0-20 cm) had adequate and above critical levels, (10 ppm) (Nazrul *et al*., 2013) soil phosphorus. But the lower profiles (20-30 cm and 40-60 cm) had levels slightly below the critical value except Changoi, Arroket and Mulindi as had also been recorded in other studies (Nazrul *et al*., 2013; Owuor *et al*., 2012; Wang *et al*., 1997). Significant ($p \leq 0.05$) reductions in soil phosphorus were observed at 20-30cm and 40-60cm soil depths. Arroket recorded high soil phosphorus at the considered profiles compared to othe sites. While other sites showed a decrease in soil phosphorus levels with depths, Mulindi recorded increasing trends. This observation at Mulindi could be attributed to the peat soil with high accumulation of soil organic carbon (Tables 2-5), even to the lower soil depths at the region. Similar variations with location in soil phosphorus (Nazrul *et al*., 2013; Wang *et al*., 1997) and mature leaf phosphorus (Kwach *et al*., 2014; Adiloğlu and Adiloğlu, 2006) had also been recorded in previous studies. The variations with location demonstrate that even with same agronomic practices, the nutrient levels will be different in Eastern Africa tea farms. Farmers in this region need to intensify management practices which could prevent phosphorus fixation as this will aid in sustainable tea production.

Table 14: Responses of Tea Clone 6/8 Soil Phosphorus Levels (ppm) to Location, Nitrogen Rates and Plucking Frequencies (Depth: 0 – 10 cm)

Site	Plucking Frq(dys)	Nitrogen Rates(KgN/ha/year)					Mean Pl Frq	Mean Site	C.V. %
		0	75	150	225	300			
Timbilil	7	9.7	10	13.7	18.7	20.7	14.5	15.2	6.1
	14	7.0	11	13.7	17	13.9	13.9		
	21	13.7	13	14	23.3	22.2	17.2		
	Mean N rates	10.1	11.3	13.8	19.7	21.2			
	LSD,p≤0.05			1.2			NS		
Changoi	7	12.7	13.3	20.3	21	19	17.3	16.6	6.3
	14	12	14.7	16.7	19	21	16.7		
	21	14	14.7	15.3	16.7	18.7	15.9		
	Mean N rates	12.9	14.2	17.4	18.9	19.6			
	LSD,p≤0.05			1.4			NS		
Arroket	7	29.7	32.3	35.3	38.0	47.0	27.9	24.1	4.3
	14	4.7	7.3	35.0	37.0	39.0	24.6		
	21	9.0	12.3	17.3	34.3	26.3	19.9		
	Mean N rates	14.4	17.3	29.2	36.4	37.4.			
	LSD,p≤0.05			1.4			NS		
Kitabi	7	12.7	14.3	16.3	32.7	15.3	18.3	15.3	7.5
	14	5.7	6.0	7.0	14.3	31.7	12.9		
	21	7.3	10.7	12.3	17.7	25.0	14.6		
	Mean N rates	8.6	10.3	11.9	21.6	24.0			
	LSD,p≤0.05			1.5			NS		
Mulindi	7	10.3	12.0	16.0	16.0	15.7	14.0	13.0	7.9
	14	8.3	11.0	14.0	15.0	16.0	12.9		
	21	12.0	12.0	12.3	21.0	15.3	14.5		
	Mean N rates	10.2	11.7	14.1	17.3	15.7			
	LSD,p≤0.05			1.4			NS		
Katoke	7	14.3	16.0	16.3	17.3	22.0	17.2	14.3	6.4
	14	10.3	11.0	12.0	15.0	9.0	11.5		
	21	12.3	13.3	15.7	14.3	16.0	14.3		
	Mean	12.3	13.4	14.7	15.6	15.7			
	LSD,p≤0.05			1.2			NS		
Maruku	7	10.7	13.0	11.7	14.3	12.0	12.3	11.4	15.2
	14	10.3	11.0	11.0	11.0	12.7	11.2		
	21	10.0	9.7	13.0	11.3	10.0	10.8		
	Mean N rates	10.3	11.2	11.9	12.2	11.6			
	LSD,p≤0.05			2.3			NS		
Mean for all 7 Sites	7	14.3	15.9	18.5	17.4	15.5	17.4		
	14	8.3	10.3	15.6	14.8	21.5	14.8		
	21	11.2	12.2	14.3	15.3	19.0	15.3		9.3
	Nrates	11.3	12.8	16.1	15.8	18.7			
LSD,p≤0.05			NS				NS	0.8	
		Site x Nrates=1.4							

*Insignificant interactions are not shown

Table 15: Responses of Tea Clone 6/8 Soil Phosphorus Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 10 – 20 cm)

Site	Plucking Frq(dys)	Nitrogen Rates(KgN/ha/year)					Mean Pl Frq	Mean site	C.V %
		0	75	150	225	300			
	7	7.3	9.3	13.3	14.3	16.0	12.1		
	14	7.3	8.9	12.0	11.3	15.0	10.9	12.6	11.6
Timbilil	21	10.0	11.3	13.0	16.7	23.0	14.8		
	Mean N rates	8.2	9.8	12.8	14.1	18.0			
	LSD,p≤0.05			1.9			NS		
	Nxpl frq			2.7					
	7	11.3	13.7	14.3	20.3	21.3	16.2		
	14	13.0	12.0	14.0	12.3	17.0	13.7	15.0	7.0
	21	14.3	13.7	15.0	17.0	15.0	15.0		
Changoi	Mean N rates	12.9	13.1	14.4	16.6	17.8			
	LSD,p≤0.05			1.5			NS		
	7	16.3	16.3	21.0	28.0	37.3	23.8		
	14	27.3	16.3	31.0	30.0	34.7	27.9	26.4	4.7
	21	15.7	36.0	21.3	31.7	33.0	27.6		
Arroket	Mean N rates	19.8	22.9	24.6	29.9	35.0			
	LSD,p≤0.05			1.6			NS		
	7	9.7	14.0	20.0	28.3	32.3	20.9		
	14	16.3	16.7	22.0	27.0	30.0	22.4	18.7	6.8
	21	11.0	12.0	11.7	14.0	16.0	12.9		
Kitabi	Mean N rates	12.3	14.2	17.9	23.1	26.1			
	LSD,p≤0.05			1.7			NS		
	7	11.7	12.7	14.3	15.7	21.0	15.1		
	14	11.7	16.7	17.7	21.0	21.7	17.7	14.5	8.3
	21	8.3	8.7	9.7	11.7	14.7	10.6		
Mulindi	Mean N ates	10.6	12.7	13.9	16.1	19.1			
	LSD,p≤0.05			1.6			NS		
	Nxpl frq			2.3					
	7	12.0	12.3	13.0	17.0	19.0	14.7		
	14	9.3	9.3	10.3	16.3	16.3	12.3	12.4	8.4
	21	7.7	8.7	8.7	10.7	15.3	10.2		
Katoke	Mean N ates	9.7	10.1	10.7	14.7	16.9			
	LSD,p≤0.05			1.4			NS		
	Nxpl frq			2.0					
	7	9.3	10.3	11.0	9.7	10.0	10.1		
	14	8.3	8.7	8.7	9.7	8.3	8.7	9.3	16.1
	21	9.0	8.7	8.3	9.0	10.0	9.0		
Maruku	Mean N rates	8.9	9.2	9.3	9.4	9.4			
	LSD,p≤0.05			0.2			NS		
	Nxpl frq			2.5					
Mean for all 7 Sites	7	11.7	12.9	16.2	20.4	19.4	16.1		
	14	13.2	14.8	16.4	18.7	18.0	16.2		
	21	10.7	12.2	14.0	16.1	18.4	14.3		10.4
	N rates	11.9	13.3	15.5	18.4	18.6			
LSD,p≤0.05				0.8			NS	0.8	
				Site x Nrates=1.6					

*Insignificant interactions are not shown

Table 16: Responses of Tea Clone 6/8 Soil Phosphorus Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 20 – 30 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean site**	**C.V %**
		0	**75**	**150**	**225**	**300**			
	7	4.7	5.7	7.3	11.3	12.7	8.3		
	14	8.0	9.0	11.3	10.3	10.7	9.9	9.2	17.5
	21	6.0	8.3	10.3	10.0	11.7	9.3		
Timbilil	Mean N rates	6.2	7.7	9.7	10.6	11.7			
	LSD,p≤0.05			NS			NS		
	Nxpl frq			3.0					
	7	11.0	11.3	13.0	12.7	11.7	11.9		
	14	12.3	13.3	11.7	12.3	15.0	12.9	13.1	9.2
	21	12.3	14.0	15.0	16.0	14.3	14.3		
Changoi	Mean N rates	11.9	12.9	13.2	13.7	13.7			
	LSD,p≤0.05			1.6			NS		
	Nxpl frq			1.3					
	7	16.0	19.3	15.7	32.7	38.0	23.3		
	14	15.0	24.3	15.3	29.7	34.0	23.7	24.9	4.1
	21	15.3	22.0	38.0	30.7	32.0	27.0		
Arroket	Mean N rates	15.4	21.9	23.0	31.0	33.0			
	LSD,p≤0.05			NS			NS		
	7	9.3	6.7	9.7	8.7	11.3	9.1		
	14	6.7	8.7	10.3	9.7	7.7	8.6	8.7	10.0
Kitabi	21	7.0	8.0	7.7	10.0	9.3	8.4		
	Mean N rates	7.7	7.8	9.2	9.4	9.4			
	LSD,p≤0.05			NS			NS		
	7	10.0	12.0	12.7	12.0	21.0	13.7		
	14	14.0	18.7	21.0	23.0	15.0	18.3	16.2	6.9
	21	13.0	17.7	15.7	18.3	19.0	16.7		
Mulindi	Mean N rates	12.3	16.1	16.4	18.0	18.3			
	LSD,p≤0.05			NS			NS		
	7	7.3	8.3	9.0	15.0	18.7	11.7		
	14	7.7	9.3	11.3	14.3	16.7	11.9	12.6	7.8
	21	11.0	13.0	14.0	16.0	17.7	14.3		
Katoke	Mean	8.7	10.2	11.4	15.1	17.7			
	LSD,p≤0.05			NS			NS		
	Nxpl frq			1.9					
	7	7.0	7.0	6.3	6.7	7.0	6.8		
	14	5.3	6.3	7.7	6.3	6.3	6.4	6.7	13.4
Maruku	21	7.3	6.3	6.0	7.3	7.0	6.8		
	Mean N rates	6.6	6.6	6.7	6.8	6.8			
	LSD,p≤0.05			NS			NS		
	7	9.3	10.4	13.3	13.5	14.0	12.1		
Mean for all	14	10.0	13.0	14.1	12.9	15.4	13.1		
7 Sites	21	10.2	12.9	14.5	16.7	15.4	13.9		9.3
	Nrates	9.9	12.1	14.0	14.3	15.0			
LSD,p≤0.05			0.6				NS	0.6	
			Site x Nrates=1.2						

*Insignificant interactions are not shown

Table 17: Responses of Tea Clone 6/8 Soil Phosphorus (ppm) Levels to Nitrogen Rates, Plucking Frequencies and Location (Depth: 40 – 60 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
	7	7.0	8.0	10.3	11.0	11.7	9.6		
	14	4.3	5.3	5.7	6.0	7.3	5.7	7.9	16.5
Timbilil	21	6.3	6.7	7.7	9.3	12.0	8.4		
	Mean N ates	5.9	6.7	7.9	8.8	10.3			
	LSD,$p\leq0.05$			NS			NS		
	7	10.7	11.7	11.0	12.0	14.0	11.9		
	14	10.3	10.7	10.7	12.3	14.7	11.7	12.4	7.7
Changoi	21	11.0	13.3	14.3	13.0	15.7	13.5		
	Mean N rates	10.7	11.9	12.0	12.4	14.8			
	LSD,$p\leq0.05$			NS			NS		
	7	14.3	15.3	14.7	14.7	15.3	14.9		
	14	13.3	13.7	13.0	13.3	15.3	13.7	14.4	6.6
Arroket	21	12.7	13.7	15.7	16.0	14.7	14.5		
	Mean N rates	13.4	14.2	14.4	14.7	15.1			
	LSD,$p\leq0.05$			1.3			NS		
	Nxpl frq			1.8					
	7	5.7	6.7	7.3	9.0	10.0	7.7		
	14	7.0	9.0	8.3	11.3	10.0	9.1	8.3	14.9
Kitabi	21	7.3	6.3	9.7	8.0	9.0	8.1		
	Mean N rates	6.7	7.3	8.4	9.4	9.7			
	LSD,$p\leq0.05$			NS			NS		
	Nxpl frq			2.3					
	7	11.0	10.7	13.0	14.3	22.0	14.2		
	14	9.0	9.3	12.3	20.0	20.0	14.1	16.0	7.5
Mulindi	21	15.0	15.7	19.7	23.0	24.3	19.5		
	Mean N rates	11.7	11.9	15.0	19.1	22.1			
	LSD,$p\leq0.05$			NS			NS		
	Nxpl frq			2.3					
	7	5.3	6.3	7.0	7.3	8.7	6.9		
	14	7.7	7.7	8.7	10.0	9.0	8.6	7.4	12.6
Katoke	21	5.3	7.0	7.0	6.7	7.3	6.7		
	Mean	6.1	7.0	7.6	8.0	8.3			
	LSD,$p\leq0.05$			1.2			NS		
	7	9.0	9.7	11.0	10.7	10.0	10.1		
	14	7.3	9.3	7.0	10.0	11.3	9.0	9.4	12.3
Maruku	21	9.0	9.3	10.7	8.3	7.7	9.0		
	Mean N rates	8.4	9.4	9.6	9.7	9.7			
	LSD,$p\leq0.05$			NS			NS		
	Nxpl frq			2.2					
Mean for all	7	9.5	9.7	10.3	11.4	12.8	10.8		
7 Sites	14	8.7	9.4	9.8	11.1	12.4	10.3		
	21	10.4	9.5	11.4	12.5	13.0	11.4		11.78
	Nrates	9.5	9.6	10.5	11.7	12.7			
LSD,$p\leq0.05$			3.3				NS	3.4	
			Site x Nrates= 6.4						

*Insignificant interactions are not shown

Soil phosphorus increased linearly with rise in rates of fertilizer as observed in earlier studies (Owuor and Wanyoko, 1996; Kamau *et al*., 2003; Owuor *et al*., 2012). Similar trends for mature leaf phosphorus were observed in earlier studies (Owuor *et al*., 2012; Kwach *et al*., 2014; Wanyoko *et al*., 1992). Although increased nitrogenous fertilizer rates have acidifying effect (Bhattacharya and Dey, 1983; Wanyoko, 1996) which enhance fixation of phosphorus on tea soils (Wanyoko *et al*., 1992; Owuor *et al*., 2012), the levels of phosphorus in the current study appeared to be increased by increasing nitrogenous fertilizer rates. This could be explained by the current study soils being rich in SOC as also reported elsewhere (Othieno, 1980; Russell, 1988) which limit phosphorus fixation through organic chemicals produced that help to solubilize hydroxyl phosphates, thus increasing the phosphorus levels in the soil. Therefore, farmers should engage in management practices which may improve soil SOC that may avail phosphorus which results in sustainable crop production in Eastern Africa tea growing regions.

There were no significant responses on soil phosphorus to plucking intervals observed at all sites and depths considered. The results agree with previous study (Kwach *et al*., 2014) for mature leaf phosphorus but at variance with yields responses to plucking intervals (Owuor *et al*., 2000; Barua *et al*., 1986) and black tea quality (Owuor *et al*., 1997; Barua *et al*., 1986). The results suggest that at every region, the soil phosphorus levels were not influenced by the plucking intervals. Therefore, provided the management practices are uniform, harvesting intervals may have no effect on soil phosphorus.

There were significant interactions between nitrogen x plucking intervals at soil depths 10-20cm for Timbilil, Mulindi, Katoke, Maruku, depth 20-30cm at Changoi, Katoke, depth 40-60cm at Arroket, Kitabi, Mulindi, and Maruku and location x nitrogenous fertilizer rates at all depths for all sites means (Tables 14-17). The results supports early findings (Kwach *et* al., 2014) for mature leaf phosphorus.The current findings indicate that the soil phosphorus variations did not follow same pattern, implying that the observed responses were unique at every site. Therefore, each location may require specific management practices to realize sustainable crop productivity.

4.3.3 Soil Potassium Levels

The changes in soil potassium levels are presented in Tables 18-21. The levels were relatively below the critical levels (80-100 ppm) (Nazrul *et al*., 2013; Ruan *et al*., 2013) at 0-10 cm, as had also been recorded previously (Owuor *et al*., 2012; Nazrul *et al*., 2013; Kamau *et al*., 2003). This situation reversed at lower soil profiles indicating that there was a lot of leaching of the nutrients. Ammonium ion in the fertilizer is the same size as potassium ion (Buurman *et al.*, 1998) thus replacing potassium. Low soil pH at upper depths (Table 6-9) could have triggered the leaching of this nutrient thus reducing its available to the plant (Owuor *et al* 2012; Kebeney *et al.,* 2010). In addition, the low soil pH i.e. very high hydrogen ion concentration within the growing zone could also influence potassium availability (Sandanam *et al.*, 1980). Similarly, the increased levels of both manganese (Tables 46-49) and aluminium (Tables 30-33) at low pH (Tables 6-9) could have reduced the levels of potassium in tea soils. The decrease in potassium levels could be one of the causative factors to decline in crop productivity (Msomba *et al.*, 2014) observed in the region.

There were significant ($p \leq 0.05$) variations in soil potassium with locations (Tables 18-21), demonstrating the status of the nutrient are influenced by varying environmental and geological factors .The amounts of soil potassium monitored at each location were adequate and above the critical value (80-100 ppm) (Ruan *et al.*, 2013; Nazrul *et al.*, 2013) for tea soils except Katoke and Maruku at 0-10cm soil depth where the levels were below 80ppm. The results were at variance with mature leaf potassium (Kwach *et al.*, 2014) that showed insignificant site variations, but agrees with changes observed in plain black tea quality parameters (Owuor *et al.*, 2009; Owuor *et al.*, 2010) and fatty acids levels (Okal *et al.*, 2012). The variations in potassium levels with site suggest that the responses are site dependent and could be one of the causes in yields differences (Msomba *et al.*, 2014) in the region.

High rates of nitrogenous fertilizers reduced ($p \leq 0.05$) the soil potassium levels (Tables 18-21). Leaf potassium levels (Kwach *et al.*, 2014; Wanyoko *et al.*, 1992; Owuor *et al.*, 2012; Kebeney *et al.*, 2010; Kamau *et al.*, 2005) also decreased with increase in rates of the nitrogenous fertilizer. The decline in soil potassium could be due to enhanced leaching triggered by ammonium ion in nitrogen fertilizers (Wanyoko *et al.*, 1992; Owuor *et al.*, 2012). Potassium and ammonium ions have similar ionic radii; 0.133 nm and 0.143 nm for K^+ and NH_4^+ respectively (Buurman, *et al.*, 1998). The decline in soil potassium could also be possibly due to the displacement of potassium ion (K^+) by ammonium ions (NH_4^+) in the nitrogenous fertilizers since their size is almost the same (Owuor *et al.*, 2012). In addition, high concentations of hydrogen ions in low soil pH influence potassium levels (Sandanam *et al.*, 1980). In some locations there was initial rise in potassium at 75kgN followed by decrease. This was attributed to application of NPK(S) fertilizers which increased the nutrient levels. The increased ammonium nitrogen in the formulation accelerated leaching of potassium and hence its reduction at high levels of nitrogen rates. Since the levels of potassium and nitrogen antagonize each other (Owuor *et al.*, 1987; Brady and Weil, 1996), there maybe need to stagger the application of the two for the tea plant to benefit from each nutrient at a time.

Table 18: Responses of Tea Clone 6/8 Soil Potassium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 0 – 10 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean site**	**C.V %**
		0	75	150	225	300			
Timbilil	7	351	249	223	222	170	243	222	4
	14	375	182	171	165	150	209		
	21	182	286	237	202	162	214		
	Mean N rates	302	239	210	196	161			
	LSD,p≤0.05			13			NS		
Changoi	7	277	351	256	222	219	265	245	3
	14	337	180	159	130	133	188		
	21	224	490	272	221	203	282		
	Mean N rates	279	340	229	191	185			
	LSD,p≤0.05			9			NS		
Arroket	7	180	188	182	170	156	175	172	2
	14	176	167	179	169	171	172		
	21	186	167	155	176	162	169		
	Mean N rates	181	174	172	172	163			
	LSD,p≤0.05			6			NS		
Kitabi	7	96	101	56	41	36	66	80	7
	14	55	89	84	72	51	70		
	21	56	190	127	104	45	104		
	Mean N rates	69	127	89	72	44			
	LSD,p≤0.05			7			NS		
Mulindi	7	90	81	69	53	44	68	80	6
	14	114	86	68	60	48	75		
	21	72	157	100	85	76	98		
	Mean N rates	92	108	79	66	56			
	LSD,p≤0.05			6			NS		
Katoke	7	61	73	66	60	32	58	62	
	14	71	75	72	69	47	67		
	21	89	77	59	42	39	61		
	Mean	73	75	66	57	39			
	LSD,p≤0.05			6			NS		
Maruku	7	112	96	80	38	37	72	78	4
	14	107	104	99	50	37	79		
	21	120	108	107	48	32	83		
	Mean N rates	113	103	95	45	35			
	LSD,p≤0.05			8			9		
	Nxpl frq			11					
Mean for all 7 Sites	7	185	185	153	140	120	157	153	4
	14	196	145	138	120	127	145		
	21	148	221	159	141	124	159		
	Nrates	176	184	150	134	123			
LSD,p≤0.05			3.2				NS	3.3	
			Site x Nrates = 6.3						

*Insignificant interactions are not shown

Table 19: Responses of Tea Clone 6/8 Soil Potassium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 10 – 20 cm)

Site	Plucking Frq(dys)	Nitrogen Rates(KgN/ha/year)					Mean Pl Frq	Mean Site	C.V %
		0	75	150	225	300			
Timbilil	7	384	364	195	192	114	250	232	4
	14	347	297	185	165	145	228		
	21	319	203	211	179	179	218		
	Mean N rates	350	288	197	179	146			
	LSD,$p \leq 0.05$			10			12		
Changoi	7	480	566	212	196	225	336	283	2
	14	337	316	288	190	107	248		
	21	257	339	270	252	208	265		
	Mean N rates	358	407	257	213	180			
	LSD,$p \leq 0.05$			9			NS		
Arroket	7	169	205	206	183	161	185	175	3
	14	151	174	171	164	161	164		
	21	175	148	182	173	205	176		
	Mean N rates	165	176	185	173	176			
	LSD,$p \leq 0.05$			6			NS		
Kitabi	7	32	91	82	79	77	72	87	4
	14	39	122	119	84	47	82		
	21	117	159	129	70	58	107		
	Mean N rates	63	124	110	78	61			
	LSD,$p \leq 0.05$			8			NS		
Mulindi	7	156	148	136	55	78	114	82	13
	14	132	55	50	46	44	65		
	21	78	115	47	38	45	65		
	Mean N rates	122	106	77	47	56			
	LSD,$p \leq 0.05$			13			NS		
Katoke	7	88	85	80	76	69	79	79	6
	14	87	77	76	71	62	74		
	21	88	88	85	84	76	84		
	Mean	87	83	80	77	69			
	LSD,$p \leq 0.05$			6			NS		
Maruku	7	107	105	101	93	91	99	88	6
	14	90	110	81	71	73	85		
	21	98	112	65	68	60	80		
	Mean N rates	98	109	82	77	75			
	LSD,$p \leq 0.05$			6			NS		
Mean for all 7 Sites	7	207	246	177	134	122	177	155	
	14	188	155	145	123	104	143		
	21	150	165	150	136	128	146		4
	Nrates	182	189	157	131	118			
LSD,$p \leq 0.05$				3			NS	4	

Site x Nrates = 6.7

[*] Insignificant interactions are not shown

Table 20: Responses of Tea Clone 6/8 Soil Potassium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 20 – 30 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year**					**Mean Pl Frq**	**Mean Site**	**C.V %**
		0	75	150	225	300			
Timbilil	7	322	274	268	162	144	234	233	4
	14	307	272	270	166	161	235		
	21	328	285	269	156	108	229		
	Mean N rates	319	277	269	161	138			
	LSD,p≤0.05			9			NS		
Changoi	7	397	374	277	285	294	277	305	2
	14	388	387	338	371	305	318		
	21	399	357	348	324	266	319		
	Mean N rates	395	373	321	327	288			
	LSD,p≤0.05			51			NS		
	Nxpl frq			74					
Arroket	7	155	278	181	188	167	194	177	2
	14	144	198	177	164	179	172		
	21	182	149	190	165	138	165		
	Mean N rates	160	208	182	172	161			
	LSD,p≤0.05			6			NS		
Kitabi	7	156	123	76	73	71	100	104	5
	14	75	187	134	82	74	110		
	21	131	149	92	90	51	103		
	Mean N rates	121	153	101	82	65			
	LSD,p≤0.05			7			NS		
Mulindi	7	137	213	212	155	115	166	195	3
	14	99	272	217	131	151	174		
	21	285	374	261	201	100	244		
	Mean N rates	174	286	230	162	122			
	LSD,p≤0.05			9			NS		
Katoke	7	138	72	72	66	63	82	84	
	14	172	66	65	59	46	82		
	21	173	71	70	66	65	89		
	Mean	161	70	69	64	58			
	LSD,p≤0.05			4			NS		
	Nxpl frq			6					
Maruku	7	140	175	136	140	141	146	131	8
	14	128	152	134	126	107	129		
	21	118	126	124	122	94	117		
	Mean N rates	129	151	131	129	114			
	LSD,p≤0.05			10			NS		
	Nxpl frq			11					
Mean for all 7 Sites	7	174	215	179	141	123	166		3
	14	148	184	163	126	125	149		
	21	235	218	182	153	113	180		
	Nrates	186	206	175	140	120			
LSD,p≤0.05				3			NS	3	

Site x Nrates = 6

*Insignificant interactions are not shown

Table 21: Responses of Tea Clone 6/8 Soil Potassium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 40 – 60 cm)

Site	Plucking Frq(dys)	Nitrogen Rates(KgN/ha/year)					Mean Pl frq	Mean site	C.V. %
		0	75	150	225	300			
	7	320	287	271	241	125	249	247	4
	14	288	276	268	253	149	247		
Timbilil	21	319	296	288	186	135	245		
	Mean N rates	309	286	276	227	136			
	LSD,p≤0.05			9			NS		
	7	333	537	448	289	272	376	360	13
	14	332	286	280	246	225	274		
	21	625	493	386	348	295	429		
Changoi	Mean N rates	430	439	371	295	264			
	LSD,p≤0.05			8			NS		
	7	100	109	123	110	102	109	177	3
	14	112	296	293	126	285	222		
	21	364	127	128	248	126	199		
Arroket	Mean N rates	192	177	181	161	171			
	LSD,p≤0.05			8			NS		
	7	131	281	276	97	63	169	133	7
	14	135	114	109	102	100	112		
Kitabi	21	116	138	133	106	91	117		
	Mean N rates	127	178	172	101	85			
	LSD,p≤0.05			0.2			NS		
	7	237	210	203	144	85	176	151	8
	14	88	242	120	151	113	143		
Mulindi	21	123	166	124	152	114	136		
	Mean N rates	149	206	149	149	104			
	LSD,p≤0.05			16			NS		
	7	178	108	73	69	62	98	89	5
	14	171	117	66	44	26	85		
Katoke	21	165	109	64	59	30	85		
	Mean	171	111	68	57	39			
	LSD,p≤0.05			4			NS		
	7	238	228	220	210	182	216	199	6
	14	242	235	231	173	188	214		
Maruku	21	190	181	164	160	148	169		
	Mean N rates	223	215	205	181	173			
	LSD,p≤0.05			NS			NS		
Mean for all	7	133	165	144	132	119	139		
7 Sites	14	111	203	168	143	142	153	149	
	21	184	171	149	158	113	155		11
	Nrates	142	179	154	144	125			
LSD,p≤0.05				8			NS	8	
		Site x Nrates =16							

*Insignificant interactions are not shown

There were no significant responses in soil potassium to intervals of harvesting except at Timbilil 10-20 cm soil depths where there was significant decrease. However, the response appeared sporadic. The factors responsible for the variations at Timbilil were not understood since all regions received same treatments. The other sites showed sporadic patterns whose causes were not identified and needs more experiments to establish them. The results are in agreement with previous work (Kwach *et al.*, 2014) for mature leaf potassium with harvesting intervals. Therefore, harvesting intervals may have little or no influence on availability of tea soil potassium in the Eastern Africa. However, there were observed significant ($p \leq 0.05$) interaction effects on soil potassium between sites x nitrogenous fertilizer rates at all depths for all sites means and N x plucking intervals at Maruku 0-10cm, Changoi, Katoke, Maruku 20-30cm soil depths as had also been shown elsewhere for mature leaf potassium (Kwach *et al.*, 2014). Thus the results suggest that the responses varied from site to site. This indicates that factors influencing the availability of soil potassium were not the same in all the regions of the area.

4.3.4 Soil Calcium

The changes in soil calcium with location, nitrogenous fertilizer rates and plucking intervals are presented in Tables 22-25. There was a general increase of calcium levels in the lower soil profile compared to the upper layers. At each site, lower depths tended to record higher amounts of the nutrient. This could be explained by enhanced leaching of calcium to deeper soil horizons. These results agree with previous findings (Dogo *et al.* 1994; Kamau *et al.*, 1998; Kebeney *et al.*, 2010) .This could be as a result of leaching of the nutrient into the lower depths as a result of higher acidity (Tables 6-9) at the top soil levels.

Soil calcium contents (Table 21-24) changed ($P \leq 0.05$) with location of production. Calcium levels were highest in Mulindi and lowest at Katoke at all studied soil depths. Similar results for soil calcium had been observed in earlier studies (Adiloğlu and Adiloğlu, 2006; Kebeney *et* al., 2010; Kamau *et al.*, 1998). These patterns followed closely those observed in the mature leaf where leaf calcium levels varied with locality (Kwach *et al.*, 2012; Adiloğlu and Adiloğlu, 2006). These differences demonstrate that environmental and geological factors influence calcium levels in the soil, emphasising how the nutrient reserves in the soils are variable.

The increased nitrogen rates (Table 21-24) decreased ($p \leq 0.05$) soil calcium at 0-10 cm and 10-20 cm but the changes were insignificant at 20-30 cm and 40-60 cm soil horizons as it had also been observed earlier (Kamau *et at.*, 1998; Owuor *et al.*, 1988; Dogo *et al.*, 1994). This could be due to increased acidity caused by nitrogenous fertilizers (Kebeney *et* al., 2010;

Owuor *et al*., 1988; Kamau *et at*., 1998). Similar patterns were observed for leaf calcium (Kwach *et al*., 2012; Wanyoko *et al*., 1992; Kamau, 2000) where increasing rates of nitrogen rates reduced mature leaf calcium contents. Too, low amount of soil calcium leads to deficiency and low tea yield (Sandanam *et al*., 1980). The results demonstrate that heavy application of nitrogen rates cause reduction in soil available calcium. This behaviuor might in the long run cause the nutrient deficiency in these regions and low yields, if calcium levels are not supplemented.

Plucking intervals did not cause significant variations in soil calcium levels at all sites and depths except at Arroket soil depth 0-10cm. The factors responsible for changes at Arroket were not clear as all sites received same treatments. Similar trends were observed for leaf calcium (Kwach *et al*., 2014) and yields (Msomba *et al*., 2014) where harvesting intervals had no influence. However, the results are at variance with Okal *et al*. (2012) where plucking intervals influenced fatty acid levels. The current result showed non-significant erratic patterns in all sites with increasing plucking intervals. Thus the results imply that harvesting intervals may have little influence on available soil calcium in the region.

There were significant ($p \leq 0.05$) interaction effects on soil calcium levels between site x nitrogen rates for means of all sites at all soil depths except at 40-60 cm, site x plucking intervals, nitrogen rates x plucking intervals at depth 0-10cm for all sites means. Mature leaf calcium (Kwach *et al*., 2014) and fatty acid levels (Okal *et al*., 2012a) showed similar interactions between nitrogen and site. This demonstrates the responses varied from site to site indicating differences in patterns of change in the observed variations of soil calcium and implies that the factors affecting calcium availability changes varied with area of production. Thus each location may require different nitrogen application rates and harvesting intervals. The results demonstrate the need to establish the optimum levels of available soil calcium contents at each location for sustainable tea yields.

Table 22: Responses of Tea Clone 6/8 Soil Calcium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 0 – 10 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean Site**	**C.V. %**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	783	670	519	478	521	594	465	6
	14	641	471	416	392	257	435		
	21	557	365	318	309	286	367		
	Mean N rates	660	502	418	393	355			
	LSD,p≤0.05			38			NS		
	Nxpl frq			55					
Changoi	7	385	366	286	192	169	280	333	2
	14	346	331	299	278	258	303		
	21	500	479	459	358	286	416		
	Mean N rates	410	392	348	276	238			
	LSD,p≤0.05			9			NS		
Arroket	7	852	552	440	269	307	484	624	15
	14	972	885	881	751	648	827		
	21	766	659	470	331	579	561		
	Mean N rates	863	699	597	450	511			
	LSD,p≤0.05			122			176		
Kitabi	7	181	172	170	160	151	167	156	4
	14	174	190	141	123	149	155		
	21	128	165	150	155	138	147		
	Mean N rates	161	175	154	146	146			
	LSD,p≤0.05			7			NS		
Mulindi	7	1465	1463	1361	1315	738	1268	1249	1
	14	1410	1443	1265	972	873	1193		
	21	1642	1431	1330	1110	914	1286		
	Mean N rates	1505	1446	1319	1133	842			
	LSD,p≤0.05			11			NS		
Katoke	7	293	293	264	244	204	260	244	3
	14	265	224	220	223	204	227		
	21	277	176	282	257	233	245		
	Mean	278	231	255	241	214			
	LSD,p≤0.05			8			NS		
Maruku	7	290	215	206	201	191	221	222	9
	14	278	234	202	210	183	221		
	21	286	248	183	221	184	224		
	Mean N rates	285	232	197	211	186			
	LSD,p≤0.05			25			NS		
Mean for all 7 Sites	7	607	533	464	409	326	468	471	9
	14	584	540	489	421	367	480		
	21	594	503	456	392	374	464		
	Nrates	595	525	470	407	356			
LSD,p≤0.05				NS			24		

Site x Nrates=39, Site x Pl frq =5, N rates x Pl frq =29

*Insignificant interactions are not shown

Table 23: Responses of Tea Clone 6/8 Soil Calcium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 10 – 20 cm)

Site	Plucking Frq(dys)	Nitrogen Rates(KgN/ha/year)					Mean Pl Frq	Mean Site	C.V %
		0	75	150	225	300			
Timbilil	7	655	451	312	235	157	362	290	6
	14	391	361	260	172	189	275		
	21	330	325	234	150	133	234		
	Mean N rates	459	379	269	186	159			
	LSD,p≤0.05			22			NS		
Changoi	7	667	529	460	445	531	526	447	1
	14	530	484	386	375	418	438		
	21	455	486	461	289	187	376		
	Mean N rates	551	500	436	369	379			
	LSD,p≤0.05			8			NS		
Arroket	7	857	837	869	771	671	801	745	1
	14	847	814	641	552	528	676		
	21	980	848	755	687	521	758		
	Mean N rates	894	833	755	670	573			
	LSD,p≤0.05			10			NS		
Kitabi	7	150	154	146	150	146	149	136	6
	14	173	163	134	89	79	127		
	21	126	196	146	108	86	133		
	Mean N rates	150	171	142	116	104			
	LSD,p≤0.05			10			NS		
Mulindi	7	1310	1213	1182	1172	1150	1205	1486	1
	14	1811	1768	1554	1445	1257	1567		
	21	2013	1733	1656	1579	1444	1685		
	Mean N rates	1711	1572	1464	1398	1284			
	LSD,p≤0.05			11			NS		
Katoke	7	281	254	181	143	150	202	218	
	14	291	258	249	189	153	228		
	21	220	254	232	221	199	225		
	Mean	264	255	221	184	167			
	LSD,p≤0.05			20			25		
Maruku	7	285	227	213	192	187	221	221	4
	14	282	287	232	197	164	232		
	21	253	214	203	207	177	211		
	Mean N rates	273	243	216	199	176			
	LSD,p≤0.05			12			NS		
Mean for all 7 Sites	7	601	524	481	444	427	495	506	
	14	618	591	494	431	398	506		
	21	625	580	527	462	392	517		2
	Nrates	615	565	500	446	406			
LSD,p≤0.05				5			NS	6	
			Site x Nrates=10						

*Insignificant interactions are not shown

Table 24: Responses of Tea Clone 6/8 Soil Calcium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 20 – 30 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean Site**	**C.V %**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	491	450	362	271	251	365	335	2
	14	305	305	275	303	205	279		
	21	371	360	398	370	305	361		
	Mean N rates	389	372	345	315	254			
	LSD,p≤0.05			NS			NS		
Changoi	7	471	427	383	450	342	415	391	2
	14	469	378	434	279	264	365		
	21	532	429	359	330	322	394		
	Mean N rates	490	411	392	353	309			
	LSD,p≤0.05			NS			NS		
Arroket	7	867	913	884	769	588	804	878	1
	14	990	1012	889	820	776	897		
	21	1112	1053	912	887	690	931		
	Mean N rates	990	993	895	825	685			
	LSD,p≤0.05			NS			NS		
Kitabi	7	169	151	136	128	112	139	144	5
	14	161	232	178	166	137	175		
	21	88	109	137	130	125	118		
	Mean N rates	139	164	150	141	125			
	LSD,p≤0.05			NS			NS		
Mulindi	7	1880	1781	1810	1576	1244	1658	1632	1
	14	1933	1881	1810	1742	1538	1781		
	21	1884	1787	1240	1210	1165	1457		
	Mean N rates	1899	1816	1620	1509	1316			
	LSD,p≤0.05			NS			NS		
Katoke	7	269	225	217	185	177	215	197	3
	14	262	194	189	167	162	195		
	21	230	188	175	166	151	182		
	Mean	254	203	193	173	163			
	LSD,p≤0.05			NS			NS		
Maruku	7	282	238	231	213	205	234	234	3
	14	287	249	230	185	148	220		
	21	292	266	245	230	210	249		
	Mean N rates	287	251	235	210	188			
	LSD,p≤0.05			NS			NS		
Mean for all 7 Sites	7	633	598	575	514	417	547	544	
	14	630	607	572	523	462	559		
	21	644	599	495	475	424	527		
	Nrates	636	601	547	504	434			
LSD,p≤0.05				NS			NS	4	
				Site x Nrates = 7					

*Insignificant interactions are not shown

Table 25: Responses of Tea Clone 6/8 Soil Calcium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 40 – 60 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean Site**	**C.V %**
		0	**75**	**150**	**225**	**300**			
	7	626	479	386	233	183	381		
	14	420	282	270	185	261	284	340	2
Timbilil	21	387	327	387	383	285	354		
	Mean N rates	477	363	348	267	243			
	LSD,p≤0.05			NS			NS		
	7	563	571	507	471	446	512		
	14	347	645	514	397	339	448	490	2
Changoi	21	646	582	480	455	388	510		
	Mean N rates	519	600	500	441	391			
	LSD,p≤0.05			NS			NS		
	7	825	819	811	784	649	778		
	14	940	913	838	815	748	851	900	1
Arroket	21	1324	1117	1107	985	832	1073		
	Mean N rates	1030	950	919	861	743			
	LSD,p≤0.05			NS			NS		
	7	91	208	177	160	157	159		
	14	138	207	182	182	173	176	170	5
Kitabi	21	198	183	180	156	160	175		
	Mean N rates	142	199	180	166	163			
	LSD,p≤0.05			NS			NS		
	7	2483	2383	2410	2311	1730	2263		
	14	2219	1985	1791	2109	1785	1978	2053	4
Mulindi	21	2385	2135	1812	1672	1581	1917		
	Mean N rates	2362	2168	2004	2030	1699			
	LSD,p≤0.05			NS			NS		
	7	281	193	187	173	169	201		
	14	290	246	176	173	157	209	206	5
Katoke	21	291	261	173	1179	135	208		
	Mean	287	233	179	175	154			
	LSD,p≤0.05			NS			NS		
	7	292	291	263	245	195	257		
	14	293	258	248	236	210	249		
Maruku	21	295	265	246	224	214	249	252	3
	Mean N rates	293	271	252	235	206			
	LSD,p≤0.05			NS			NS		
Mean for all	7	737	706	677	618	511	650		
7 Sites	14	664	648	574	596	514	599		
	21	789	696	626	565	528	641	630	1
	Nrates	730	683	626	593	518			
LSD,p≤0.05				NS			NS	4	

Site x Nrates=NS

*Insignificant interactions are not shown

4.3.5 Soil Magnesium Levels

The effects of sites, NPK(S) fertilizer rates and plucking frequencies on the soil magnesium levels are shown in Table 26- 29. There was a general increase in magnesium levels down the soil profiles. The results showed similar patterns as observed in previous studies (Wanyoko *et al*., 1997; Kebeney *et al*., 2010). Low soil pH and high rainfall observed in the sites under study triggers leaching of the nutrient (Do *et al*., 1980) into the depths lower in the soil profiles.

Soil magnesium levels changed ($p \leq 0.05$) with location of production (Table 26-29). Arroket and Mulindi recorded higher ($p \leq 0.05$) values compared to the othe sites. These changes observed with locations follow those in mature leaf magnesium levels (Kwach *et al*., 2014; Kebeney *et al*., 2010; Adiloğlu and Adiloğlu, 2006), demonstrating difference in responses of the nutrient with site of production. These variations observed could be attributed to differences in climatic factors and soil chemical characteristics like pH (Venkatesan, 2006) and organic carbon (Dudal and Deckers, 1993; Karlen *et al*., 1997; Adanu and Aliyu, 2012). The soil pH levels (Tables 6-9) and organic carbon contents (Tables 2-5) might have contributed to the patterns observed for magnesium levels. The results demonstrate that locations with high SOC contents like Mulindi had relatively high magnesium levels compared to other regions. And soil organic carbon could enhance magnesium levels in tea soils.

Magnesium contents in the soil decreased linearly with increasing nitrogen fertilizer rates (Tables 26-29). The effects were significant ($p \leq 0.05$) at 0-10 cm soil depth but the changes in lower profiles were insignificant. The results agree with early work (Wanyoko *et al*., 1997, 1992; Kebeney *et al*., 2010; Ruan *et al*., 2006) where increased nitrogenous fertilizer rates reduced soil magnesium contents. This pattern observed was repeated at all sites. These results follow what was observed in mature leaf (Kwach *et al*., 2014; Kebeney*et al*., 2010; Wanyoko *et al*., 1992) and young leaf (Wanyoko *et al*., 1992) where magnesium levels declined linearly with increased nitrogen fertilizer rates. The significantly lower levels of exchangeable magnesium in tea soils were possibly a result of depletion through the continuous harvesting of young shoots (Ranganathan and Natesan, 1985; Owuor *et al*., 2011a) and increased leaching due to soil acidification (Ramos and Varela, 1990; Owuor *et al*., 1997) and high rainfall. Therefore, high rates of nitrogen fertilizers applications (>250 KgN/ha/yr) lead to reduction in soil magnesium levels in tea farms in East African. This might be one of the causes for the variations in yields (Table 50) in the regions. These effects could be mitigated by application of magnesium fertilizers for farmers to realize economic benefits in tea production.

Table 26: Responses of Tea Clone 6/8 Soil Magnesium (ppm) Levels to Nitrogen Rates, Plucking Frequencies and Location (Depth: 0 – 10 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean Site**	**C.V. %**
		0	**75**	**150**	**225**	**300**			
	7	106	55	50	28	21	52		
	14	96	70	52	36	31	57		
Timbilil	21	85	77	75	57	51	69	59	4
	Mean N rates	96	68	59	40	34			
	LSD,p≤0.05			3			NS		
	7	57	93	75	62	55	68		
	14	69	66	78	55	45	63		
Changoi	21	70	81	64	38	26	56	62	8
	Mean N rates	65	80	72	51	42			
	LSD,p≤0.05			7			NS		
	7	244	230	176	151	144	189		
	14	205	114	95	64	60	108		
Arroket	21	218	223	132	72	46	138	145	5
	Mean N rates	222	189	134	96	84			
	LSD,p≤0.05			9			NS		
	7	78	65	91	61	59	71		
	14	91	81	56	54	66	69		
Kitabi	21	82	71	65	69	52	68	69	7
	Mean N rates	84	72	71	61	59			
	LSD,p≤0.05			7			NS		
	7	193	150	153	130	108	147		
	14	116	136	101	121	119	118		
Mulindi	21	140	118	103	96	95	110	125	5
	Mean N rates	149	134	119	116	107			
	LSD,p≤0.05			8			NS		
	7	135	93	83	82	62	91		
	14	91	89	80	75	70	81		
Katoke	21	136	107	97	89	76	101	91	6
	Mean N rates	121	97	86	82	69			
	LSD,p≤0.05			7			NS		
	7	133	97	90	82	65	93		
	14	128	114	93	86	79	100		
Maruku	21	93	134	116	92	85	104	99	6
	Mean N rates	118	115	100	86	77			
	LSD,p≤0.05			8			9		
Mean for all	7	135	112	103	85	74	102		
7 Sites	14	114	96	79	70	67	85		
	21	118	116	93	74	62	92		6
	Nrates	122	108	92	77	67			
LSD,p≤0.05			3				6	3	
			Site x Nrates=5						

*Insignificant interactions are not shown

Table 27: Responses of Tea Clone 6/8 Soil Magnesium (ppm) Levels to Nitrogen Rates, Plucking Frequencies and Location (Depth: 10 – 20 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean Site**	**C.V %**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	103	50	49	31	28	52	53	3
	14	76	54	44	32	22	46		
	21	71	72	64	56	46	62		
	Mean N rates	83	59	52	40	32			
	LSD,p≤0.05			NS			NS		
Changoi	7	123	97	88	68	53	86	72	8
	14	108	92	91	53	50	79		
	21	85	67	41	35	30	52		
	Mean N rates	105	86	73	52	44			
	LSD,p≤0.05			NS			NS		
Arroket	7	176	162	163	115	75	138	151	14
	14	187	156	175	112	77	142		
	21	179	158	179	190	155	172		
	Mean N rates	181	159	173	139	102			
	LSD,p≤0.05			NS			NS		
Kitabi	7	86	73	69	64	58	70	76	7
	14	78	94	71	58	76	75		
	21	104	91	77	62	87	84		
	Mean N rates	89	86	72	61	74			
	LSD,p≤0.05			NS			NS		
Mulindi	7	204	181	159	138	113	159	139	6
	14	204	177	146	110	85	145		
	21	159	137	108	84	75	113		
	Mean N rates	189	165	138	111	91			
	LSD,p≤0.05			NS			NS		
Katoke	7	79	78	72	63	56	70	68	9
	14	82	71	59	64	55	66		
	21	83	77	77	67	61	73		
	Mean	81	75	69	65	58			
	LSD,p≤0.05			NS			NS		
Maruku	7	123	113	96	90	88	102	97	6
	14	106	104	91	80	76	91		
	21	125	109	90	86	74	97		
	Mean N rates	118	109	93	85	79			
	LSD,p≤0.05			NS			9		
	Nxpl frq			10					
Mean for all 7 Sites	7	128	108	99	81	67	97		
	14	120	107	97	73	63	92		
	21	115	102	91	83	75	93		
	Nrates	121	105	96	79	69			11
LSD,p≤0.0				NS			5	4	
			Site x Nrates = 10						

*Insignificant interactions are not shown.

Table 28: Responses of Tea Clone 6/8 Soil Magnesium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 20 – 30 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean site**	**C.V %**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	75	63	47	34	32	50	62	3
	14	72	76	79	66	54	70		
	21	65	92	76	55	46	67		
	Mean N rates	70	77	67	52	44			
	LSD,p≤0.05			NS			NS		
Changoi	7	137	138	84	62	72	99	104	7
	14	121	109	118	111	92	110		
	21	125	110	90	99	90	103		
	Mean N rates	128	119	98	91	85			
	LSD,p≤0.05			NS			NS		
Arroket	7	241	209	186	161	135	186	203	4
	14	184	289	253	228	202	231		
	21	258	190	178	167	160	191		
	Mean N rates	228	229	206	185	166			
	LSD,p≤0.05			NS			NS		
Kitabi	7	73	86	68	52	69	70	76	8
	14	83	84	75	77	63	76		
	21	87	93	92	75	61	81		
	Mean N rates	81	88	78	68	64			
	LSD,p≤0.05			NS			NS		
Mulindi	7	217	203	189	183	165	191	171	4
	14	214	185	174	137	149	172		
	21	219	168	155	113	88	149		
	Mean N rates	217	185	173	144	134			
	LSD,p≤0.05			NS			NS		
Katoke	7	80	79	71	63	54	70	66	8
	14	85	67	67	62	54	67		
	21	83	67	61	55	49	63		
	Mean	82	71	66	60	52			
	LSD,p≤0.05			NS			NS		
Maruku	7	115	99	87	72	77	90	85	10
	14	100	89	76	80	69	83		
	21	107	94	77	67	62	81		
	Mean N rates	107	94	80	73	69			
	LSD,p≤0.05			NS			NS		
Mean for all 7 Sites	7	134	125	105	90	86	108		
	14	123	129	120	109	98	116		
	21	135	116	104	90	79	105		
	Nrates	130	123	110	96	88			
LSD,p≤0.05				NS			NS	NS	

*Insignificant interactions are not shown

Table 29: Responses of Tea Clone 6/8 Soil Magnesium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 40 – 60 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean Site**	**C.V. %**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	97	64	53	44	46	61	68	3
	14	66	83	85	72	65	74		
	21	71	82	74	64	49	68		
	Mean N rates	78	76	71	60	53			
	LSD,$p \leq 0.05$			NS			NS		
Changoi	7	112	99	85	72	65	87	95	7
	14	126	114	91	109	86	105		
	21	131	113	91	74	61	94		
	Mean N rates	123	109	89	85	71			
	LSD,$p \leq 0.05$			NS			NS		
Arroket	7	107	181	192	172	171	165	134	4
	14	109	167	83	74	70	101		
	21	110	189	181	114	85	136		
	Mean N rates	109	179	152	120	109			
	LSD,$p \leq 0.05$			NS			NS		
Kitabi	7	92	91	86	77	68	83	74	8
	14	70	75	62	71	58	67		
	21	91	80	77	52	52	71		
	Mean N rates	85	82	75	67	59			
	LSD,$p \leq 0.05$			NS			NS		
Mulindi	7	248	221	203	187	157	203	223	3
	14	281	255	236	213	173	232		
	21	282	256	225	217	195	235		
	Mean N rates	270	244	221	206	175			
	LSD,$p \leq 0.05$			NS			NS		
Katoke	7	70	65	63	61	56	63	64	7
	14	69	66	62	58	55	62		
	21	87	73	66	60	46	66		
	Mean	75	68	64	60	52			
	LSD,$p \leq 0.05$			NS			7		
Maruku	7	117	100	92	84	80	95	93	7
	14	108	103	87	76	78	90		
	21	111	98	94	85	79	94		
	Mean N rates	112	100	91	82	79			
	LSD,$p \leq 0.05$			NS			NS		
Mean for all 7 Sites	7	120	117	111	100	92	108		
	14	118	124	101	96	83	105		
	21	126	127	116	95	81	109		
	Nrates	122	123	109	97	85			
LSD,$p \leq 0.05$				NS			NS	NS	

[*] Insignificant interactions are not shown

Harvesting intervals did not cause significant ($p \leq 0.05$) change on soil magnesium levels except at Maruku at soil depths 0-10cm and 10-20cm. The factors responsible for the variations at Maruku were not understood since all locations received same treatments. The patterns were sporadic at almost all the sites. The observations agree with what had also been observed on mature leaf magnesium levels (Kwach *et al.*, 2014) and yields (Msomba *et al.*, 2014), where variations to plucking intervals were insignificant. The results demonstrate that plucking intervals does not influence magnesium leves in the region. These variations could be attributed to varying climatic conditions experienced at each site of production. The erratic patterns need more experiments to establish their causes.

The interaction effects for soil magnesium levels were insignificant except at Maruku soil depth 10-20 cm between nitrogen rates x plucking intervals and nitrogen rates x site for means of all sites at soil depth 0-10 cm and 10-20 cm. Therefore, the results demonstrate that the responses varied from site to site suggesting that factors influencing soil magnesium levels changed with location of production. Similar patterns were observed for mature leaf magnesium (Kwach *et al.*, 2014) and yields (Msomba *et al.*, 2014) where differences in the pattern of response changed with sites leading to significant interactions effects. These significant interactions imply that at different sites variations due to the two variables did not always follow the same patterns. This could be one of the reasons why there were insignificant responses in soil magnesium to plucking intervals. Nitrogen rates decreased ($p \leq 0.05$) soil magnesium levels at some sites while at others the responses were not significant. Thus even with uniform nitrogen fertilizer rates and harvesting intervals, soil magnesium responses would be different. Therefore, each location may require different nitrogen rates and plucking interval for magnesium levels to realize sustainable crop productivity.

4.3.6 Soil Aluminium Levels

Tables 30-33 show the effects of sites, NPK(S) fertilizer rates and plucking frequencies on the soil extractable aluminium levels at the four soil depths. There was a general decrease in aluminium levels down the soil profiles. These results confirm what was observed earlier in tea soils (Owuor and Cheruiyot, 1989; Ruan *et al.*, 2006) where aluminium levels were higher in the upper soil layers compared to the lower depths. This could be attributed to low soil pH (Ruan *et al.*, 2004; Tachibana *et al.*, 1995), litter fall and decomposition (Wang *et al.*, 1997; Ruan and Wong 2001; Wong *et al.*, 1998) and tea prunings left *in situ* (Ruan *et al.*, 2006; Wang *et al*., 1997). Aluminium reduces uptake of potassium (Ishigaki, 1972; Matsumoto and Yamaya, 1986) and calcium (Memon *et al*., 1981; Korcak, 1984) by tea. Therefore, the accumulation of aluminium levels at the upper soil depths might interfere with the uptake of base ions and lead to reduced crop productivity.

Significant ($p \leq 0.05$) changes were observed in aluminium levels with location of production except at soil layer 40-60 cm. At each site there was an observed decrease in aluminium concentrations down the soil profiles as had also been recorded previously (Owuor and Cheruiyot, 1989; Ruan *et al*., 2006). Increased levels of soil aluminium were also observed at different locations from tea plantations of different ages (Ding and Huang, 1991). Mature leaf aluminium levels (Ruan *et al*., 2006; Wong *et al*., 1998) varied with location of production. The variable aluminium levels in different regions may influence the plant uptake of aluminium and consequently, crop productivity.

Increasing rates of nitrogen fertilizer increased ($p \leq 0.05$) aluminium contents at all sites. There appeared to be an increase in soil aluminium levels with increase in applied rates of nitrogen and at all sites means except at depth 40-60cm. The results agree with previous studies (Owuor and Cheruiyot, 1989; Ruan *et al*., 2004; Ruan *et al*., 2006) where increasing rates of nitrogen improved the levels of aluminium in tea soils. Increased nitrogen fertilizer rates decrease soil pH (Wanyoko *et al*., 1992; Bhavanandan and Sunderlingham, 1971) influencing availability of aluminium (Bhattacharrya *et al*., 1983; Owuor *et* al., 1990; Aitken, 1992) and hence the observed linear increase in the aluminium content at each site. In Russia, Sarishvili and Egorashvili (1978) noted that raising rates of nitrogen from 100 to 500 kg N/ha/year caused an increase in soil-available aluminium. However, increasing rates of nitrogenous fertilizers reduced the total aluminium in black teas (Owuor *et al*., 1990). And no significant relationship was noted between tasters' evaluation with total aluminium in tea or aluminium in infused liquors (Owuor *et al*., 1990). In young tea plants, the growth rate is accelerated by addition of aluminium (Matsumoto *et al*., 1976; Ishigaki, 1984; Kinoshi *et al*., 1985), suggesting that aluminium could be an essential nutrient for tea. If the soil pH continues to decrease, aluminium contents might increase to toxic levels and affect tea productivity. Tea farmers should engage in management practices which may improve soil pH and lower aluminium contents for sustainable crop productivity.

Plucking intervals influenced ($p \leq 0.05$) soil Al levels at all sites except at Arroket at depth 0-10cm, but the patterns were erratic at all sites and depths. In different genotypes black tea quality and yields (Baruah *et al*., 1986; Owuor *et al*., 1997; Owuor *et al*., 2000) and fatty acids levels (Okal *et al*., 2012a) vary with plucking intervals. The sporadic patterns with plucking intervals for aluminium responses require monitoring the same experiments for longer periods to establish the factors responsible for those factors.

There were interaction effects ($p \leq 0.05$) between N rates x site, N rates x plucking intervals, site x N rates and site x N rates x plucking intervals on aluminium levels except at depth 20-30cm for all sites means where insignificant interactions were observed between Site x Plucking frequency, N rates x Plucking frequency, Site x N rates x plucking frequency. This demonstrates that the responses varied from site to site. Similar patterns were observed for yield responses (Msomba *et al*., 2014) and fatty acid levels (Okal *et al*., 2012a). Significant interactions were also noted between nitrogenous fertilizer rates and frequency of fertilizer application (Owuor *et al*., 1990) in black tea aluminium content.The significant interaction effects imply that at different locations variations due to nitrogen fertilizer rates and plucking intervals did not always follow the same patterns. Therefore, there is need to develop region specific nitrogen rates and plucking management practices to enhance yields in tea.

Table 30: Responses of Tea Clone 6/8 Soil Aluminium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 0 – 10 cm)

Site	Plucking Frq(dys)	Nitrogen Rates(KgN/ha/year)					Mean Pl Frq	Mean site	C.V.%
		0	75	150	225	300			
Timbilil	7	1630	1930	1880	1963	1988	1878	1861	7.91
	14	1487	1637	1887	2000	2117	1825		
	21	1630	1870	1980	1888	2027	1879		
	Mean N rates	1582	1812	1916	1951	2044			
	LSD,p≤0.05			19			23		
	Nxpl frq			28					
Changoi	7	1902	1966	2031	1952	2128	1996	1963	5.22
	14	1360	1915	1951	2089	1996	1862		
	21	2003	2038	2066	1963	2081	2030		
	Mean N rates	1755	1973	2016	2002	2068			
	LSD,p≤0.05			13			15		
	Nxpl frq			18					
Arroket	7	1147	1380	1389	1430	2612	1592	1610	7.77
	14	1430	1183	1580	1978	2043	1643		
	21	1382	1510	1732	1477	1878	1596		
	Mean N rates	1320	1358	1567	1629	2178			
	LSD,p≤0.05			127			NS		
	Nxpl frq			236					
Kitabi	7	1487	1509	1523	1529	1405	1490	1474	5.51
	14	1359	1477	1505	1548	1593	1496		
	21	1415	1285	1412	1513	1545	1434		
	Mean N rates	1420	1424	1480	1530	1514			
	LSD,p≤0.05			11			13		
	Nxpl frq			15					
Mulindi	7	996	1040	1177	1264	1375	1170	1157	7.64
	14	921	1113	1185	1272	1379	1174		
	21	986	1011	1152	1188	1304	1128		
	Mean N rates	967	1055	1171	1241	1353			
	LSD,p≤0.05			12			14		
	Nxpl frq			17					
Katoke	7	1219	1257	1289	1366	1402	1307	1428	7.52
	14	1347	1354	1431	1586	1467	1437		
	21	1518	1409	1561	1588	1624	1540		
	Mean	1361	1340	1427	1513	1498			
	LSD,p≤0.05			13			16		
	Nxpl frq			19					
Maruku	7	984	1112	1217	1386	1458	1231	1269	5.96
	14	1269	1288	1389	1426	1451	1364		
	21	1185	1218	1117	1256	1282	1212		
	Mean N rates	1146	1206	1241	1356	1397			
	LSD,p≤0.05			10			12		
	Nxpl frq			14					
Mean for all 7 Sites	7	1338	1456	1501	1556	1819	1534	1541	
	14	1310	1424	1561	1700	1721	1543		
	21	1446	1477	1575	1553	1677	1546		
	Nrates	1365	1452	1546	1603	1739			6.67
LSD,p≤0.05				5			6	5	
	Site x Nrates=10, Site x Pl frq =8, N rates x Pl frq =7, Site x N rates x pl frq=17								

Table 31: Responses of Tea Clone 6/8 Soil Aluminium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 10 – 20 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean site**	**C.V.%**
		0	75	150	225	300			
Timbilil	7	1630	1897	1887	1990	1913	1863	1754	6.73
	14	1570	1858	1790	1953	1888	1812		
	21	1580	1583	1530	1523	1713	1586		
	Mean N rates	1593	1779	1736	1822	1838			
	LSD,p≤0.05			15			19		
	Nxpl frq			22					
Changoi	7	1260	1362	1479	1890	1970	1592	1762	5.09
	14	1536	1870	1681	1894	1996	1795		
	21	1605	1866	1959	2024	2045	1900		
	Mean N rates	1467	1699	1706	1936	2004			
	LSD,p≤0.05			117			141		
	Nxpl frq			169					
Arroket	7	1239	1433	1391	1466	1495	1405	1471	6.22
	14	1206	1383	1434	1390	1463	1375		
	21	1433	1581	1682	1697	1766	1632		
	Mean N rates	1293	1466	1502	1518	1575			
	LSD,p≤0.05			12			14		
	Nxpl frq			17					
Kitabi	7	1180	1265	1310	1371	1498	1325	1419	6.37
	14	1310	1456	1476	1573	1487	1460		
	21	1390	1479	1511	1445	1535	1472		
	Mean N rates	1293	1400	1433	1463	1507			
	LSD,p≤0.05			12			14		
	Nxpl frq			17					
Mulindi	7	884	1254	1352	1485	1884	1372	1442	5.16
	14	913	1255	1460	1787	2019	1487		
	21	1171	1264	1554	1587	1760	1467		
	Mean N rates	989	1257	1455	1619	1888			
	LSD,p≤0.05			10			11		
	Nxpl frq			14					
Katoke	7	1221	1357	1385	1526	1566	1411	1578	5.45
	14	1326	1430	1309	1524	1572	1432		
	21	1783	1759	1797	2005	2107	1890		
	Mean	1443	1516	1497	1685	1748			
	LSD,p≤0.05			11			14		
	Nxpl frq			16					
Maruku	7	1152	1246	1285	1313	1335	1266	1267	8.54
	14	1223	1188	1276	1377	1414	1296		
	21	1118	1162	1254	1319	1346	1239		
	Mean N rates	1164	1199	1271	1336	1365			
	LSD,p≤0.05			26			31		
	Nxpl frq			37					
Mean for all 7 Sites	7	1224	1402	1441	1577	1666	1462	1527	
	14	1298	1491	1489	1643	1691	1522		
	21	1438	1528	1612	1652	1753	1597		
	Nrates	1320	1474	1514	1624	1704			10.9
LSD,p≤0.05				17			21	18	
	Site x Nrates=34, Site x Pl frq =28, N rates x Pl frq =11, Site x N rates x pl frq=58								

Table 32: Responses of Tea Clone 6/8 Soil Aluminium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 20 – 30 cm)

Site	Plucking Frq(dys)	Nitrogen Rates(KgN/ha/year)					Mean Pl Frq	Mean site	C.V.%
		0	75	150	225	300			
Timbilil	7	1243	1630	1613	1497	1635	1524	1575	8.37
	14	1550	1530	1437	1657	1695	1574		
	21	1433	1647	1603	1718	1742	1629		
	Mean N rates	1409	1602	1551	1624	1691			
	LSD,p≤0.05			18			22		
	Nxpl frq			26					
Changoi	7	1002	1253	1273	1738	1930	1439	1543	8.69
	14	886	1130	1453	1645	1897	1402		
	21	1638	1674	1655	1800	2163	1786		
	Mean N rates	1175	1352	1461	1728	1996			
	LSD,p≤0.05			18			22		
	Nxpl frq			26					
Arroket	7	879	1172	1223	1261	1285	1164	1111	7.89
	14	783	835	1173	1252	1208	1050		
	21	991	1106	1104	1145	1250	1119		
	Mean N rates	884	1038	1167	1219	1248			
	LSD,p≤0.05			11			14		
	Nxpl frq			17					
Kitabi	7	1103	1212	1246	1369	1358	1258	1247	5.64
	14	1051	1222	1272	1351	1332	1246		
	21	978	1070	1286	1387	1462	1237		
	Mean N rates	1044	1168	1268	1369	1384			
	LSD,p≤0.05			11			13		
	Nxpl frq			15					
Mulindi	7	833	1282	1389	1570	1748	1364	1380	6.60
	14	736	1410	1688	1871	1950	1609		
	21	865	1052	1282	1387	1633	1777		
	Mean N rates	811	1248	1453	1609	1777			
	LSD,p≤0.05			11			13		
	Nxpl frq			15					
Katoke	7	1020	1045	1206	1266	1287	1165	1289	5.64
	14	1344	1355	1271	1384	1416	1354		
	21	1243	1268	1322	1387	1524	1349		
	Mean	1202	1223	1266	1346	1409			
	LSD,p≤0.05			11			13		
	Nxpl frq			15					
Maruku	7	1223	1257	1281	1292	1322	1275	1215	6.64
	14	1116	1145	1183	1214	1246	1181		
	21	1136	1157	1175	1227	1254	1190		
	Mean N rates	1158	1186	1213	1244	1274			
	LSD,p≤0.05			10			13		
	Nxpl frq			15					
Mean for all 7 Sites	7	1039	1266	1323	1425	1505	1312	1363	
	14	1454	1211	1356	1487	1553	1412		
	21	1205	1307	1359	1432	1519	1364		
	Nrates	1233	1261	1346	1448	1526			13.3
LSD,p≤0.05			NS				NS	242	
			Site x Nrates= 458						

Table 33: Responses of Tea Clone 6/8 Soil Aluminium Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 40 – 60 cm)

Site	Plucking Frq(dys)	Nitrogen Rates(KgN/ha/year)					Mean Pl Frq	Mean site	C.V. %
		0	75	150	225	300			
Timbilil	7	1493	1558	1662	1677	1680	1614	1562	7.37
	14	1547	1630	1561	1508	1590	1567		
	21	1366	1387	1538	1574	1655	1504		
	Mean N rates	1469	1525	1587	1586	1642			
	LSD≤0.05			16			19		
	I.E≤0.05			23					
Changoi	7	1715	1600	1700	1725	1820	1712	1633	5.36
	14	1621	1659	1727	1793	1803	1721		
	21	1119	1159	1323	1792	1932	1465		
	Mean N rates	1485	1473	1583	1770	1852			
	LSD,p≤0.05			8			9		
	Nxpl frq			11					
Arroket	7	844	918	1091	1092	1172	1023	1062	7.35
	14	979	1040	1210	979	1232	1088		
	21	977	1041	1088	1138	1132	1075		
	Mean N rates	934	1000	1130	1070	1178			
	LSD,p≤0.05			10			13		
	Nxpl frq			15					
Kitabi	7	1003	1107	1167	1270	1338	1177	1231	9.28
	14	1060	1277	1386	1390	1473	1317		
	21	1113	1115	1199	1279	1290	1199		
	Mean N rates	1058	1166	1251	1313	1367			
	LSD,p≤0.05			15			18		
	Nxpl frq			21					
Mulindi	7	1022	1052	1112	1177	1253	1123	1175	4.79
	14	879	1028	1253	1217	1335	1257		
	21	1092	1113	1311	1378	1402	1330		
	Mean N rates	997	1064	1225	1257	1330			
	LSD,p≤0.05			7			9		
	Nxpl frq			10					
Katoke	7	1134	1088	1156	1186	1210	1155	1236	7.64
	14	1133	1173	1224	1253	1276	1212		
	21	1313	1334	1295	1377	1382	1340		
	Mean N rates	1193	1198	1225	1272	1289			
	LSD,p≤0.05			12			14		
	Nxpl frq			17					
Maruku	7	1054	1077	1095	1126	1151	1101	1137	7.55
	14	1132	1154	1185	1265	1276	1202		
	21	998	1045	1075	1153	1262	1107		
	Mean N rates	1061	1092	1118	1181	1230			
	LSD,p≤0.05			11			13		
	Nxpl frq			16					
Mean for all 7 Sites	7	1179	1200	1283	1322	1374	1272	1290	
	14	1193	1280	1364	1344	1426	1321		
	21	1140	1171	1261	1384	1436	1278		
	Nrates	1171	1217	1303	1350	1412			7.80
LSD,p≤0.05				4			5	5	

Site x Nrates = 9, Site x Pl frq = 7, N rates x Pl frq = 6,
Site x N rates x pl frq = 15

4.3.7 Soil Iron Levels

Soil iron is one of the essential micro-nutrients required by tea for its productivity (Özyazici *et al*., 2011). The limit value for soil iron are classified low when less than 2.5ppm and high when greater than 4.5ppm (Lindsay and Norvell, 1978). Soil iron levels (Table 34-37) were sufficient for all locations (Özyazici *et al*., 2011; Adiloğlu and Adiloğlu, 2006) for the tea production. There was an observed general increase of soil iron contents down the soil profiles as it had also been observed elsewhere (Sitienei *et al*., 2016; Kacar, 1984; Özyazici *et al*., 2011). These observations could be attributed to high levels of soil organic carbon (Table 2-5) in the four soil profiles and increase in pH in the soils which results in increased iron concentration in the soil (Nath, 2013). A complexation reaction occurs between iron and organic carbon and results in the retention of the micronutrient in the soil. Therefore, soil iron contents in tea farming could be improved with proper management of organic carbon levels. From the results, the iron content in the soils of the regions were above the critical value (Lindsay and Norvell, 1978) and as such iron may not be a constraining factor in tea production in Eastern Africa.

Iron contents of the soils investigated changed ($p \leq 0.05$) with location of production. Soil iron levels at Katoke and Maruku were relatively low, while Mulindi had the highest iron ($p \leq 0.05$) contents compared to the other sites. Iron levels decreased with soil depths except at Mulindi where the patterns showed opposite trend. Mulindi soils are peat soils characterized by high SOC contents explaining why its iron contents were different from the other sites. The patterns observed in six locations, (except at Mulindi), agree with what had also been obtained elsewhere (Dang, 2002) for soil iron, (Kumar *et al*., 2005; Kwach *et al*., 2014) for mature leaf iron levels and for iron contents in black tea (Omwoyo *et al*., 2014). These trends could be attributed to different climatic patterns and levels of soil organic carbon (Huang and Wang, 1997) where low iron contents at lower depths corresponds to a lower organic carbon contents with depths. The differences in soil iron levels recorded could be attributed to variations in soil organic carbon contents at each location. The significant variations in soil iron levels with location demonstrate how the iron reserves in the soils are variable. This could be one of the factors causing differences in yields observed in tea productivity within Eastern Africa (Msomba *et al*., 2014). The close association between soil organic carbon and iron levels imply the need for farmers to embrace management practices such as leaving tea prunings *in situ* which could improve organic carbon and consequently iron levels for sustainable tea productivity.

Iron increased (p≤0.05) with rise in nitrogenous fertiliser rates at all sites. Similar patterns were repeated for all sites values as had also been observed elsewhere (Gabisoniya *et al*., 1973; Sitienei *et al*., 2016). These patterns follow closely those observed in the mature leaf iron levels (Kwach *et* al., 2014) where iron levels increased with increase in nitrogen rates. Raised rates of nitrogen fertilizer lower soil pH and enhances solubilization of iron making it available to the tea crop (Nath, 2013). Therefore, the nutrient deficiency in tea plants can be corrected by surface application of nitrogenous fertilizers in all tea growing regions in East Africa.

Harvesting intervals had varied responses in soil iron levels. At soil depth 0-10cm changes in soil iron contents with harvesting intervals were insignificant at all locations and at Changoi, Kitabi soil depth 10-20cm (Table 34), Kitabi and Maruku at depth 40-60cm (Table 36). The rest of the sites and depths soil iron contents varied (p≤0.05) with harvesting intervals even though the order was sporadic. Overall the variations were also significant. The results were at variance with mature leaf iron (Kwach *et al*., 2014), yields (Msomba *et al*., 2014) where harvesting intervals to mature leaf iron and yields responses were insignificant respectively. However, the results agreed with fatty acids level (Okal *et al*., 2012a) and black tea quality (Owuor *et al*., 2000). Factors causing the sporadic patterns were not clearly understood and therefore, monitoring the same trials for longer periods is required to establish the factors responsible for the varied responses in soil iron levels with harvesting intervals.

There were interaction effects on soil iron levels between nitrogen rates x plucking intervals at Timbilil, Changoi all soil depths, Arroket, Katoke and Maruku at the last three soil depths, Kitabi soil depth 20-30cm, Mulindi depths 20-30cm and 40-60cm. Overall, there were significant (p≤0.05) interaction effects on soil iron levels between sites x nitrogen rates at all depths. The results are similar to the patterns observed for mature leaf iron (Kwach *et al*., 2014) and yield responses (Msomba *et al*., 2014). The significant interactions imply that at different locations the extent of variations due to the two variables did not always follow the same patterns. While nitrogen fertilizer rates increased (p≤0.05) soil iron contents at some sites, at some other locations the responses were insignificant. Although there were variations in soil iron with locations in all sites, the levels were above the critical limits (Lindsay and Norvell, 1978) for tea growing. Soil iron is therefore not a constraining factor to tea growing in Eastern Africa.

Table 34: Responses of Tea Clone 6/8 Soil Iron Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 0 – 10 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	89	100	140	165	138	126	142	6
	14	125	135	160	175	166	152		
	21	111	136	154	154	180	147		
	Mean N rates	108	124	151	164	161			
	LSD,p≤0.05			12			NS		
	N x Pl frq			17					
Changoi	7	107	95	104	115	181	120	109	7
	14	73	85	104	116	118	99		
	21	80	90	95	119	156	108		
	Mean N rates	86	90	101	117	151			
	LSD,p≤0.05			10			NS		
Arroket	7	60	123	134	155	171	129	110	5
	14	17	37	54	72	141	64		
	21	76	144	155	137	165	136		
	Mean N rates	51	101	114	122	159			
	LSD,p≤0.05			8			NS		
Kitabi	7	212	246	386	413	406	332	350	2
	14	337	340	371	388	391	365		
	21	269	274	390	407	415	351		
	Mean N rates	273	287	382	403	404			
	LSD,p≤0.05			10			NS		
Mulindi	7	329	357	381	394	401	372	354	5
	14	322	348	373	359	412	363		
	21	284	294	314	347	392	326		
	Mean N rates	312	333	356	366	401			
	LSD,p≤0.05			22			NS		
Katoke	7	16	26	59	82	93	55	59	10
	14	18	54	88	74	93	65		
	21	22	54	63	53	85	56		
	Mean Nrates	19	45	70	70	90			
	LSD,p≤0.05			8			9		
Maruku	7	20	28	38	64	117	53	60	10
	14	35	32	49	79	87	56		
	21	41	31	50	82	144	70		
	Mean N rates	32	30	46	75	116			
	LSD,p≤0.05			7			NS		
Mean for all 7 Sites	7	119	139	177	198	215	170		
	14	132	147	171	180	201	166		
	21	126	146	175	186	220	170		5
	Nrates	126	144	174	188	212			
LSD,p≤0.05				5			4	5	

Site x Nrates = 9

*Insignificant interactions are not shown

Table 35: Responses of Tea Clone 6/8 Soil Iron Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 10 – 20 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	88	105	105	120	123	108	118	8
	14	92	114	109	148	142	121		
	21	111	93	125	141	156	125		
	Mean N rates	97	104	113	137	140			
	LSD,p≤0.05			12			15		
	N x Pl frq			18					
Changoi	7	98	88	106	117	147	111	107	5
	14	85	110	118	87	130	106		
	21	106	66	108	121	112	103		
	Mean N rates	96	88	111	109	130			
	LSD,p≤0.05			7			NS		
	N x Pl frq			11					
Arroket	7	31	111	123	135	166	113	130	5
	14	125	123	133	154	172	142		
	21	66	127	161	157	172	137		
	Mean N rates	74	120	139	149	170			
	LSD,p≤0.05			8			12		
	N x Pl frq			12					
Kitabi	7	306	337	341	362	374	344	339	8
	14	293	313	334	353	333	325		
	21	280	341	378	380	352	346		
	Mean N rates	293	330	351	365	353			
	LSD,p≤0.05			34			NS		
Mulindi	7	336	362	375	389	412	375	374	2
	14	337	369	393	396	406	380		
	21	334	347	377	382	395	367		
	LSD,p≤0.05	336	359	382	389	404			
	N x Pl frq			9			11		
Katoke	7	20	43	65	69	74	54	55	9
	14	19	36	44	57	78	47		
	21	30	46	63	87	94	64		
	Mean N rates	23	42	57	71	82			
	LSD,p≤0.05			6			7		
	N x Pl frq			9					
Maruku	7	17	44	63	88	88	60	59	11
	14	22	34	47	70	78	50		
	21	21	45	60	88	116	66		
	Mean N rates	20	41	57	82	94			
	LSD,p≤0.05			9			11		
	N x Pl frq			13					
Mean for all 7 Sites	7	169	156	168	184	199	175		
	14	141	156	168	180	192	167		
	21	135	152	182	193	197	172		
	Nrates	148	155	173	186	196			
LSD,p≤0.05				26			NS	27	

Site x Nrates=51, Site x Pl frq =NS, N rates x Pl frq =57

*Insignificant interactions are not shown

Table 36: Responses of Tea Clone 6/8 Soil Iron Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 20 – 30 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates(KgN/ha/year)**					**Mean Pl Frq**	**Mean site**	**C.V%**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	103	111	113	115	133	115	113	8
	14	79	91	115	108	124	103		
	21	105	95	112	135	159	121		
	Mean N rates	95	99	113	119	138			
	LSD,p≤0.05			12			14		
	N x Pl frq			17					
Changoi	7	70	91	95	111	121	98	89	5
	14	68	91	103	115	111	98		
	21	47	59	69	87	96	72		
	Mean N rates	62	80	89	104	109			
	LSD,p≤0.05			6			8		
	N x Pl frq			9					
Arroket	7	115	113	127	143	172	134	135	4
	14	115	146	162	138	172	147		
	21	112	110	121	131	143	123		
	Mean N rates	114	123	137	137	162			
	LSD,p≤0.05			8			9		
	N x Pl frq			11					
Kitabi	7	271	314	348	365	351	330	315	5
	14	250	277	332	372	364	319		
	21	207	241	299	363	378	297		
	Mean N rates	243	277	326	366	364			
	LSD,p≤0.05			22			26		
	N x Pl frq			31					
Mulindi	7	348	388	412	582	583	463	462	1
	14	389	403	546	596	610	509		
	21	331	380	432	461	466	414		
	Mean N rates	356	390	463	546	553			
	LSD,p≤0.05			9			11		
	N x Pl frq			13					
Katoke	7	21	48	69	110	78	65	55	11
	14	21	32	62	87	89	58		
	21	18	13	38	59	80	41		
	Mean N rates	20	31	56	86	82			
	LSD,p≤0.05			8			9		
	N x Pl frq			11					
Maruku	7	24	28	39	50	69	42	44	13
	14	21	44	59	73	86	56		
	21	16	16	37	43	49	32		
	Mean N rates	20	29	45	55	68			
	LSD,p≤0.05			7			9		
	N x Pl frq			11					
Mean for all 7 Sites	7	136	156	172	211	215	178		
	14	135	155	197	213	222	184	173	
	21	119	131	158	183	196	157		5
	Nrates	130	147	176	202	211			
LSD,p≤0.05				4			NS	5	
		Site x Nrates = 9,							

Table 37: Responses of Tea Clone 6/8 Soil Iron Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 40 – 60 cm)

Site	Plucking Frq(dys)	Nitrogen Rates(KgN/ha/year)					Mean Pl Frq	Mean site	C.V%
		0	75	150	225	300			
Timbilil	7	98	97	91	119	148	111	99	6
	14	89	77	99	110	105	96		
	21	70	92	86	101	106	91		
	Mean N rates	85	89	92	112	120			
	LSD,p≤0.05			7			9		
	N x Pl frq			11					
Changoi	7	40	39	77	87	90	67	55	10
	14	54	30	36	57	82	52		
	21	20	38	44	49	82	46		
	Mean N rates	38	35	52	64	85			
	LSD,p≤0.05			7			9		
	N x Pl frq			11					
Arroket	7	116	126	131	104	152	126	121	4
	14	106	113	109	127	132	117		
	21	126	109	111	119	129	119		
	Mean N rates	116	116	117	116	138			
	LSD,p≤0.05			6			7		
	N x Pl frq			11					
Kitabi	7	269	309	345	347	367	327	303	9
	14	235	237	310	332	325	288		
	21	219	291	306	325	330	294		
	Mean N rates	241	279	320	334	341			
	LSD,p≤0.05			35			NS		
Mulindi	7	334	384	408	417	434	395	398	2
	14	361	378	391	409	429	394		
	21	384	392	400	424	433	407		
	Mean N rates	359	384	400	417	432			
	LSD,p≤0.05			10			12		
	N x Pl frq			15					
Katoke	7	29	49	66	76	92	63	57	9
	14	14	32	47	67	86	49		
	21	15	40	57	93	91	59		
	Mean N rates	20	40	57	79	90			
	LSD,p≤0.05			7			8		
	N x Pl frq			10					
Maruku	7	19	24	34	40	45	32	32	17
	14	14	12	28	42	51	30		
	21	13	25	27	47	55	33		
	Mean N rates	15	20	30	43	33			
	LSD,p≤0.05			7			NS		
	N x Pl frq			10					
Mean for all 7 Sites	7	129	147	165	170	190	160	152	
	14	125	125	146	163	173	146		
	21	121	141	147	165	175	150		8
	Nrates	125	138	153	166	179			
LSD,p≤0.05				6			NS	NS	

Site x Nrates=11, Site x Pl frq =NS, N rates x Pl frq =8

4.3.8 Soil Zinc Levels

The critical soil zinc levels are classified as ≤ 0.7 ppm- low, ≤ 2.4 ppm- sufficient and > 8.0 ppm –very high (Özyazici *et al.*, 2011). The available soil zinc contents in locations are presented in Tables 38-41. The levels ranged between low and sufficient with exceptions of Arroket and Mulindi which recorded very high levels at some depths. There was a general decrease in soil zinc levels down the soil profiles except at Mulindi and Katoke. The high organic carbon contents in the upper soil profiles (Tables 2-5) and low soil pH (Tables 6-9) could have led to improved availability of zinc as it had also been reported elsewhere (Zhang *et al.*, 2006; Nath, 2013). This is as a result of a complexation reaction which occurs between zinc and organic carbon resulting in the retention of the metal in the soil. In a study on the status of micronutrients in tea plantations, organic carbon of the soil was positively correlated with zinc levels (Nath, 2013). Increased soil zinc levels lead to improved yield and quality of tea (Sedaghathoor et al., 2009). This implies that continuous improvement of organic carbon will increase the soil zinc status in the soil and enhance crop productivity.

Zinc contents varied ($p \leq 0.05$) with location of production. These patterns followed closely what had also been observed in mature leaf zinc levels (Kwach *et al.*, 2014) and soil zinc levels (Adiloğlu and Adiloğlu, 2006) where zinc changed with site. The variations observed in tea soils studied demonstrate that the zinc reserves in the soils changed widely with locations and/or environmental factors controlling zinc were not constant in different locations. The zinc levels increased with increase in organic carbon content in the soil (Nath, 2013) and low pH (Özyazici *et al.*, 2011). The tea soils showing high levels of zinc contents, that is Mulindi and Arroket, had high organic carbon contents (Tables 2-5). The variations in soil zinc contents may be one of the factors responsible for variations in yields. Tea farmers may improve soil zinc levels through practices which help raise organic carbon levels in their fields for sustainable crop production.

Generally, increasing rates of nitrogenous fertiliser application decreased ($p \leq 0.05$) the soil zinc contents at all locations and depths. The results agree with earlier findings (Wanyoko and Mwakha, 1991) where leaf zinc contents decreased with high rates of nitrogen fertilizers. Conditions that induce zinc deficiencies include low pH; peat soils; high phosphate status; a high concentration of magnesium among others (Alloway, 2008). Zinc has a tendency of being strongly bound to organic matter, oxides and carbonates in high soil pH conditions (Zhang *et al.*, 2006). But the low pHs reported herein (Tables 6-9) resulted in the availability of the zinc metal. The current results are at variance with what had been observed elsewhwere for both soil and mature leaf zinc levels (Pitigala *et al*., 2013) where increased nitrogen rates did not influence their levels. However, mature leaf zinc icreased significantly with high nitrogen rates (Kwach *et al*., 2014). These differences could possibly be due to varying environmental factors and soil characteristics in the locations. This could be due to increase in acidity in the soil which results in increase zinc concentration in the soil (Nath, 2013), limiting the nutrient uptake by tea plants. Therefore, the nitrogenous fertilizer should be applied judiciously to avoid acidifying tea soils and which might hinder the uptake of zinc. Plucking intervals influenced ($p \leq 0.05$) zinc levels widely at all areas. The patterns observed were erratic. At soil depth 0-10cm long plucking intervals increased ($p \leq 0.05$) zinc levels at Changoi and Mulindi but the other sites the changes did not reach significant levels. At soil profile 10-20cm only Changoi, Mulindi, Katoke and Maruku recorded variations ($p \leq 0.05$). The changes at depths 20-30cm varied at Mulindi and Katoke and at soil depth 40-60cm were significant except at Timbilil, Changoi, and Mulindi. In previous work plucking intervals had no significant influence on mature leaf zinc levels (Kwach *et al*., 2014) but plucking intervals influenced yield (Odhiambo, 1989; Owuor *et al*., 2009; Owuor *et al*., 2013a) and fatty acid levels (Okal *et al*., 2012a; Owuor and Kwach, 2012). The variations in soil zinc levels with plucking intervals imply that the nutrient levels are influenced by site of production. However, the factors for sporadic changes in soil zinc with plucking intervals were not well understood. Therefore more trials are needed for their identity.

The significant ($p \leq 0.05$) interactions between nitrogen rates and locations, nitrogen rates and plucking intervals imply that patterns of changes in soil zinc levels were different from location to location as it had also been observed elsewhere (Kwach *et al*., 2014) for mature leaf zinc for nitrogen x site. This also explains the reasons why there were no responses in soil zinc due to plucking intervals at some sites.

Table 38: Responses of Tea Clone 6/8 Soil Zinc Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 0 – 10 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year)** 0	75	150	225	300	**Mean Plucking frq**	**Mean site**	**C.V.%**
	7	3.7	2.7	2.0	2.3	2.0	2.5		
	14	4.7	3.7	2.3	2.0	2.0	2.9	2.8	21.5
Timbilil	21	4.7	3.3	2.3	2.0	2.0	2.9		
	MeanNrates	4.3	3.2	2.2	2.1	2.0			
	LSD,p≤0.05			0.8			NS		
	7	5.0	4.0	2.0	1.3	1.0	2.7		
	14	2.7	5.0	2.7	2.3	3.3	3.2	3.2	15.7
	21	5.3	4.7	3.7	3.3	2.0	3.8		
Changoi	MeanN rates	4.3	4.6	2.8	2.3	2.1			
	LSD,p≤0.05			0.7			0.8		
	N x Pl frq			1.0					
	7	15.7	13.3	8.0	10.7	7.0	10.9		
	14	19.0	14.0	13.3	12.0	9.0	13.5	11.3	10.6
	21	12.0	10.0	7.3	7.3	10.3	9.5		
Arroket	Mean N rates	15.6	12.6	9.6	10.0	8.8			
	LSD,p≤0.05			1.6			NS		
	7	1.3	1.7	2.0	2.3	2.0	1.9		
	14	1.7	2.0	2.0	2.3	2.7	2.1	2.1	21.4
	21	2.0	2.0	2.7	2.3	2.7	2.3		
Kitabi	Mean N rates	1.7	1.9	2.2	2.3	2.4			
	LSD,p≤0.05			0.6			NS		
	7	8.0	7.0	6.0	5.3	5.0	6.3		
	14	8.3	6.7	5.7	5.0	4.0	5.9	6.3	8.8
	21	9.0	7.3	7.0	5.7	4.3	6.7		
Mulindi	Mean N rates	8.4	7.0	6.2	5.3	4.4			
	LSD,p≤0.05			0.7			0.9		
	7	2.5	2.0	1.8	1.7	1.3	1.9		
	14	2.4	1.7	1.7	1.4	1.3	1.7	1.9	2.9
Katoke	21	3.8	2.3	1.5	1.4	1.2	2.1		
	Mean N rates	2.9	2.0	1.7	1.5	1.3			
	LSD,p≤0.05			0.1			NS		
	7	2.6	2.5	2.3	1.7	1.3	2.1		
	14	3.2	2.6	2.5	2.3	1.7	2.5		
	21	3.8	3.3	2.7	2.4	1.5	2.8	2.4	0.9
Maruku	Mean N rates	3.2	2.8	2.5	2.2	1.5			
	LSD,p≤0.05			0.03			NS		
Mean for all	7	5.5	4.7	3.4	3.6	2.8	4.0		
7 Sites	14	6.0	5.1	4.3	3.9	3.4	4.5		
	21	5.8	4.8	3.9	3.5	3.4	4.3		13.9
	Nrates	5.8	4.9	3.9	3.7	3.2			
LSD,p≤0.05				0.3			NS	3.1	
				Site x Nrates = 0.6					

*Insignificant interactions are not shown

Table 39: Responses of Tea Clone 6/8 Soil Zinc Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 10 – 20 cm)

Site	Plucking Frq(dys)	Nitrogen Rates (KgN/ha/year)					Mean Pl frq	Mean Site	C.V.%
		0	75	150	225	300			
Timbilil	7	4.3	4.0	2.0	2.7	1.7	2.9	3.2	17.8
	14	3.7	3.3	3.0	2.0	3.0	3.0		
	21	6.3	3.0	2.0	3.3	3.7	3.7		
	Mean N rates	4.8	3.4	2.3	2.7	2.8			
	LSD,p≤0.05			1.2			NS		
	N x Pl frq			1.7					
Changoi	7	3.7	3.3	3.7	3.0	3.7	3.5	2.9	17.5
	14	3.3	3.3	2.7	2.0	2.0	2.7		
	21	2.7	2.3	2.7	3.0	2.3	2.6		
	Mean N rates	3.2	3.0	3.0	2.7	2.7			
	LSD,p≤0.05			0.7			0.8		
	N x Pl frq			1.0					
Arroket	7	12.0	8.0	6.3	11.7	10.3	9.7	12.5	22.4
	14	16.3	16.7	11.7	12.0	10.3	13.4		
	21	21.0	16.7	14.0	13.7	6.7	14.4		
	Mean N rates	16.4	13.8	10.7	12.4	9.1			
	LSD,p≤0.05			3.7			4.4		
	N x Pl frq			5.3					
Kitabi	7	1.7	2.0	2.3	2.3	2.3	2.1	2.1	21.6
	14	1.3	1.7	2.0	2.0	2.7	1.9		
	21	1.0	2.0	2.7	2.7	3.0	2.3		
	Mean N rates	1.3	1.9	2.3	2.3	2.7			
	LSD,≤0.05			0.6			NS		
Mulindi	7	17.7	15.0	13.3	13.0	11.3	14.1	12.6	6.3
	14	14.3	12.3	11.7	11.3	10.3	12.0		
	21	15.7	14.7	12.7	12.3	3.3	11.7		
	Mean N rates	15.9	14.0	12.6	12.2	8.3			
	LSD,p≤0.05			1.0			1.2		
	N x Pl frq			1.0					
Katoke	7	2.7	3.7	2.2	1.1	1.1	2.2	2.3	20.2
	14	2.7	2.2	1.2	1.1	1.2	1.7		
	21	3.2	4.2	3.0	2.8	1.8	3.0		
	Mean N rates	2.8	3.4	2.1	1.7	1.4			
	LSD,p≤0.05			0.6			0.7		
	N x Pl frq			0.9					
Maruku	7	5.6	4.3	3.4	2.8	1.8	3.6	3.6	2.5
	14	5.9	4.2	3.5	2.2	2.2	3.6		
	21	4.6	3.4	3.6	3.4	3.0	3.6		
	Mean N rates	5.4	4.0	3.5	2.8	2.3			
	LSD,p≤0.05			0.1			NS		
Mean for all 7 Sites	7	6.8	5.8	4.7	5.2	4.6	5.4		
	14	6.8	6.3	5.1	4.7	4.5	5.5		
	21	7.8	6.6	5.8	5.9	3.4	5.9		21.0
	Nrates	7.1	6.2	5.2	5.3	4.2			
LSD,p≤0.05				0.6			0.4	0.6	

Site x Nrates = 1.1

*Insignificant interactions are not shown

Table 40: Responses of Tea Clone 6/8 Soil Zinc Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 20 – 30 cm)

Site	Plucking Frq(dys)	Nitrogen Rates (KgN/ha/year)					Mean Pl frq	Mean Site	C.V.%
		0	75	150	225	300			
	7	5.7	3.7	2.3	2.0	1.7	3.1		
	14	4.7	6.3	5.3	5.0	2.0	4.7	3.8	23.7
	21	3.3	3.7	3.3	3.0	2.3	3.7		
Timbilil	Mean N rates	4.6	5.6	3.7	3.3	2.0			
	LSD,p≤0.05			1.2			1.4		
	N x Pl frq			1.7					
	7	3.7	3.3	2.7	1.7	1.3	2.5		
	14	3.3	3.0	2.7	2.0	1.7	2.5	2.6	18.4
	21	3.7	3.0	2.7	2.3	2.0	2.7		
Changoi	Mean N rates	3.6	3.1	2.7	2.0	1.7			
	LSD,p≤0.05			0.6			NS		
	7	11.0	18.3	13.0	12.7	7.0	12.4		
	14	9.0	10.0	7.7	4.0	3.3	6.8	9.5	8.0
	21	13.0	10.7	10.3	8.7	4.3	9.4		
Arroket	Mean N rates	11.0	13.0	10.3	8.4	4.9			
	LSD,p≤0.05			1.0			1.4		
	N x Pl frq			1.0					
	7	1.0	1.3	1.7	2.0	2.3	1.7		
	14	1.3	1.7	2.0	2.3	2.7	2.0	1.9	35.7
	21	1.3	1.7	2.0	2.3	2.3	1.9		
Kitabi	Mean N rates	1.2	1.6	1.9	2.2	2.4			
	LSD,p≤0.05			0.9			NS		
	7	15.0	25.3	21.0	14.7	12.7	17.7		
	14	17.3	12.7	11.7	8.0	7.7	11.5	14.1	9.8
	21	13.3	14.0	12.7	13.3	12.3	13.1		
Mulindi	Mean N rates	15.2	17.3	15.1	12.0	10.9			
	LSD,p≤0.05			1.8			2.1		
	N x Pl frq			2.6					
	7	4.1	3.1	1.3	1.3	1.2	2.2		
	14	5.1	4.3	3.4	3.0	2.9	3.7	2.8	14.9
	21	2.8	3.9	1.8	1.5	2.3	2.5		
Katoke	Mean N rates	4.0	3.8	2.2	2.0	2.1			
	LSD,p≤0.05			0.6			0.6		
	N x Pl frq			0.8					
	7	2.4	2.2	1.9	1.6	2.4	2.1		
	14	3.9	3.4	2.8	2.6	1.6	2.9		
	21	4.2	3.3	3.3	4.8	1.9	3.5	2.8	2.1
Maruku	Mea N rates	3.5	3.0	2.6	3.0	2.0			
	LSD,p≤0.05			0.1			0.1		
	N x Pl frq			0.1					
Mean for all 7 Sites	7	6.1	8.2	6.3	5.1	4.1	6.0		
	14	6.4	5.9	5.1	3.9	3.1	4.9	5.4	
	21	6.0	6.2	5.2	5.1	3.9	5.3		14.5
	Nrates	6.2	6.8	5.5	4.7	3.7			
LSD,p≤0.05				0.4			NS	0.4	

Site x Nrates = 0.8

[*] Insignificant interactions are not shown

Table 41: Responses of Tea Clone 6/8 Soil Zinc Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 40 – 60 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Plucking frq**	**Mean site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	4.7	2.7	2.0	1.7	2.0	2.6	3.0	25.1
	14	5.3	3.3	3.0	2.7	2.3	3.3		
	21	4.3	3.7	2.3	2.7	2.0	3.0		
	Mean N rates	4.8	3.2	2.4	2.3	2.1			
	LSD,p≤0.05			1.0			1.2		
	N x Pl frq			1.4					
Changoi	7	6.3	5.3	4.3	3.3	2.3	4.3	3.7	12.6
	14	4.3	3.0	2.3	3.0	2.0	2.9		
	21	7.0	4.3	3.3	2.7	2.0	3.9		
	Mean N rates	5.9	4.2	3.3	3.0	2.1			
	LSD,p≤0.05			0.6			0.7		
	N x Pl frq			0.9					
Arroket	7	8.3	6.3	8.0	4.7	4.3	6.3	7.0	13.7
	14	8.0	5.0	5.0	5.3	5.0	5.7		
	21	9.7	9.0	9.3	8.3	8.7	9.0		
	Mean N rates	8.7	6.8	7.4	6.1	6.0			
	LSD,p≤0.05			1.3			1.5		
	N x Pl frq			1.8					
Kitabi	7	1.0	1.7	2.0	2.0	2.3	1.8	1.7	18.8
	14	1.0	1.7	1.3	2.0	2.0	1.6		
	21	1.7	1.3	1.7	2.0	2.0	1.7		
	Mean N rates	1.2	1.6	1.7	2.0	2.1			
	LSD,p≤0.05			0.9			NS		
Mulindi	7	33.3	23.7	17.0	11.7	10.7	19.3	17.2	5.8
	14	23.3	18.3	16.7	13.7	11.0	16.6		
	21	21.3	18.0	14.3	13.3	11.0	15.6		
	Mean N rates	26.0	20.0	16.0	12.9	10.9			
	LSD,p≤0.05			1.3			NS		
Katoke	7	4.9	4.5	3.6	2.6	2.4	3.6	3.2	2.2
	14	3.4	3.4	2.8	2.5	1.9	2.8		
	21	3.9	3.4	3.0	2.8	2.2	3.1		
	Mean N rates	4.1	3.8	3.1	2.6	2.2			
	LSD,p≤0.05			0.1			0.1		
	N x Pl frq			0.1					
Maruku	7	4.1	4.4	3.6	2.6	2.2	3.4	2.6	1.4
	14	3.8	3.3	2.8	1.4	1.1	2.5		
	21	3.7	2.1	1.1	1.3	1.0	1.8		
	Mean N rates	3.9	3.3	2.5	1.8	1.5			
	LSD,p≤0.05			0.1			0.01		
	N x Pl frq			0.07					
Mean for all 7 Sites	7	9.0	6.9	5.8	4.1	3.8	5.9	5.5	12.2
	14	7.0	5.4	4.8	4.4	3.6	5.1		
	21	7.4	6.0	5.0	4.7	4.1	5.4		
	Nrates	7.8	6.1	5.2	4.4	3.8			
LSD,p≤0.05				0.3			NS	0.3	

Site x Nrates = 0.7

*Insignificant interactions are not shown

4.3.9 Soil Copper Levels

Copper is one of the essential elements in tea nutrition (Mitini-Nkhoma, 1987). Copper forms part of structural regulatory proteins and it also takes part in plant photosynthesis among other fuctions (Fernandes and Henriques, 1991; Yruela, 2005). Copper application increased yield and quality of tea (Barua and Dutta, 1972, Willson and Clifford, 1992; Barooah *et al.*, 2005; Saikh, 2007). In terms of tea quality, copper forms polyphenol oxidase, an essential copper containing enzyme in the fermentation process of black tea manufacturing (Seenivasan *et al.*, 2008). Increased copper levels improved fermentation process in black tea (Sedaghathoor *et al.*, 2009). The maximum permissible limits for copper in soils are 2 to 250 ppm (Nath, 2013) with a critical value of 0.2 ppm (Lindsay and Norvell, 1978). The available copper contents of the soils are shown in Table 42-45. Soil copper contents in the four depths tended to increase with soil depths even though the levels were below 2 ppm for most of the depths. These results agreed with previous studies (Sitienei *et al.*, 2016; Kacar, 1984; Özyazici *et al.*, 2011) where copper contents accumulated in lower soil depths. This could be attributed to increased acidity in tea soil which tends to solubilize copper from the solid phase of the soils (Mozaffari *et al.*, 1996) and enhance its leaching to lower soil profiles. The increased copper levels at lower soil profiles could lead to decrease in soil nitrogen (Kumar *et al.*, 1990) affecting tea productivity. High soil pH and high total organic matter content have a higher retention capacity of copper metal in the soil. Copper exists in soil as organically bound (Stevenson, 1991) and residual forms or as acid soluble forms (Alva *et al.*, 2000). Even though the higher pH favors the nutrient retention in soil, it limits the copper uptake by tea plants (Nath, 2013) and may result in yield decline.

The copper levels changed ($p \leq 0.05$) with location of production, further emphasising how the nutrient reserves in the soils are variable (Tables 42-45). Copper levels were higher ($p \leq 0.05$) at Katoke, Changoi and Arroket but lower at Maruku. At all sites copper contents were above the sufficient limits (greater than 0.2 ppm) (Lindsay and Norvell, 1978) except at Maruku which had below the low limits but within the crical value of 0.2 ppm. Similar variations with location in soil copper were observed in previous work (Adiloğlu and Adiloğlu, 2006; Nath, 2013), mature leaf copper levels (Kwach *et al.*, 2014; Adiloğlu and Adiloğlu, 2006; Nath, 2013) and copper contents of black tea (Omwoyo *et al.*, 2014). The differences in soil pH (Tables 6-9) and organic carbon (Tables 2-5) could be the contributing factor for the nutrient variations observed in the current study. The result indicates that different regions have varied copper reserves. This may be one of the causes in yield and quality variations in the regions of Eastern Africa.

Copper contents increased ($p \leq 0.05$) with rise in nitrogenous fertiliser rates at all sites. Similar results had been observed in earlier studies in soil (Pitigala *et al*., 2013) and for mature leaf (Kwach *et al*., 2014; Pitigala *et al*., 2013) copper levels. The increase in soil copper levels with nitrogen fertilizer in the current study can be explained by soil acidity observed in the regions. The reduced pH solubilize copper (Mozaffari *et al*., 1996) increasing its concentations and improve the nutrient uptake by tea (Chong *et al*., 2008; Kwach *et al*., 2014). Increased nitrogen fertilizer rates raise soil acidity which helps solubilize copper from its insoluble hydroxides, making the nutrient available in the soils. Therefore, copper levels can be improved in tea soils by judiciasily using nitrogen fertilizers.

Harvesting frequency had significant ($p \leq 0.05$) but non uniform influence on soil copper levels at all locations except at Changoi, Kitabi, Mulindi and Katoke for depth 0-10cm, at depth 10-20 except Timbilil, and Kitabi, at soil depth 20-30cm except Kitabi and at depth 40-60cm sporadic significance influence was observed at Changoi, Arroket and Mulindi. The variations in copper levels with harvesting intervals supports what had also been observed for mature leaf copper (Kwach *et al*., 2014). Yields and quality in different genotypes (Baruah *et al*. 1986; Owuor *et al*. 1997, 2000) improved with short plucking intervals and fatty acids levels (Okal *et al*., 2012a) increased with longer plucking frequency. The patterns observed were sporadic and the causes were unclear, and therefore, monitoring the same experiments for longer periods is required to establish the factors responsible.

There were significant ($p \leq 0.05$) interactions effects for copper levels between site and nitrogen rates for overall values at all depths, nitrogen rates x plucking intervals at depths 10-20cm except at Kitabi and Katoke, 20-30cm except at Timbilil, Changoi and Katoke, 40-60cm except at Kitabi and Maruku. The interactions indicate differences in patterns of change in the observed variations of the soil copper levels. Similar patterns for copper levels were also observed between location and clones (Omwoyo *et al*., 2014) and mature leal copper (Kwach *et al*., 2014). The resulst demonstrates that soil copper levels varied with location and that the responses were not similar. Thus it is necessary to develop region specific agronomic practices which could improve soil copper contents for sustainable crop productivity.

Table 42: Responses of Tea Clone 6/8 Soil Copper Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 0 – 10 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year**					**Mean Pl frq**	**Mean site**	**C.V. %**
		0	**75**	**150**	**225**	**300**			
	7	2.33	2.67	3.33	3.67	7.00	3.80	3.38	18.12
	14	2.67	3.00	4.33	4.67	3.33	3.60		
	21	1.67	2.33	3.00	3.67	3.00	2.73		
Timbilil	MeanNrates	2.22	2.67	3.56	4.00	4.44			
	LSD,p≤0.05			0.80			0.96		
	7	1.67	2.33	2.67	3.33	3.67	2.73	2.56	20.68
	14	1.33	1.67	2.67	4.00	3.67	2.67		
Changoi	21	1.67	1.67	2.33	2.67	3.00	2.27		
	Mean N rates	1.56	1.89	2.56	3.33	3.44			
	LSD,p≤0.05			NS			NS		
	7	9.00	12.33	13.33	13.33	17.33	13.06	12.11	6.99
	14	11.67	11.67	13.00	15.33	13.33	13.00		
Arroket	21	7.00	11.67	9.33	14.00	15.33	11.47		
	Mean N rates	9.22	11.89	11.89	14.22	15.33			
	LSD,p≤0.05			1.11			1.33		
	7	1.00	1.33	2.00	2.33	2.67	1.87	1.93	27.18
	14	1.33	1.67	2.00	2.67	2.33	2.00		
Kitabi	21	1.00	1.67	2.00	2.33	2.67	1.93		
	Mean N rates	1.11	1.56	2.00	2.44	2.56			
	LSD,p≤0.05			0.69			NS		
	7	1.00	1.67	2.00	2.67	3.67	2.20	2.56	19.78
	14	1.00	1.67	2.00	2.67	3.33	2.13		
Mulindi	21	1.33	2.67	3.67	4.33	4.67	3.33		
	Mean N rates	1.11	2.00	2.56	3.22	3.89			
	LSD,p≤0.05			0.66			NS		
	7	12.00	14.67	31.00	36.00	28.67	24.47	24.78	9.48
	14	19.33	26.00	31.67	34.67	41.00	30.53		
	21	14.00	15.00	19.33	19.67	28.67	19.33		
Katoke	Mean N rates	15.11	18.56	27.33	30.11	32.78			
	LSD,p≤0.05			3.08			NS		
	7	0.20	0.21	0.36	0.45	1.00	0.44	0.45	2.88
	14	0.20	0.22	0.47	0.64	1.26	0.56		
	21	0.21	0.35	0.37	0.38	0.52	0.37		
Maruku	Mean N rates	0.20	0.26	0.40	0.49	0.93			
	LSD,p≤0.05			0.02			NS		
Mean for all 7 Sites	7	3.03	5.03	7.81	8.83	9.14	6.77		
	14	5.36	6.56	8.02	9.23	9.75	7.78		
	21	3.84	5.05	5.72	6.72	8.26	5.92		15.95
	Nrates	4.08	5.55	7.18	8.26	9.05			
LSD,p≤0.05				0.54			NS	0.56	
			Site x Nrates = 1.06						

*Insignificant interactions are not shown

Table 43: Responses of Tea Clone 6/8 Soil Copper Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 10 – 20 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Pl frq**	**Mean site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
	7	1.33	2.00	2.67	3.33	3.33	2.53		
	14	1.67	2.00	2.67	3.67	1.33	2.27	2.24	16.21
	21	1.33	1.67	1.00	2.67	3.00	1.93		
Timbilil	MeanN rates	1.44	1.89	2.11	3.22	2.56			
	LSD,p≤0.05			0.80			NS		
	N x Pl frq			1.10					
	7	12.67	13.00	16.00	34.67	31.67	21.60		
	14	5.00	21.00	28.00	33.00	31.67	23.73	21.80	9.59
	21	10.67	8.33	21.33	28.67	31.33	20.07		
Changoi	MeanN rates	9.44	14.11	21.78	32.11	31.56			
	LSD,p≤0.05			2.73			3.28		
	N x Pl frq			3.90					
	7	12.00	15.67	19.33	20.67	19.00	17.33		
	14	8.00	12.33	12.00	13.33	13.33	11.80	14.56	9.20
	21	12.67	14.67	12.00	16.00	17.33	14.53		
Arroket	MeanN rates	10.89	14.22	14.44	16.67	16.56			
	LSD,p≤0.05			1.75			2.00		
	N x Pl frq			2.52					
	7	1.00	1.67	2.00	2.00	2.33	1.80		
	14	1.00	1.00	1.67	1.67	2.00	1.47	1.64	29.27
	21	1.00	1.33	1.67	2.00	2.33	1.67		
Kitabi	MeanN rates	1.00	1.33	1.78	1.89	2.22			
	LSD,p≤0.05			0.63			NS		
	7	1.33	2.67	3.67	4.33	4.67	3.33		
	14	3.33	4.00	4.67	5.67	6.67	4.87	3.89	15.44
	21	2.33	3.67	4.00	2.67	4.67	3.47		
Mulindi	MeanN rates	2.33	3.44	4.11	4.22	5.33			
	LSD,p≤0.05			0.79			0.94		
	N x Pl frq			1.13					
	7	10.00	12.33	18.67	28.00	37.00	21.20		
	14	18.67	30.33	40.33	55.00	48.00	38.47	32.11	8.58
	21	11.33	29.00	30.33	57.00	55.67	36.67		
Katoke	MeanN rates	13.33	23.89	29.78	46.67	46.89			
	LSD,p≤0.05			3.61			4.30		
	7	0.25	0.35	0.47	0.87	1.14	0.62		
	14	0.14	0.32	0.38	0.87	0.96	0.53		
	21	0.17	0.23	0.36	0.44	0.50	0.34	0.50	14.47
Maruku	MeanN rates	0.19	0.30	0.40	0.72	0.86			
	LSD,p≤0.05			0.04			0.05		
	N x Pl frq			0.05					
Mean for	7	5.51	6.81	8.97	13.41	14.16	9.77		
	14	5.40	10.14	12.82	16.17	14.85	11.88		
all 7 Sites	21	5.64	8.41	10.10	15.63	16.40	11.24		13.92
	N rates	5.52	8.46	10.63	15.07	15.14			
LSD≤0.05				0.33			NS	0.79	

Site x Nrates=1.48

*Insignificant interactions are not shown

Table 44: Responses of Tea Clone 6/8 Soil Copper Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 20 – 30 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Pl frq**	**Mean Site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	1.33	1.67	2.67	3.00	3.33	2.40	2.16	24.52
	14	1.00	1.67	2.33	2.67	1.67	1.87		
	21	1.33	1.67	2.33	2.67	3.00	2.20		
	MeanNrates	1.22	1.67	2.44	2.78	2.67			
	LSD,p≤0.05			0.69			0.83		
Changoi	7	6.67	13.00	14.33	25.67	27.33	17.40	20.98	14.31
	14	5.67	24.33	28.67	36.33	31.67	25.33		
	21	13.00	14.00	15.67	34.33	24.00	20.20		
	MeanNrates	8.44	17.11	19.56	32.11	27.67			
	LSD,p≤0.05			3.9			4.70		
Arroket	7	13.33	18.00	23.00	24.00	27.33	21.13	16.02	5.48
	14	12.33	13.00	13.67	13.67	14.67	13.47		
	21	12.00	12.33	13.33	12.00	17.67	13.47		
	MeanNrates	12.56	14.44	16.67	16.56	19.89			
	LSD,p≤0.05			1.10			1.40		
	N x Pl frq			1.70					
Kitabi	7	1.33	1.67	1.67	3.00	3.33	2.20	1.78	28.17
	14	1.00	1.00	1.33	2.00	2.33	1.53		
	21	1.00	1.67	2.00	1.33	2.00	1.60		
	Mean rates	1.11	1.44	1.67	2.11	2.56			
	LSD,p≤0.05			0.66			NS		
	N x Pl frq			0.94					
Mulindi	7	2.67	3.67	5.67	5.67	3.67	4.27	5.96	9.25
	14	2.67	5.33	5.67	6.67	7.00	5.47		
	21	6.00	7.33	8.33	8.67	10.33	8.13		
	Mean rates	3.78	5.44	6.56	7.00	7.00			
	LSD,p≤0.05			0.72			0.87		
	N x Pl frq			1.0					
Katoke	7	16.00	22.67	26.00	43.00	56.33	32.80	34.98	8.77
	14	15.67	30.00	36.33	49.00	58.00	37.80		
	21	16.00	22.00	32.00	46.00	55.67	34.33		
	MeanN rates	15.89	24.89	31.44	46.00	56.67			
	LSD,p≤0.05			4.00			4.82		
Maruku	7	0.13	0.22	0.33	0.46	0.86	0.40	0.47	6.17
	14	0.26	0.35	0.53	0.67	0.84	0.53		
	21	0.16	0.32	0.46	0.51	0.95	0.48		
	Mea N rates	0.18	0.30	0.44	0.55	0.88			
	LSD,p≤0.05			0.09			0.11		
	N x Pl frq			0.14					
Mean for all 7 Sites	7	5.92	8.70	10.52	14.97	17.46	11.51		
	14	5.51	10.81	12.65	15.86	16.60	12.29		
	21	7.07	8.47	10.59	15.07	16.23	11.49		15.16
	Nrates	6.17	9.33	11.25	15.30	16.76			
LSD≤0.05				0.88			1.06	0.92	
				Site x Nrates=1.74					

*Insignificant interactions are not shown

Table 45: Responses of Tea Clone 6/8 Soil Copper Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 40 – 60 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year**					**Mean Plucking frq**	**Mean Site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	1.33	1.67	2.00	2.33	2.33	1.93	2.04	31.60
	14	1.67	1.67	2.33	2.67	2.33	2.13		
	21	1.67	2.00	2.00	2.33	2.33	2.07		
	Mean N rates	1.56	1.78	2.11	2.44	2.33			
	LSD,p≤0.05			0.85			NS		
	N x Pl frq			1.20					
Changoi	7	6.67	11.67	11.00	17.00	15.33	12.33	10.53	9.96
	14	6.00	12.33	13.33	14.00	14.33	12.00		
	21	1.67	6.00	8.00	9.67	11.00	7.27		
	Mean N rates	4.78	10.00	10.78	13.56	13.56			
	LSD,p≤0.05			1.4			1.6		
	N x Pl frq			1.97					
Arroket	7	23.00	25.33	24.00	24.00	27.00	24.67	24.07	2.33
	14	22.00	23.33	23.67	25.67	24.00	23.73		
	21	24.00	23.33	23.00	24.00	24.67	23.80		
	Mean N rates	23.00	24.00	23.56	24.56	25.22			
	LSD,p≤0.05			0.73			0.90		
	N x Pl frq			1.10					
Kitabi	7	0.67	1.00	1.33	1.33	1.67	1.20	1.27	43.58
	14	0.67	1.00	1.33	1.67	1.33	1.20		
	21	1.00	1.00	1.33	1.67	2.00	1.40		
	MeanN rates	0.78	1.00	1.33	1.56	1.67			
	LSD,p≤0.05			0.72			NS		
Mulindi	7	4.33	4.67	6.67	7.00	7.67	6.07	6.51	7.91
	14	3.33	4.00	6.33	8.33	9.67	6.33		
	21	4.33	6.33	7.33	8.67	9.00	7.13		
	Mean N rates	4.00	5.00	6.78	8.00	8.78			
	LSD,p≤0.05			0.67			0.81		
	N x Pl frq			0.97					
Katoke	7	18.67	26.33	34.00	26.67	49.33	31.00	36.22	9.98
	14	20.67	30.00	33.67	41.67	51.33	35.47		
	21	30.33	29.67	38.67	48.00	64.33	42.20		
	Mea N rates	23.22	28.67	35.44	38.78	55.00			
	LSD,p≤0.05			4.7			NS		
	N x Pl frq			6.81					
Maruku	7	0.25	1.09	1.15	1.42	1.47	1.08	0.83	11.54
	14	0.63	0.38	0.45	0.91	1.13	0.70		
	21	0.39	0.47	0.64	0.84	1.17	0.70		
	Mea N rates	0.42	0.65	0.75	1.06	1.26			
	LSD,p≤0.05			2.11			NS		
Mean for all 7 Sites	7	7.85	10.25	11.45	11.39	14.97	11.93		
	14	7.85	10.39	11.59	13.56	14.88	11.65		
	21	9.01	9.83	11.57	13.60	16.36	12.07		14.99
	Nrates	8.24	10.16	11.54	12.85	15.40			
LSD,p≤0.05				0.86			NS	0.90	

Site x Nrates=1.70, N rates x Pl frq =1.24

*Insignificant interactions are not shown

4.3.10 Soil Manganese Levels

Manganese aid in plant photosynthesis and activate several enzymes (Roy *et* al., 2006). Low levels of manganese improved tea yields (Gohain *et* al., 2001). Soil manganese levels between 4-14 ppm, 14-50 ppm, 50-170 ppm and >170 ppm are classified as low, sufficient, high and very high respectively (FAO, 1990). Results on soil manganese levels are presented in Tables 46-49. There was a general decrease in manganese contents down the soil profiles. The upper soil layers recorded higher manganese contents in comparison to lower depths .These results are in line with what had also been observed elsewhere (Sitienei *et al*., 2016; Kacar, 1984; Özyazici *et al*., 2011). The patterns could be explained by the decrease in organic carbon (Tables 2-5) and soil acidity (Tables 6-9) down the soil profiles. The concentration of manganese increases with increase in organic matter content in the soil (Nath, 2013). The upper soil depths showing high levels of zinc had high organic matter content. High levels of zinc also reduce the ability of soil to absorb manganese (Francis and Masilamoni, 2012). Increased zinc levels might lead to reduced levels of manganese in tea soil affecting crop productivity.

Manganese levels changed significantly ($p \leq 0.05$) at all sites. Kitabi had the lowest (below critical value of 14 ppm) (FAO, 1990) manganese levels that ranged from 2-3 ppm while Timbilil, Changoi and Arroket had ($p \leq 0.05$) higher contents compared to the other four sites. Changes with location in soil manganese had also been recorded in the soil (Kebeney *et al*., 2010; Adiloğlu and Adiloğlu, 2006), mature leaf (Kebeney *et al*., 2010; Adiloğlu and Adiloğlu, 2006; Kwach *et al*., 2014) and manganese content of black tea (Omwoyo *et al*., 2014). The differences in manganese levels with location of production indicate that the sites have varied reserves of the nutrient. The large variations in manganese contents (Tables 46-49) could be one of the constraining factors in tea production in Eastern Africa. Therefore, farmers should engage in practices which can improve soil manganese levels for sustainable crop production.

Increasing nitrogen fertilizer application rates raised ($p \leq 0.05$) the levels of soil manganese at all sites. The results agreed with what had been observed earlier (Kebeney *et al*., 2010; Wanyoko and Mwakha, 1991; Wanyoko *et al*., 1990; 1992) where increased nitrogen rates improved the levels of available manganese. The increase in the nutrient levels may be due to solubilization of the nutrient as the soil acidity increases. Increased nitrogen rates have been demonstrated to increase mature leaf manganese (Ruan *et al*., 2006; Wanyoko and Mwakha, 1991). The increase was attributed to reduced soil pH caused by nitrogenous fertilizer rates which made the element more available. Therefore, high levels of nitrogen fertilizer application might increase manganese uptake by tea plants and thus improve crop productivity in Eastern Africa.

Harvesting intervals had sporadic ($p \leq 0.05$) patterns for soil manganese levels at all sites and depths except at Kitabi and Maruku for depth 0-10 cm, at Changaoi for soil depth 10-20 cm, at Katoke and Changoi for depth 20-30 cm and at soil depth 40-60 cm for all sites. The changes were insignificant ($p \leq 0.05$) and erratic for overall values at all soil profiles. The results were at variance with mature leaf manganese (Kwach *et* al., 2014) where plucking intervals did not influence soil manganese levels at any location of production. However, the trends were irregular and varied from site to site. Monitoring the trials for longer periods might help to accertain the factors responsible for the sporadic patterns.

There were interaction effects ($p \leq 0.05$) between site and nitrogen rates, nitrogen x plucking interval at some sites for manganese, meaning that the responses did not occur in the same pattern. The interaction effects suggest that the extent of variations due to nitrogen rates and plucking intervals varied with location of production. Indeed, this explains why in some areas there were no responses in soil manganese due to plucking intervals. The results support earlier work (Omwoyo *et al*., 2014) who recorded significant interactions between clones and location for mature leaf manganese levels. These results indicate that due to variations in environmental factors at the sites, even with the application of the same agronomic inputs, the levels of the manganese will be different.

Table 46: Responses of Tea Clone 6/8 Soil Manganese Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 0 – 10 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Pl frq**	**Mean site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
	7	320	361	377	381	393	366	358	2
	14	359	371	345	383	383	368		
	21	281	345	373	342	352	338		
Timbilil	Mean N rates	320	359	365	369	376			
	LSD,p≤0.05			8			NS		
	7	183	192	226	245	402	250	282	2
	14	191	192	291	286	385	269		
	21	190	279	378	404	392	329		
Changoi	Mean N rates	188	221	298	312	393			
	LSD,p≤0.05			7			NS		
	7	256	309	346	431	462	361	319	2
	14	152	244	324	341	419	296		
	21	169	216	251	385	475	299		
Arroket	Mean N rates	192	256	307	386	452			
	LSD,p≤0.05			3			NS		
	7	2	2	2	3	4	2	3	17
	14	2	2	3	3	3	3		
	21	2	2	3	4	4	3		
Kitabi	Mean N rates	2	2	3	3	4			
	LSD,p≤0.05			4			1		
	7	39	57	65	72	123	71	72	8
	14	28	43	61	83	74	58		
	21	37	61	86	108	147	88		
Mulindi	Mean N rates	35	54	71	88	115			
	LSD,p≤0.05			9			NS		
	7	17	19	19	23	28	21	25	12
	14	15	21	34	44	53	33		
	21	13	18	23	15	28	19		
Katoke	Mean N rates	15	19	25	27	36			
	LSD,p≤0.05			2			NS		
	7	8	11	12	13	15	12	12	7
	14	10	11	12	13	17	13		
	21	8	10	11	13	16	12		
Maruku	Mean N rates	9	10	12	13	16			
	LSD,p≤0.05			3			1		
Mean for all 7 Sites	7	126	136	150	169	194	155		
	14	106	126	158	165	187	148		
	21	113	133	156	183	192	155		3
	Nrates	115	132	155	172	191			
LSD,p≤0.05				2			NS	2	

Site x Nrates=5

*Insignificant interactions are not shown

Table 47: Responses of Tea Clone 6/8 Soil Manganese Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 10 – 20 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Pl frq**	**Mean Site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
	7	374	350	357	345	388	363		
	14	391	363	398	401	389	388	374	1
Timbilil	21	335	392	374	384	367	370		
	Mean N rates	367	368	376	377	382			
	LSD,p≤0.05			7			8		
	N x Pl frq			10					
	7	159	186	235	284	347	242		
	14	158	164	182	198	225	186	213	3
Changoi	21	174	188	208	245	245	212		
	Mean N rates	164	179	208	242	272			
	LSD,p≤0.05			8			10		
	N x Pl frq			12					
	7	207	228	274	367	387	293		
	14	232	270	303	344	388	308	307	2
Arroket	21	191	291	338	380	397	319		
	Mean N rates	210	263	305	364	391			
	LSD,p≤0.05			8			9		
	N x Pl frq			11					
	7	2	3	3	4	3	3		
	14	2	2	3	3	4	3	3	17
Kitabi	21	2	2	2	3	2	2		
	Mean N rates	2	2	3	3	3			
	LSD,p≤0.05			0.58			0.71		
	7	36	76	84	92	109	79		
	14	47	77	86	112	124	89	80	8
Mulindi	21	34	52	68	76	121	70		
	Mean N rates	39	68	79	93	118			
	LSD,p≤0.05			8			10		
	N x Pl frq			12					
	7	13	15	16	21	26	18		
	14	17	23	17	32	44	27	24	12
Katoke	21	12	15	23	33	47	26		
	Mean N rates	14	17	19	29	39			
	LSD,p≤0.05			3.6			4.3		
	N x Pl frq			NS					
	7	10	11	11	13	14	12		
	14	7	9	11	12	13	10		
Maruku	21	8	10	11	14	8	10	11	7
	Mean N rates	8	10	11	13	12			
	LSD,p≤0.05			1.0			1.2		
	N x Pl frq			1.4					
Mean for all 7 Sites	7	116	124	142	161	178	144		
	14	122	130	142	158	171	144	144	
	21	113	136	141	162	170	144		3
	Nrates	117	130	142	160	173			
LSD,p≤0.05				2 Site x Nrates=5			NS	3	

Table 48: Responses of Tea Clone 6/8 Soil Manganese Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 20 – 30 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Plucking frq**	**Mean site**	**C.V. %**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	335	350	363	358	374	356	352	1
	14	345	342	380	390	394	370		
	21	296	363	316	327	351	331		
	Mean N rates	325	352	353	358	373			
	LSD,p≤0.05			6			7		
	N x Pl frq			9					
Changoi	7	209	226	263	271	283	250	205	3
	14	141	151	172	180	205	170		
	21	183	193	200	208	195	196		
	Mean N rates	178	190	212	220	227			
	LSD,p≤0.05			10			NS		
Arroket	7	183	195	228	285	349	248	259	3
	14	218	225	259	289	317	262		
	21	171	180	272	343	369	267		
	Mean N rates	191	200	253	305	345			
	LSD,p≤0.05			9			10		
	N x Pl frq			12					
Kitabi	7	2	2	3	3	4	3	2	18
	14	2	2	2	2	3	2		
	21	2	2	3	3	2	2		
	Mean N rates	2	2	3	3	3			
	LSD,p≤0.05			1			1		
	N x Pl frq			1					
Mulindi	7	44	95	106	151	170	113	106	6
	14	72	86	117	138	148	112		
	21	48	52	77	135	147	92		
	Mean N rates	55	78	100	141	155			
	LSD,p≤0.05			8			10		
	N x Pl frq			11					
Katoke	7	11	17	18	17	25	18	18	14
	14	10	13	18	25	26	18		
	21	14	16	18	19	24	18		
	Mean N rates	12	15	18	20	25			
	LSD,p≤0.05			3			NS		
	N x Pl frq			5					
Maruku	7	8	8	9	9	10	9	9	8
	14	8	8	9	8	9	8		
	21	7	8	8	11	12	9		
	Mean N rates	8	8	9	10	11			
	LSD,p≤0.05			1			1		
	N x Pl frq			1					
Mean for all 7 Sites	7	113	128	142	156	173	142		3
	14	114	118	137	148	157	135		
	21	103	116	128	149	157	131		
	Nrates	110	121	135	151	163			
LSD,p≤0.05			2				NS	2	
		Site x Nrates=4							

*Insignificant interactions are not shown

Table 49: Responses of Tea Clone 6/8 Soil Manganese Levels (ppm) to Nitrogen Rates, Plucking Frequencies and Location (Depth: 40 – 60 cm)

Site	**Plucking Frq(dys)**	**Nitrogen Rates (KgN/ha/year)**					**Mean Plucking frq**	**Mean Site**	**C.V. %**
		0	**75**	**150**	**225**	**300**			
Timbilil	7	281	289	352	304	390	323	332	2
	14	278	316	341	380	368	337		
	21	241	339	359	375	370	337		
	Mean N rates	267	315	351	353	376			
	LSD,$p\leq0.05$			7			NS		
Changoi	7	65	115	121	156	268	145	126	4
	14	65	106	185	192	202	150		
	21	54	64	74	86	133	82		
	Mean N rates	61	95	127	144	201			
	LSD,$p\leq0.05$			7			NS		
Arroket	7	224	251	265	280	302	265	276	2
	14	254	254	296	309	335	289		
	21	193	224	294	298	367	275		
	Mean N rates	224	243	285	296	335			
	LSD,$p\leq0.05$			8			NS		
Kitabi	7	2	2	2	3	2	2	2	21
	14	2	2	3	2	3	2		
	21	2	2	3	3	3	3		
	Mean N rates	2	2	3	2	3			
	LSD,$p\leq0.05$			1			NS		
Mulindi	7	85	81	107	113	134	104	86	6
	14	61	67	58	87	89	72		
	21	36	59	95	108	117	83		
	Mean N rates	61	69	86	103	113			
	LSD,$p\leq0.05$			7			NS		
Katoke	7	15	21	18	25	28	21	22	12
	14	17	21	31	33	38	28		
	21	13	13	17	23	24	18		
	Mean N rates	15	19	22	27	30			
	LSD,$p\leq0.05$			4			NS		
	N x Pl frq			5					
Maruku	7	9	10	8	9	11	9	9	8
	14	8	8	9	10	11	9		
	21	7	8	9	10	11	9		
	Mean N rates	8	9	9	9	11			
	LSD,$p\leq0.05$			1			NS		
	N x Pl frq			1					
Mean for all 7 Sites	7	97	110	125	139	150	124	122	4
	14	98	111	132	143	151	127		
	21	78	101	122	128	147	115		
	Nrates	91	107	126	137	149			
LSD,$p\leq0.05$				2			NS	2	

Site x Nrates=4

*Insignificant interactions are not shown

The changes in SOC, pH and nutrients with location of production, nitrogenous fertilizer rates and harvesting intervals are presented in Tables 2-48. All the soil levels of these parameters changed ($p \leq 0.05$) with location of production. The results demonstrated that the variations were specific to the area of production. Therefore, due to variations in environmental factors at the sites, even with same agronomic inputs the levels of these parameters will be different. These variations maybe the cause in part of the variations in yields of tea due to locations observed in the past.

While calcium, magnesium, potassium, zinc and pH declined ($p \leq 0.05$), levels of soil aluminium, copper, iron, phosphorus, nitrogen, manganese and SOC increased ($p \leq 0.05$) with rise in nitrogenous fertilizer rates at all sites. The rsults demonstrated that nitrogen fertilizer application is one way of improving levels of soil organic carbon in tea farms. However, continuous application of high rates of nitrogenous fertilizers could cause deficiency of some soil nutrients while increasing levels of other nutrients like aluminium and manganese to detrimental limits for tea productivity.

Generally, soil organic carbon, pH and nutrients were not affected by harvesting intervals. However, the patterns observed were sporadic and may require more trials for a longer period to establish factors responsible for the patterns. There were interaction ($p \leq 0.05$) effects between sites x nitrogenous fertilizer rates indicating differences in patterns of change in observed variations of soil quality indicators.

4.4 Relationship between Soil Nutrients Levels and Yields in East Africa Tea Growing Regions

The effects of sites, nitrogenous fertilizer application rates and plucking frequencies on mean yields of tea (Msomba *et al*., 2014) are presented in Table 50.

Table 50: Effects of Nitrogen Fertilizer Rates, Plucking Frequencies and Sites on Mean Yields (kg mt/ ha) (2014)

SITE	**Plucking frq(dys)**	**Nitrogen Rates(Kgn/Ha/Year)**					**Mean Plucking frq**	**Mean site**	**C.V.%**
		0	**75**	**150**	**225**	**300**			
	7	3946	4187	4515	4463	4569	4336	4249	5.79
	14	3645	4028	4216	4383	4213	4097		
	21	3881	4115	4298	4559	4709	4313		
Timbilil	Mean N rates	3824	4110	4343	4468	4497			
	LSD≤0.05			322			NS		
	7	4426	4870	4907	5054	5313	4914	5037	5.74
	14	4818	4974	5545	5505	5207	5210		
	21	4582	4762	4807	5253	5531	4986		
Changoi	Mean N rates	4609	4869	5086	5270	5350			
	LSD≤0.05			378			NS		
	7	5421	6038	6291	5882	6419	6010	6219	6.83
	14	5580	5837	6240	6825	6342	6165		
	21	5537	6331	6211	7044	7283	6481		
Arroket	Mean N rates	5513	6068	6247	6584	6681			
	LSD≤0.05			256			367		
	7	4143	4089	4552	5429	5256	4694	4467	13.06
	14	3234	4306	4551	5148	4764	4401		
	21	3382	2994	5391	5276	4487	4306		
Kitabi	Mean N rates	3587	3796	4831	5284	4836			
	LSD≤0.05			763			NS		
	7	2229	2346	2847	2430	2572	2485	1902	25.23
	14	2063	1656	2012	1591	1802	1825		
	21	1140	1500	1120	1388	1841	1399		
Mulindi	Mean N rates	1811	1834	1993	1803	2072			
	LSD≤0.05			NS			754		
	7	3346	3052	3564	3693	3750	3481	3420	10.94
	14	3249	3474	3400	3598	3718	3488		
	21	2854	3139	3506	3680	3284	3292		
Katoke	Mean	3150	3222	3490	3657	3584			
	LSD≤0.05			490			NS		
	7	2440	2717	2351	2799	2858	2633	2476	13.4
	14	2190	2402	2706	2812	2363	2494		
	21	2101	2441	2232	2602	2231	2301		
Maruku	Mean N rates	2244	2487	2430	2738	2484			
	LSD,p≤0.05			NS			NS		
Mean for all 7 Sites	7	3705	3833	4044	4170	4328	4016		
	14	3528	3819	4026	4198	4021	3918		
	21	3346	3651	3939	4203	4183	3862		11.7
	Nrates	3526	3763	4003	4191	4177			
LSD≤0.05	NS			191			NS		223

Source: **Msomba *et al*., 2014**

The relationship between yields (Msomba *et al*., 2014) and nutrients levels were computed using Tables 50 and Tables 10-49. The results are as given in Tables 51-54. At soil depth 0-10cm (Table 50) yield was significantly and positively correlated ($p \leq 0.05$, $r \geq 0.878$) to soil phosphorus at Timbilil, Changoi, Arroket, Katoke; soil nitrogen at Changoi and Katoke; aluminium and iron at Timbilil, Changoi, Kitabi, and Katoke, copper at Timbilil, Changoi, Arroket, Kitabi, Katoke and Mn at Timbilil, Changoi, and Kitabi, indicating an increase in these soil nutrients levels leads to increased yields. Increase in yields with increase in these soil nutrients levels was expected, since the nutrients play a significant role in the tea plant development. There was a negative ($p \leq 0.05$, $r \geq -0.878$) relationship between yields and potassium, calcium, magnesium and zinc at some sites except Kitabi which had a positive correlation with zinc. This may require further investigations to establish the cause. The resulsts demonstrate that although these nutrients decreased, yields increased. The decrease in these nutrients could be probably due to fixation (Chong, 2008; Wanyoko *et al*., 1992; Kebeney *et al*., 2010), leaching (Owuor *et al*., 1997; Ruan *et al*., 2006; Venkatesane *et al*., 2004) and removal through harvested crop (Do *et al*., 1980; Kamau *et al*., 2005). This pattern was repeated at all sites and depths except at some sites where the associations were insignificant ($p \leq 0.05$, $r \geq -0.878$). The results obtained previously in these regions (Owuor *et al*., 2009, 2010a; Wachira *et al*., 2002; Msomba *et al*., 2014) demonstated that yields of tea vary with nitrogenous fertilizer rates.

The current study indicates that yield is influenced by soil nutrients.These observations are coherent with results of Sharma and Sharma, (1995), Godziashvili and Peterburgsky, (1985), Salukvadze, (1980) and Venkatesan *et al*., (2004) who also reported a positive and negative correlations between tea yields and some soil nutrients levels. Similar relationship between mature leaf nutrients and yields had also been reported elsewhere (Kebeney *et al*., 2010; Venkatesane *et al*., 2004). Mature leaf has been used to predict the tea bush nutritional requirements (Bonheure and Willson, 1992). While the mature leaf has been observed to be sensitive and a good predictor for most macronutrients deficiencies in East Africa (Tolhurst, 1976; Othieno, 1988) and Central Africa (TRFCA, 1990), mature leaf was only sensitive predictor for phosphorus deficiency in Sri Lanka (Sivapalan *et al*., 1986) and potassium deficiency in South India (UPASI, 1987). Soil chemical analysis details the potential of plant nutrients in the soil and the ability of plant to extract those nutrients (Anon 2002; Kamau *et al*. 2008). The current results (Tables 51-54) demonstrate that there is either positive or negative relationship between soil nutrients levels and yield. Thus yields are affected by the levels of soil nutrients. Therefore, in addition to making a fertilizer program, not only leaf analysis but also soil samples analysis should be evaluated together to solve nutrition problems since plant analysis elucidates the nutrients taken up by the plant (Nathan and Warmund 2008) but not total nutrients in the soil.

4.5 The Relationship (r) between Soil Organic Carbon Contents and Soil Nutrients Level

Correlation statistical analysis for soil organic carbon contents and nutrients levels are presented in Tables 51-54. Soil organic carbon correlated ($r \geq -0.878$, $p \leq 0.05$,) negatively with potassium, calcium, magnesium and zinc at all seven sites except Kitabi which had a positive association with zinc. This may require further experimentation to understand the cause. The decrease in these nutrients with increased soil organic carbon could be as a result of immobilization of these nutrients (Paul and Clark, 1989; Smith *et al*., 1993) by the high levels of organic carbon contents observed in the regions.

The other four soil nutrients (nitrogen, phosphorus, aluminium, iron, copper and manganese) had a statistically ($r \geq 0.878$, $p \leq 0.05$) positive relation with soil organic carbon in all the sites under investigation. This implies that increased soil organic carbon contents led to increase in those soil nutrients levels. These results are in agreement with previous findings (Özyazic *et al*., 2011; Reitam *et al*., 2005; Nath, 2014) who reported a significant positive relationship between soil organic carbon with zinc and iron levels. The results demonstrate that soil organic carbon influence soil zinc and iron levels. The high SOC contents in the regions (Tables 2-5) could have led to improved soil iron and zinc levels as in the previous studies (Nath, 2013). In contrast, soil manganese and copper levels had a significant ($p \leq 0.05$, $r = -0.878$) negative correlation with organic carbon in their findings. These variations could be attributed to management practices where tea prunings are not left *in situ* resulting into low levels of organic carbon. In other findings (Nath, 2013; Nath and Bhattacharyya 2014), organic carbon highly significantly correlated to nitrogen, phosphorus and potassium. The existence of a significant positive correlation between soil organic carbon and soil nitrogen indicates that increasing nitrogen application rates result in improved soil organic carbon content. Similar observations were reported by Venkatesan *et al*, (2004) and Thenmozhi *et al*, (2012). Tea soils are known to accumulate more extractable aluminium levels (Ruan *et al*., 2004; Ding and Huang, 1991) which is attributed to increased organic carbon contents in tea soils (Ruan *et al*., 2006). The current study supports the observations made by Dong *et al*.,

(1999) who also reported a positive correlation between soil organic carbon and aluminium levels. Soil calcium and magnesium levels had a strong significant ($r \geq -0.878$, $p \leq 0.05$) negative correlation with soil organic carbon contents supporting early observations (Adiloğlu and Adiloğlu, 2006; Eyüpoğlu, 1999). This could be probably due to leaching of these nutrients in acidic tea soils causing their decrease and consequently negative linear association with organic carbon. Therefore, the levels of these nutrients can be improved if farmers use management practices which reduce soil acidity. The strong correlation between soil organic carbon and nutrients suggest that, tea farms with sufficient organic carbon can supply sufficient nutrients to the plant (Othieno, 1980) during its decomposition and mineralization and thus enhance crop productivity. The study demonstrates that soils with high SOC may have increased levels of nitrogen, phosphorus, aluminium, iron, copper and manganese, while soils with low SOC may have reduced levels in soil potassium, calcium, magnesium and zinc.

4.6 The Relationship (r) between Soil Organic Carbon Contents, pH and Yields of Tea.

The correlations of soil organic carbon, pH and yields of tea are represented in Tables 50-53. The data revealed that yields of tea had a positive relationship with soil organic carbon which reached significant levels ($r \geq 0.878$, $p \leq 0.05$) in Timbilil, Arroket and Kitabi at 0-10cm, Timbilil, Changoi, Arroket, Katoke at 10-20cm, Timbilil, Changoi, Arroket at 20-30cm, Timbilil, Changoi, Arroket and Katoke at 40-60cm soil profiles. These observations support earlier findings by Thu and Nguyen, (2011) and Venkatesan *et al*. (2004). Soil organic carbon is often considered the most important proportion of SOM in providing nutrients to plants (Wolf and Snyder, 2003). Soil nutrients from SOC are mineralized and released as plant available forms into the soil mineral nutrient pool (Doxbury *et al*., 1989; Baldock and Nelson, 1999), thus improving yields of tea (Venkatesan *et al*., 2004; Kamau *et al*., 2008). The study demonstrates that soils with improved soil organic carbon could lead to improved crop productivity. Since there seems to be an association between yield and soil organic carbon, farmers could have sustained crop production if they maintain sufficient soil organic carbon in their fields.

Soil organic carbon ontents showed a negative correlation ($r \geq -0.878$, $p \leq 0.05$) with pH at all sites and depths (Tables 50-53). This indicates that SOC increases with decreasing soil pH, an observation supported by other researchers (Özyazici *et al*., 2011; Nath, 2013). This relationship may be attributed to soil nitrogen which tends to influence soil pH (Mc Andrew and Malhi, 1992, Thenmozhi *et al*., 2012) and release of organic acids during decomposion of plant litter (Stevenson, 1982; Tabatabai *et al*., 1992; Dang, 2002). The decrease in soil pH might lead to fixation of other nutrients like phosphorus, accumulation of others like manganese and aluminium and leaching of base ions. This might lead to decline in crop production. Therefore, judicious use of nitrogen fertilizers in association with other appropriate management practices will make possible sustained increased production of tea in East Africa. Also the relationship between soil organic carbon and pH demonstrates that soil organic carbon influence pH levels in tea soil. Therefore, the amount of organic carbon contents should be monitored from time to time to mitigate the increase in soil acidity and ensure improved crop productivity.

Table 51: Correlation coefficients (r) of soil organic carbon, pH, nutrients levels and yields (Depth 0-10 cm)

Site	**TRI**		**Changoi**		**Arroket**		**Kitabi**		**Mulindi**		**Katoke**		**Maruku**	
	SOC	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**
parameter	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**
N	0.867	0.870	0.977	0.734	0.967	0.959	0.986	0.861	0.798	0.841	0.907	0.926	0.978	0.662
P	0.947	0.898	0.860	0.987	0.988	0.933	0.960	0.794	0.741	0.720	0.849	0.978	0.847	0.302
K	-0.971	-0.975	-0.762	-0.795	-0.942	-0.966	-0.908	-0.804	-0.66	-0.573	-0.993	-0.779	-0.84	-0.777
Ca	-0.967	-0.990	-0.941	-0.951	-0.914	-0.975	-0.856	-0.833	-0.781	-0.670	-0.694	-0.528	-0.937	-0.599
Mg	-0.997	-0.982	-0.841	-0.676	-0.983	-0.970	-0.936	-0.839	-0.961	-0.680	-0.832	-0.880	-0.961	-0.624
Al	0.967	0.982	0.715	0.900	0.852	0.798	0.966	0.969	0.907	0.680	0.886	0.961	0.933	0.716
Fe	0.969	0.988	0.998	0.867	0.865	0.962	0.955	0.975	0.881	0.740	0.840	0.900	0.866	0.438
Zn	-0.950	-0.990	-0.821	-0.915	-0.909	-0.946	0.972	0.930	-0.946	-0.625	-0.768	-0.887	-0.949	-0.541
Cu	0.970	0.970	0.875	0.980	0.842	0.988	0.983	0.922	0.934	0.629	0.880	0.970	0.881	0.356
Mn	0.928	0.948	0.954	0.953	0.947	0.962	0.941	0.780	0.886	0.678	0.950	0.856	0.959	0.500
pH	-0.642	-0.701	-0.897	-0.936	-0.703	-0.802	-0.982	-0.948	-0.989	-0.505	-0.848	-0.700	-0.908	-0.494
Yield	0.984		0.862		0.910		0.903		0.503		0.810		0.614	

(n=5, p≤0.05, r =± 0.878)

Table 52: Correlation coefficients of soil organic carbon, pH, nutrients levels and yields (Depth 10-20 cm)

Site	**TRI**		**Changoi**		**Arroket**		**Kitabi**		**Mulindi**		**Katoke**		**Maruku**	
	SOC	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**
parameter	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**
N	0.990	0.955	0.882	0.953	-0.599	-0.520	0.922	0.856	0.979	0.501	0.984	0.937	0.894	0.689
P	0.966	0.913	0.959	0.930	0.959	0.942	0.914	0.857	0.943	0.656	0.920	0.820	0.993	0.812
K	-0.992	-0.974	-0.927	-0.881	0.535	0.517	-0.955	-0.915	-0.983	-0.581	-0.923	-0.822	-0.904	-0.571
Ca	-0.989	-0.984	-0.928	-0.987	-0.963	-0.945	-0.786	-0.783	-0.987	-0.674	-0.994	-0.944	-0.914	-0.663
Mg	-0.991	-0.98	-0.964	-0.993	-0.795	-0.828	-0.889	-0.979	-0.981	-0.609	-0.968	-0.904	-0.895	-0.679
Al	0.895	0.894	0.920	0.967	0.938	0.966	0.935	0.830	0.977	0.675	0.909	0.820	0.857	0.688
Fe	0.943	0.914	0.936	0.811	0.976	0.985	0.948	0.928	0.994	0.674	0.977	0.937	0.888	0.719
Zn	-0.844	-0.908	-0.888	-0.951	-0.911	-0.878	0.951	0.833	-0.907	-0.791	-0.930	-0.899	-0.956	-0.743
Cu	0.839	0.876	0.937	0.979	0.950	0.990	0.970	0.878	0.965	0.750	0.975	0.948	0.791	0.671
Mn	0.956	0.924	0.985	0.960	0.988	0.982	0.968	0.963	0.970	0.671	0.914	0.802	0.931	0.896
pH	-0.937	-0.948	-0.919	-0.875	-0.968	-0.942	-0.872	-0.830	-0.997	-0.655	-0.930	-0.833	-0.786	-0.494
Yield	0.985		0.960		0.982		0.960		0.589		0.974		0.781	

(n=5, p≤0.05, r =± 0.878)

Table 53: Correlation coefficients of soil organic carbon, pH, nutrients levels and yields (Depth 20-30 cm)

Site	TRI		Changoi		Arroket		Kitabi		Mulindi		Katoke		Maruku	
	SOC	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**
Parameter	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**R**	**r**	**r**
N	0.988	0.954	0.254	0.412	0.801	0.923	0.988	0.844	0.972	0.461	0.945	0.955	0.953	0.674
P	0.955	0.981	0.875	0.978	0.966	0.942	0.878	0.974	0.934	0.477	0.868	0.869	0.933	0.695
K	-0.972	-0.951	-0.900	-0.924	-0.862	-0.992	-0.763	-0.806	-0.504	-0.327	-0.945	-0.842	-0.948	-0.700
Ca	-0.837	-0.859	-0.878	-0.978	-0.938	-0.853	-0.975	-0.798	-0.952	-0.692	-0.989	-0.886	-0.971	-0.700
Mg	-0.674	-0.761	-0.981	-0.986	-0.951	-0.884	-0.810	-0.791	-0.982	-0.527	-0.972	-0.891	-0.936	-0.724
Al	0.923	0.872	0.865	0.947	0.922	0.983	0.984	0.928	0.967	0.615	0.856	0.878	0.991	0.650
Fe	0.855	0.883	0.907	0.996	0.940	0.882	0.965	0.958	0.993	0.500	0.875	0.985	0.991	0.617
Zn	-0.675	-0.754	-0.906	-0.985	-0.88	-0.717	0.996	0.888	-0.814	-0.442	-0.856	-0.980	-0.969	-0.578
Cu	0.941	0.986	0.822	0.949	0.948	0.915	0.979	0.798	0.960	0.539	0.905	0.893	0.993	0.480
Mn	0.966	0.923	0.977	0.991	0.954	0.915	0.831	0.963	0.982	0.529	0.931	0.866	0.988	0.541
pH	-0.922	-0.929	-0.947	-0.973	-0.917	-0.964	-0.965	-0.860	-0.973	-0.447	-0.912	-0.766	-0.941	-0.778
Yield	0.982		0.940		0.878		0.850		0.502		0.862		0.551	

(n=5, $p \leq 0.05$, r =± 0.878)

Table 54: Correlation coefficients of soil organic carbon, pH, nutrients levels and yields (Depth 40-60 cm)

Site	TRI		Changoi		Arroket		Kitabi		Mulindi		Katoke		Maruku	
	SOC	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**	**SOC**	**Yield**
Parameter	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**r**	**R**	**r**	**r**
N	0.899	0.897	0.941	0.957	0.909	0.968	0.867	0.932	0.969	0.531	0.992	0.899	0.989	0.690
P	0.913	0.925	-0.742	0.848	0.948	0.988	0.934	0.925	0.818	0.587	0.983	0.938	0.887	0.782
K	-0.936	-0.953	0.401	0.390	-0.779	-0.889	-0.948	-0.963	-0.379	-0.651	-0.838	-0.736	-0.982	-0.719
Ca	-0.956	-0.967	-0.737	-0.757	-0.847	-0.929	-0.947	-0.943	-0.887	-0.825	-0.982	-0.930	-0.973	-0.600
Mg	-0.831	-0.871	-0.929	-0.984	-0.983	-0.968	-0.891	-0.823	-0.927	-0.698	-0.974	-0.867	-0.999	-0.757
Al	0.965	0.963	0.924	0.911	0.927	0.866	0.980	0.891	0.945	0.684	0.927	0.918	0.959	0.626
Fe	0.807	0.846	0.868	0.886	0.464	0.562	0.984	0.937	0.957	0.616	0.978	0.943	0.906	0.873
Zn	-0.964	-0.978	-0.937	-0.981	-0.847	-0.945	0.959	0.859	-0.982	-0.593	-0.983	-0.948	-0.997	-0.715
Cu	0.858	0.974	0.968	0.969	0.769	0.910	0.956	0.926	0.937	0.606	0.942	0.798	0.975	0.682
Mn	0.978	0.984	0.921	0.951	0.902	0.932	0.684	0.737	0.902	0.589	0.970	0.924	0.798	0.320
pH	-0.964	-0.930	-0.92	-0.973	-0.68	-0.793	-0.989	-0.832	-0.757	-0.063	-0.988	-0.919	-0.958	-0.681
Yield	0.946		0.974		0.957		0.864		0.573		0.933		0.745	

(n=5, p≤0.05, r =± 0.878)

CHAPTER FIVE

SUMMARY, CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS FOR FUTURE STUDIES

5.1 Summary

i. Soil organic carbon, pH and nutrients levels differed ($p \leq 0.05$) with location of production

ii. Calcium, magnesium, potassium, zinc and pH declined ($p \leq 0.05$), while levels of soil aluminium, copper, iron, phosphorus, nitrogen, manganese and SOC increased ($p \leq 0.05$) with increase in nitrogenous fertilizer rates at all sites.

iii. Nitrogenous fertilizer application rates above 200kgN/ha/year led to decline in soil pH to as low as 3.10 in some regions.

iv. Generally, soil organic carbon, pH and nutrients were not influenced by harvesting intervals. However, the patterns observed were sporadic

v. There were interaction ($p \leq 0.05$) effects between sites x nitrogenous fertilizer rates indicating differences in patterns of change in observed variations of soil quality indicators

vi. There was a positive ($p \leq 0.05$) linear association between yield and soil posphorus, nitrogen, aluminium, copper, and manganese contents but negative ($p \leq 0.05$) correlation with potassium, calcium, magnesium, and zinc levels. Therefore, increase in soil posphorus, nitrogen, aluminium, copper, and manganese could lead to improved crop productivity while decline in levels of potassium, calcium, magnesium, and zinc could cause a reduction in tea yields.

vii. Soil organic carbon correlated ($p \leq 0.05$) positively with phosphorus, nitrogen, aluminium, iron, copper and manganese levels but negatively with potassium, calcium, magnesium and zinc levels. Therefore, soils with high SOC may have improved levels of phosphorus, nitrogen, aluminium, iron, copper and manganese. Those with low SOC contents may have declined levels of potassium, calcium, magnesium and zinc levels.

viii. Soil organic carbon correlated ($p \leq 0.05$) positively with yields but negatively with soil pH. This implies that improved soil organic contents could result in increased crop productivity but decreased soil pH.

5.2 Conclusions

- Location of production determines soil organic carbon contents, pH and nutrients levels.
- Nitrogenous fertilizer rates increase soil aluminium, copper, iron, phosphorus, nitrogen, manganese and soil organic carbon contents but decreases Calcium, magnesium, potassium, zinc and pH levels.
- Nitrogenous fertilizer application rates above 200kgN/ha/year decrease soil pH below optimal levels for tea productivity.
- Harvesting intervals do not change soil organic carbon contents, pH and nutrients levels.
- Increase in soil posphorus, nitrogen, aluminium, copper, and manganese could lead to improved crop productivity while decline in levels of potassium, calcium, magnesium, and zinc could cause a reduction in tea yields.
- Soils with high SOC may have improved levels of phosphorus, nitrogen, aluminium, iron, copper and manganese. Those with low SOC contents may have declined levels of potassium, calcium, magnesium and zinc levels.
- Improved soil organic contents could result in increased crop productivity but decrease soil pH.

5.3 Recommendations

- Soil organic carbon contents and some nutrients levels in tea farms could be improved by addition of nitrogenous fertilizers.
- High nitrogen fertilizer rates acidify soil. And since tea prunings are left in the fields, nitrogen rates below 200KgN/ha/year could be appropriate for tea productivity in Eastern Africa tea growing regions.
- Correlations between soil nutrients levels and yields indicate that farmers should engage in management activities that could result in improved soil nutrients to realize high tea yields.
- The correlation between soil organic carbon and nutrients suggest that, tea farmers should engage in management practices that ensure optimal SOC contents to improve nutrients levels for crop productivity.

- Farmers should engage in management practices that could improve soil organic carbon contents for sustainable crop productivity. However, the amount of soil organic should be monitored from time to time to mitigate the increase in soil acidity.

5.4 Suggestions for Future Studies

- Monitoring the same trials for a longer period of time is needed to establish the causes of sporadic patterns demonstrated by harvesting intervals.
- Each location should be evaluated for optimum nitrogenous fertilizer rates that would ensure optimum SOC, pH, soil nutrients levels for sustainable production
- Positive correlations between SOC and soil zinc levels observed at Kitabi may require further experimentation to understand the cause.

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APPENDICES

Appendix I: Experimental Layout for Clone 6/8 Fertilizer Trials in the Sites.

1 N300 Pf7	2 N0 Pf21	3 N150 Pf21	4 N225 Pf14	5 N0 Pf7
10 N300 Pf 21	9 N150 Pf7	8 N300 Pf14	7 N225 Pf21	6 N75 Pf14
11 N225 Pf7	12 N150 Pf14	13 N75 Pf21	14 N0 Pf14	15 N75 Pf7
20 N225 Pf21	19 N225 Pf14	18 N150 Pf21	17 N75 Pf14	16 N0 Pf21
21 N225 Pf7	22 N300 Pf14	23 N150 Pf14	24 N300 Pf7	25 N300 Pf21
30 N75 Pf21	29 N0 Pf14	28 N0 Pf7	27 N75 Pf7	26 N150 Pf7
31 N25 Pf14	32 N75 Pf14	33 N225 Pf21	34 N150 Pf21	35 N225 Pf7
40 N75 Pf7	39 N300 Pf7	38 N300 Pf14	37 N150 Pf14	36 N0 Pf21
41 N300 Pf21	42 N150 Pf7	43 N0 Pf7	44 N75 Pf21	45 N0 Pf14
Note: REP 1 Plots 1-15; REP 2 Plots 16-30; REP 3 Plots 31-45. N150 Pf21 denotes; Nitrogen fertilizer application at 150 kg N/Ha/yr as NPKS and a plucking frequency of 21 days. Plant population per plot: 50 bushes, Spacing: 1.22 m x 0.9m				

Appendix II: Data Collection and Analysis Clips

Soil sampling at one of the sites (Timbilil)

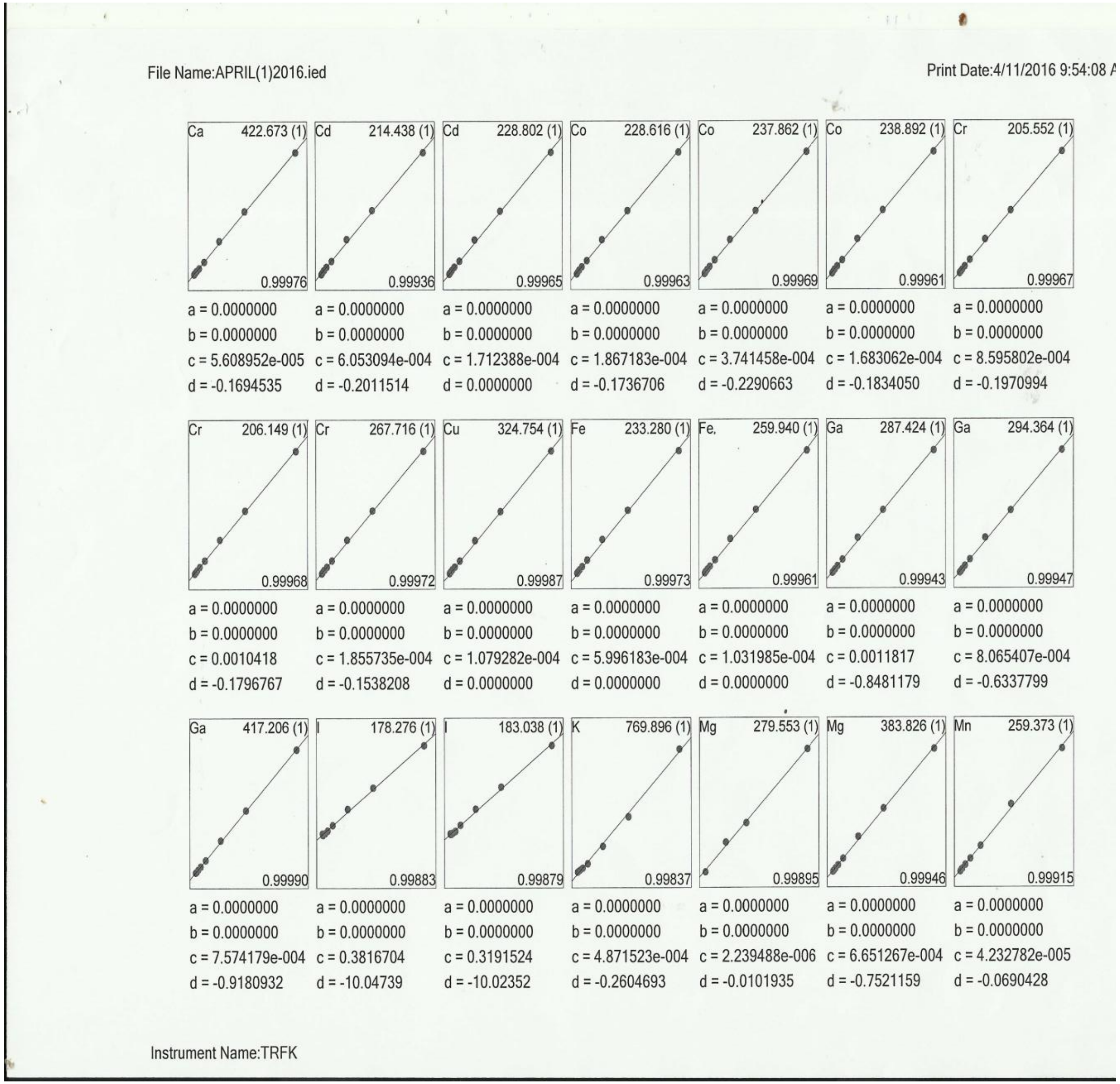
Soil drying under shade

Soil pH determination

Determination of Nitrogen- Kjeldahl method (steam distillation)

Soil samples preparation for SOC and nutrients determination

Appendix III: Calibration Curves for Soil Nutrients Analysi



File Name:APRIL(1)2016.ied

Print Date:4/11/2016 9:54:08 A

Ca 422.673 (1)
0.99976
a = 0.0000000
b = 0.0000000
c = 5.608952e-005
d = -0.1694535

Cd 214.438 (1)
0.99936
a = 0.0000000
b = 0.0000000
c = 6.053094e-004
d = -0.2011514

Cd 228.802 (1)
0.99965
a = 0.0000000
b = 0.0000000
c = 1.712388e-004
d = 0.0000000

Co 228.616 (1)
0.99963
a = 0.0000000
b = 0.0000000
c = 1.867183e-004
d = -0.1736706

Co 237.862 (1)
0.99969
a = 0.0000000
b = 0.0000000
c = 3.741458e-004
d = -0.2290663

Co 238.892 (1)
0.99961
a = 0.0000000
b = 0.0000000
c = 1.683062e-004
d = -0.1834050

Cr 205.552 (1)
0.99967
a = 0.0000000
b = 0.0000000
c = 8.595802e-004
d = -0.1970994

Cr 206.149 (1)
0.99968
a = 0.0000000
b = 0.0000000
c = 0.0010418
d = -0.1796767

Cr 267.716 (1)
0.99972
a = 0.0000000
b = 0.0000000
c = 1.855735e-004
d = -0.1538208

Cu 324.754 (1)
0.99987
a = 0.0000000
b = 0.0000000
c = 1.079282e-004
d = 0.0000000

Fe 233.280 (1)
0.99973
a = 0.0000000
b = 0.0000000
c = 5.996183e-004
d = 0.0000000

Fe. 259.940 (1)
0.99961
a = 0.0000000
b = 0.0000000
c = 1.031985e-004
d = 0.0000000

Ga 287.424 (1)
0.99943
a = 0.0000000
b = 0.0000000
c = 0.0011817
d = -0.8481179

Ga 294.364 (1)
0.99947
a = 0.0000000
b = 0.0000000
c = 8.065407e-004
d = -0.6337799

Ga 417.206 (1)
0.99990
a = 0.0000000
b = 0.0000000
c = 7.574179e-004
d = -0.9180932

I 178.276 (1)
0.99883
a = 0.0000000
b = 0.0000000
c = 0.3816704
d = -10.04739

I 183.038 (1)
0.99879
a = 0.0000000
b = 0.0000000
c = 0.3191524
d = -10.02352

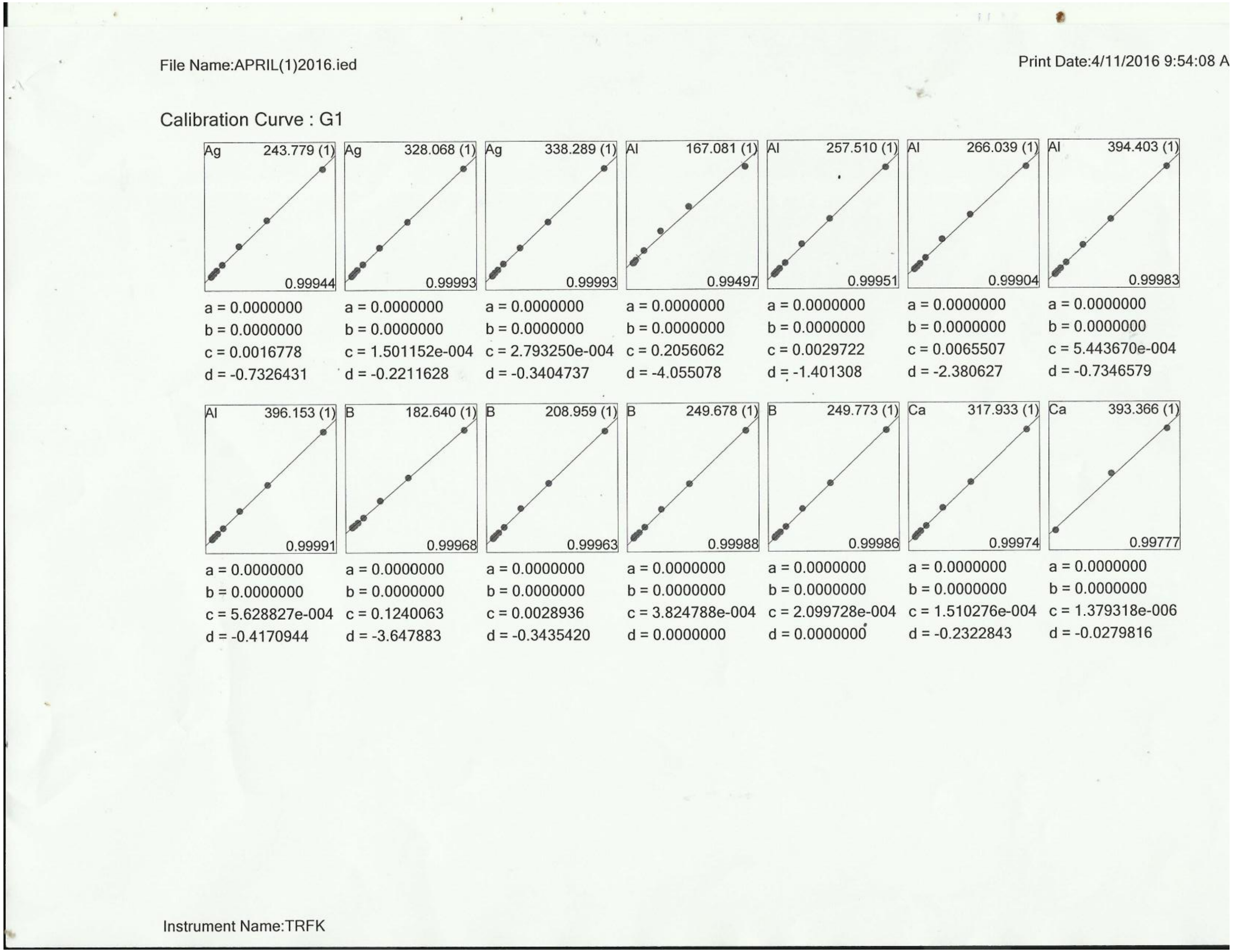
K 769.896 (1)
0.99837
a = 0.0000000
b = 0.0000000
c = 4.871523e-004
d = -0.2604693

Mg 279.553 (1)
0.99895
a = 0.0000000
b = 0.0000000
c = 2.239488e-006
d = -0.0101935

Mg 383.826 (1)
0.99946
a = 0.0000000
b = 0.0000000
c = 6.651267e-004
d = -0.7521159

Mn 259.373 (1)
0.99915
a = 0.0000000
b = 0.0000000
c = 4.232782e-005
d = -0.0690428

Instrument Name:TRFK



File Name:APRIL(1)2016.ied

Print Date:4/11/2016 9:54:08 A

Calibration Curve : G1

Ag 243.779 (1)
0.99944
a = 0.0000000
b = 0.0000000
c = 0.0016778
d = -0.7326431

Ag 328.068 (1)
0.99993
a = 0.0000000
b = 0.0000000
c = 1.501152e-004
d = -0.2211628

Ag 338.289 (1)
0.99993
a = 0.0000000
b = 0.0000000
c = 2.793250e-004
d = -0.3404737

Al 167.081 (1)
0.99497
a = 0.0000000
b = 0.0000000
c = 0.2056062
d = -4.055078

Al 257.510 (1)
0.99951
a = 0.0000000
b = 0.0000000
c = 0.0029722
d = -1.401308

Al 266.039 (1)
0.99904
a = 0.0000000
b = 0.0000000
c = 0.0065507
d = -2.380627

Al 394.403 (1)
0.99983
a = 0.0000000
b = 0.0000000
c = 5.443670e-004
d = -0.7346579

Al 396.153 (1)
0.99991
a = 0.0000000
b = 0.0000000
c = 5.628827e-004
d = -0.4170944

B 182.640 (1)
0.99968
a = 0.0000000
b = 0.0000000
c = 0.1240063
d = -3.647883

B 208.959 (1)
0.99963
a = 0.0000000
b = 0.0000000
c = 0.0028936
d = -0.3435420

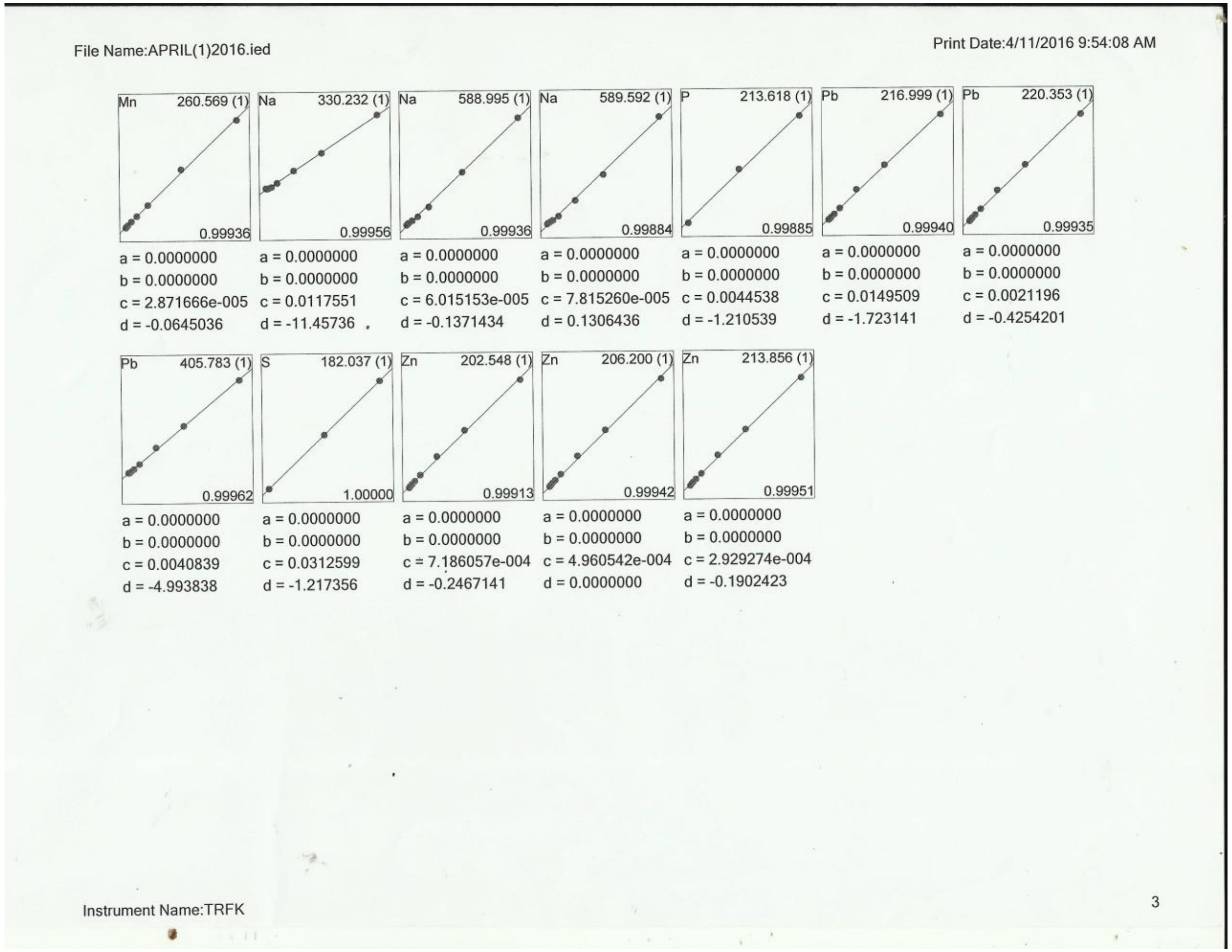
B 249.678 (1)
0.99988
a = 0.0000000
b = 0.0000000
c = 3.824788e-004
d = 0.0000000

B 249.773 (1)
0.99986
a = 0.0000000
b = 0.0000000
c = 2.099728e-004
d = 0.0000000

Ca 317.933 (1)
0.99974
a = 0.0000000
b = 0.0000000
c = 1.510276e-004
d = -0.2322843

Ca 393.366 (1)
0.99777
a = 0.0000000
b = 0.0000000
c = 1.379318e-006
d = -0.0279816

Instrument Name:TRFK



File Name:APRIL(1)2016.ied

Print Date:4/11/2016 9:54:08 AM

Mn 260.569 (1)
0.99936
a = 0.0000000
b = 0.0000000
c = 2.871666e-005
d = -0.0645036

Na 330.232 (1)
0.99956
a = 0.0000000
b = 0.0000000
c = 0.0117551
d = -11.45736

Na 588.995 (1)
0.99936
a = 0.0000000
b = 0.0000000
c = 6.015153e-005
d = -0.1371434

Na 589.592 (1)
0.99884
a = 0.0000000
b = 0.0000000
c = 7.815260e-005
d = 0.1306436

P 213.618 (1)
0.99885
a = 0.0000000
b = 0.0000000
c = 0.0044538
d = -1.210539

Pb 216.999 (1)
0.99940
a = 0.0000000
b = 0.0000000
c = 0.0149509
d = -1.723141

Pb 220.353 (1)
0.99935
a = 0.0000000
b = 0.0000000
c = 0.0021196
d = -0.4254201

Pb 405.783 (1)
0.99962
a = 0.0000000
b = 0.0000000
c = 0.0040839
d = -4.993838

S 182.037 (1)
1.00000
a = 0.0000000
b = 0.0000000
c = 0.0312599
d = -1.217356

Zn 202.548 (1)
0.99913
a = 0.0000000
b = 0.0000000
c = 7.186057e-004
d = -0.2467141

Zn 206.200 (1)
0.99942
a = 0.0000000
b = 0.0000000
c = 4.960542e-004
d = 0.0000000

Zn 213.856 (1)
0.99951
a = 0.0000000
b = 0.0000000
c = 2.929274e-004
d = -0.1902423

Instrument Name:TRFK

3