VARIATIONS IN YIELDS AND YIELD COMPONENTS WITH GEOGRAPHICAL LOCATION AND RESPONSE OF CLONAL TEA (*Camellia sinensis*) TO NITROGENOUS FERTILISER RATES IN KENYA

BY

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DECLARATION

I certify that this thesis has not been previously presented for a degree in Maseno University or in any other university. The work reported herein is my original work and all sources of information have been supported by relevant references.

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DEDICATION

This work is dedicated to my dear daughters Cynthia Atieno, Audrey Atieno, Roxxanne Amondi, Maxxinne Achieng and beloved sons Antwonne Sijenyi and Arphaxad Odhiambo.

ABSTRACT

Tea provides income and employment to rural populations in many countries. Tea, grown in east and west of the Rift Valley, is the leading export commodity crop in Kenya. Variable responses among genotypes to different environments and fertilizer influence growth, productivity, leaf nutrients, and quality. However, husbandry practices are uniform in all tea growing regions. These recommendations may not be optimum universally. Genotypes planted and management practices may therefore not give desired yields as resource allocation and productivity may not be optimal. Optimized regional fertilizer needs have not accompanied development of region-specific cultivars. Understanding the variations in growth parameters and yields to varying environments may help optimize husbandry practices in different regions. Responses in shoot densities, weights; growth rates and radiation interception of 20 tea clones to ambient temperatures, rainfall, humidity and saturation deficits; the nitrogen use efficiency and responses of clone TRFK 6/8 to nitrogen rates, were studied in different tea growing regions varying in altitude, in two experiments. A genotype x environment clonal evaluation experiment was established in Kangaita, Timbilil and Sotik; fertiliser rate trials were instituted in Timbilil, Changoi and Sotik, each replicated three times in RCBD. Yield and yield components responses to weather parameters varied with genotype, location and season. Shoot growth rates (Timbilil (r = 0.476)) and shoot density (Kangaita (r = 0.652)) significantly ($p \leq 0.05$) correlated with yields. Yield and weather parameters' contribution to yield changed with locations. Conversion efficiency, it's constituent components and temperature, combined were related to yields. Altitude significantly determined conversion efficiency, drought reduced yields and rainfall distribution affected seasonal yield distribution. Yield increased with ($p \leq 0.05$) nitrogen application, with low responses in Timbilil. Nitrogen application between 75-300Kg N did not significantly change harvestable shoots nitrogen contents though amount of nitrogen removed with crop varied considerably. Nitrogen Use Efficiency decreased with nitrogen rates. Only Ca and Fe leaf contents varied ($p \leq 0.001$) with nitrogen rates. All leaf nutrients, except Mn varied significantly with location. No relationships existed between leaf nutrient contents and nitrogen rate at any location. Yield and yield components response to nitrogen rates varied with location and cultivars. Yield components cannot apply as yield indicators in clonal selection, universally. Leaf nutrient content may not indicate plant response to fertilization. Yield and yield components response to nitrogen varied with location. Tea crop response to fertilizer is site specific and universal application of fertilizer may only apply as general guideline but will not optimize production.

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LIST OF ABBREVIATIONS/ACRONYMS

DM: Dry Matter

GC: Ground cover

HI: Harvest Index

HIRUE: Harvest Index Radiation Use Efficiency

kPa: KiloPascal

KTDA: Kenya Tea Development Agency

LAI: Leaf Area Index

MJ: Mega Joules

mV: millivolts

NUE: Nitrogen use efficiency

RUE: Radiation use efficiency

Sd/sd: Shoot density

SD: Saturation Deficit

Sd: Shoot density

Sdwt:Shoot dry weight

Sgr: Shoot growth rste

SRC : Shoot replacement cycle

SVPD: Saturated Vapour Pressure Deficit

Svpd:Saturated vapour pressure deficit

Swp: Shoot water potential

TRFK:Tea Research Foundation of Kenya

Vpd : Vapour pressure deficit

DEFINITION OF TERMS

Canopy extinction coefficient: an expression of the power of a canopy to absorb light

Clones/Cultivars/ Genotype: A plant or group of plants identical within themselves but genetically distinct from other plant(s)

Commercially: used in trade

Leaf Area Index: Proportion of the ground under the canopy, covered by the leaf area fraction of

Nitrogen use efficiency: Units of dry matter produced per unit of nitrogen

Radiation energy: Energy of sunlight

Radiation Use efficiency/ Conversion efficiency: Units of dry matter produced per unit of

Radiations: Electromagnetic energy from sunlight

Radiative power: power in watts from sunlight radiation

Seedling tea: Tea plants that are derived from seeds

Site/ Location: The physical geographical position of a block of land

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CHAPTER ONE

INTRODUCTION

1.1.1 Background of the Study

Tea (*Camellia sinensis* (L). O Kuntze) is a perennial tree belonging to the *Theacea* family (Bokuchava and Skobelova, 1969; Hara *et al.*, 1995) that is managed as a low bush in continuous phase of vegetative growth. Commercially, three main varieties are recognized, namely: C*amellia sinensis* var. *sinensis*, a chinary type with small leaves, *Camellia sinensis* var. *assamica*, an Assam variety with broad leaves and *Camellia sinensis* var *assamica spp. lasiocalyx*, a variety thought to be a hybrid between the first two and originating from Cambodia (Wight, 1962, Banerjee, 1992). These varieties are extensively commercially exploited (Banerjee, 1992). However, two new varieties *Camellia sinesis* var. *pubilimba* and *Camellia sinesis* var. *Kucha* were recently recognized to have commercial potential in China (Yao *et al.,* 2008).

The tea plant is an important cash crop providing income to farmers and employment to rural populations in many parts of the world. In East Africa it is grown in Kenya, Tanzania, Uganda, Rwanda and Burundi occupying 224,642 Ha with a total production of 443,875 metric tonnes of made tea in 2016 (ITC, 2016). The industry was estimated to sustain directly or indirectly about 20 million people in the region (Kinyili, 2003; Techno-Serve, 2006). In Kenya tea was grown on 157,720 hectares (ha) that produced 399,000,000 tonnes of made tea in 2016 (ITC 2016; TBK, 2016), and contributed to 4% of GDP and 28% (equivalent to KShs 102 billion) of export earnings. This was the highest export earnings from a single commodity and crop. In East Africa, tea is grown in the highlands which differ widely in elevation, climatic and edaphic factors thus falling into different geographical regions ranging in altitude from 970m above mean sea level (a.m.s.l) in Southern Tanzania (Kigalu and Rarikiel, 2009) to 2700m a.m.s.l in Olenguruone, Kenya and Gisovu, Rwanda

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(Anon, 2002a; Owuor *et al.,* 2008). In Kenya, the crop is grown in the high rainfall highland areas: foothills of the Aberdares ranges and Mt Kenya, in the east of the Rift Valley and the Mau ranges; Nandi, Kisii and Kagamega hills and slopes of Mt. Elgon in the west of the Rift Valley (Owuor *et al.,* 1997), which range in altitude from 1300m to 2700m (Anon, 2002a). These areas lie close to and almost along the equator and shoots are harvested every 7 to 14 days (Eden, 1931) throughout the year. However, yields (Squire, 1979; Tanton, 1992) and quality (Owuor, 1990; Owuor, 1994; Owuor, 1992a; Owuor, 1992b) are affected by fluctuations in weather factors within a year and between years in any one location. Despite production close to the equator, the differences in geographical areas of production have been recorded to influence leaf nutrients levels (Kwach *et al. ,* 2014; Omwoyo *et al.,* 2013; Omwoyo *et al.,* 2014), growth (Obaga *et al*., 1988; Squire *et al.,* 1993), productivity (Msomba *et al.,* 2014; Wachira *et al.,* 2002) precursors of tea quality parameters (Cherotich *et al.,* 2013; Kwach *et al.,* 2013; Kwach *et al.,* 2016; Okal *et al.,* 2012a,b Owuor *et al*., 2013a; Owuor *et al*., 2011) and quality (Owuor *et al.,* 1990, Owuor *et al.,* 2009; Owuor *et al.,* 2010a,b) of tea. Thus, despite use of similar/same genotypes and management practices, yields, leaf nutrients and quality vary across the region. This suggests growth patterns in different genotypes may not be the same in the region. Consequently, performance of same cultivar may vary with location of production despite the current assumption that good cultivars maintain their performance in all regions. The variations in growth patterns of different genotypes with location have not been ascertained. It is therefore uncertain whether yields in different locations could be predicted from the yields components.

Tea productivity (Squire *et al.,* 1993;; Anandacoomaraswamy *et al*., 2000) and quality varied with soil types (Fung *et al*., 2003; Li *et al*., 2007 Jin *et al*., 2008), altitude (Owuor *et al*., 1990; Mahanta *et al*., 1988) and weather factors (Othieno *et al.*, 1992; Balasuriya, 1999; Ng'etich *et al*.,

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2001). There was yield reduction during dry and cool seasons (Tanton, 1979; Odhiambo *et al*., 1993). Indeed, the variations in yield performance of genotypes relative to each other and to the environment have been widely documented (Wachira *et al.,* 2002; Ng'etich *et al.,* 2001; Wickramaratne, 1981) with the phenomenon having been formulated in the Genotype by Environment (G×E) interaction concept (Wickramaratne, 1981). However, the mechanisms causing the variations in yields are not widely documented, especially since the level and extents of the variations may change with genotypes. The seasonal variations in responses of tea yield components with genotypes and locations are not well elucidated to provide an explanation to the observed yield responses which may lead to development of management practices that enhance productivity in different clones in different locations.

Fertilizers, especially nitrogenous fertilizers, are widely used in tea production in East Africa. Indeed, nitrogenous fertilizer use is the second largest agronomic tea production cost item after plucking (Sharma, 1987; Willson, 1992; Mwaura *et al.,* 2010). The nitrogenous fertilizer applications are beneficial to tea production (Bonheure, and Willson, 1992; Venkatesan *et al*., 2004). Positive responses of tea yield to nitrogenous fertilizer application in Kenya have been reported widely (Wanyoko *et al.,* 1990; Owuor *et al.,* 1994; Owuor *et al.,* 2008b; Owuor *et al.,* 2013b; Kamau *et al.,* 2003; Msomba *et al.,* 2014). Tea yields in Kenya can be increased by soil application of fertilizers up to a maximum of 470 kg N ha^{-1} (Owuor and Othieno, 1996), although the economic rate lies, at between 100-220kg ha^{-1} year^{-1} (Othieno, 1988; Kiprono *et al.,* 2010). Optimal fertiliser rates were established to vary with clone and geographical area of production (Kamau *et al.,* 1998). However, the general recommended nitrogenous fertilizer application rate remains the same, at between 150-225 kg N ha^{-1} year^{-1} throughout Kenya (Anon, 2002a; Owuor and Othieno, 1996; Owuor and Wanyoko, 1996). Though variations in tea yields response to fertilizers among cultivars have been observed (Owuor and Othieno, 1996; Han *et al.,* 2008; Wanyoko and Njuguna, 1984), most of the

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results were from single clones in single sites and only few studies have compared the same cultivar in different regions (Owuor *et al.,* 2010a; Msomba *et al.,* 2014). From the single site studies, it has not been possible to isolate the effects of environment from that of cultivars. This would give insight into the cause of the variations. However, there is paucity of information on evaluation of a single cultivar under similar management in different environments.

Differences in the ability of clonal teas to extract nutrients from the soil have also been reported (Wanyoko, 1982; Hettierachchi *et al.,* 1997; Kwach *et al.,* 2011; Kwach *et al.,* 2014). This could be complicated further by the large variations in soil fertility across different regions and the uniform use of fertilizer across East Africa (Othieno, 1988). Indeed, these direfrences have resulted in variations in yield responses (Wachira *et al.,* 2002; Owuor *et al.,*2010a; Msomba *et al.,* 2014) and mature leaf nutrient content differences (Kamau *et al.,* 2005; Kwach *et al.,* 2013; Kwach *et al.,* 2014) to fertilizer across different geographical regions. The mechanisms leading to these variations have not been well studied. Correlation studies and field fertiliser trials have proven in many natural environments that nitrogen is one of the primary factors limiting plant growth. The question of which physiological and morphological features of plants serve as adaptations to nitrogen deficient environments and which features lead to high fitness in nitrogen rich environments can only be answered by defining the parameters that measure efficiency of uptake, allocation, residence time and final use from the soil. The measure of efficiency of uptake and use of nitrogen, also referred to as nitrogen use efficiency, is not well studied in tea.

Expression of tea yields is controlled by environment, management practices and plant genome (Tanton, 1979). The yields are a function of a number of components namely: shoot density, shoot growth rate, unit shoot weight at harvest (Burgess, 1992) and rate of shoot regeneration (Odhiambo *et al.,* 1993). Tea yields decline due to reduced shoot growth rate with increase in altitude (Mwakha, 1985; Obaga *et al.,* 1988). Indeed, under Kericho tea growing conditions, yields decrease at the rate

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of 1kg made tea for every 100m rise in altitude (Othieno *et al*., 1992). The variations of the interactions between growth parameters and tea response to fertilizers have not been well defined. These parameters have not been used to evaluate the relationships between tea plant responses to nitrogen in varying environments in Kenya.

1.2 Statement of the Problem

Despite the observed variations in tea responses to environments, the recommended cultural practices have been applied uniformly across tea growing regions in Kenya. The necessary adjustments in the management practices have not been able to be undertaken because: the variations in growth patterns of different genotypes with location have not been ascertained; the mechanisms causing the variations in yields are also not well defined, especially since the level and extents of the variations change with genotypes; the seasonal variations in responses of tea yield components with genotypes and locations are not well elucidated to provide an explanation to the observed yield responses. There is also lack of information on the evaluation of nitrogen rate responses of a single tea cultivar (clone) under similar management in different environments. In this regard: the parameters that measure efficiency of uptake, allocation, residence time and final use of nitrogen from the soil by tea have not been defined; applied nitrogen use efficiency, and particularly in relation to different environments is not well studied in tea and it is also not known whether plant growth and weather parameters may be used to evaluate the relationships between tea plant responses to varying environments to be applied in yield estimation models.

1.3 Broad Objective

To determine the effects of different geographic locations on the responses of growth parameters and yields of some tea clones and that of a tea clone to nitrogenous fertilisers in Kenya.

1.3.1 Specific Objectives

1. To evaluate the annual and seasonal responses of growth parameters and yield of clonal tea to in different geographic locations, in Kenya.

2. To determine the Radiation Use Efficiency (RUE) of clonal teas in different geographic locations, in Kenya.

3. To determine the Nitrogen Use Efficiency of clone TRFK 6/8 in different geographic locations, in Kenya.

4. To determine the nutrient uptake of clone TRFK 6/8 at different rates of fertilizer in different geographic locations, in Kenya.

5. To establish the relationships between tea yield components and varying environment parameters under different N:P:K (25:5:5) fertilizer regimes.

1.4 Null hypotheses (H$_o$)

1. The annual and seasonal response of growth parameters and yield of clonal tea do not vary with geographic locations.

2. The Radiation Use Efficiency (RUE) of clonal teas do not vary with geographic locations

3. The Nitrogen Use Efficiency of clone TRFK 6/8 do not vary with geographic locations

4. The nutrient uptake of clone TRFK 6/8 at different rates of fertilizer do not vary with geographic locations

5. The relationships between tea yield components and varying environment parameters do not vary with N:P:K (25:5:5) fertilizer regimes

1.5 Justification of the Study

Evaluation of the interactive influence of several crop growth variables and their contribution to potential yields of different clones under varying environmental conditions would establish the potential of the use of yields component of tea and environmental parameters as indicators of yield potential of clonal tea and may thereby be used to develop simulation models of the crop system. These would provide a tool for optimization of resource utilization, including fertilization, which would eventually help region or site-specific management to achieve maximum returns from tea cultivation and reducing environmental degradation. The identification of the interactions between growth parameters, yield components and fertilizer rates, how these respond to climate parameters will determine whether the relationships can be used to estimate yield in different locations and thus be used as a guide for fertilizer rate recommendation in different areas for all released clones in all regions.

1.6. Significance of the Study

The development of simulation models of the crop system would provide a tool for optimization of resource utilization, which would eventually help region or site-specific management to achieve maximum returns from tea cultivation thereby improving rural livelihoods and reducing environmental degradation. The possible utilization of the interactions between growth parameters, yield components, fertilizer rates and, climate parameters to estimate yield in different locations and as a guide for fertilizer rate recommendation in different areas as a less expensive alternative to fertilizer trials for all released clones in all regions thus realizing cost savings in adaptive research.

1.7. Framework of Analysis

A modification the framework proposed by Burgess, (1992) as shown in Figure 1 was used to review and quantify plant physiological responses, which may cause differences in yield response due to geographic location and fertiliser rates. The framework below postulates that solar radiation and fertilizer as an input are the precursors of dry matter. Solar radiation will vary with the environment while uptake of fertilizer will depend on the environment to determine the ultimate extent and rate of growth of the growth parameters and hence the yields.

```
┌──────────────────────────┐          ┌──────────────────┐
│   SOLAR RADIATION        │          │  FERTILISER      │
└──────────────────────────┘          └──────────────────┘
         f_s │                                f_w │
┌──────────────────────────┐          ┌──────────────────┐
│  INTERCEPTED RADIATION    │          │  N UPTAKE        │
└──────────────────────────┘          └──────────────────┘
         E_s │                                N_w │
┌────────────────────────────────────────────────────────┐
│              DRY MATTER PRODUCTION                       │
└────────────────────────────────────────────────────────┘
                          │
              ┌──────────────────────────┐
              │   NUMBER OF SHOOTS        │ ◄───────┐
              └──────────────────────────┘          │ Replacement of
                                                     │ shoots
              ┌──────────────────────────┐
              │   INITIAL LENGTH          │
              └──────────────────────────┘
                  Extension Rate  │
              ┌──────────────────────────┐
              │   LENGTH AT HARVEST       │
              └──────────────────────────┘

   Length/ mass ratio                Length/ stage ratio
   Dry matter content

┌────────────────────┐          ┌────────────────────┐
│  DRY MASS OF        │          │  PLUCKABLE SHOOT   │
│  HARVESTED SHOOTS   │          │  DENSITY           │
└────────────────────┘          └────────────────────┘
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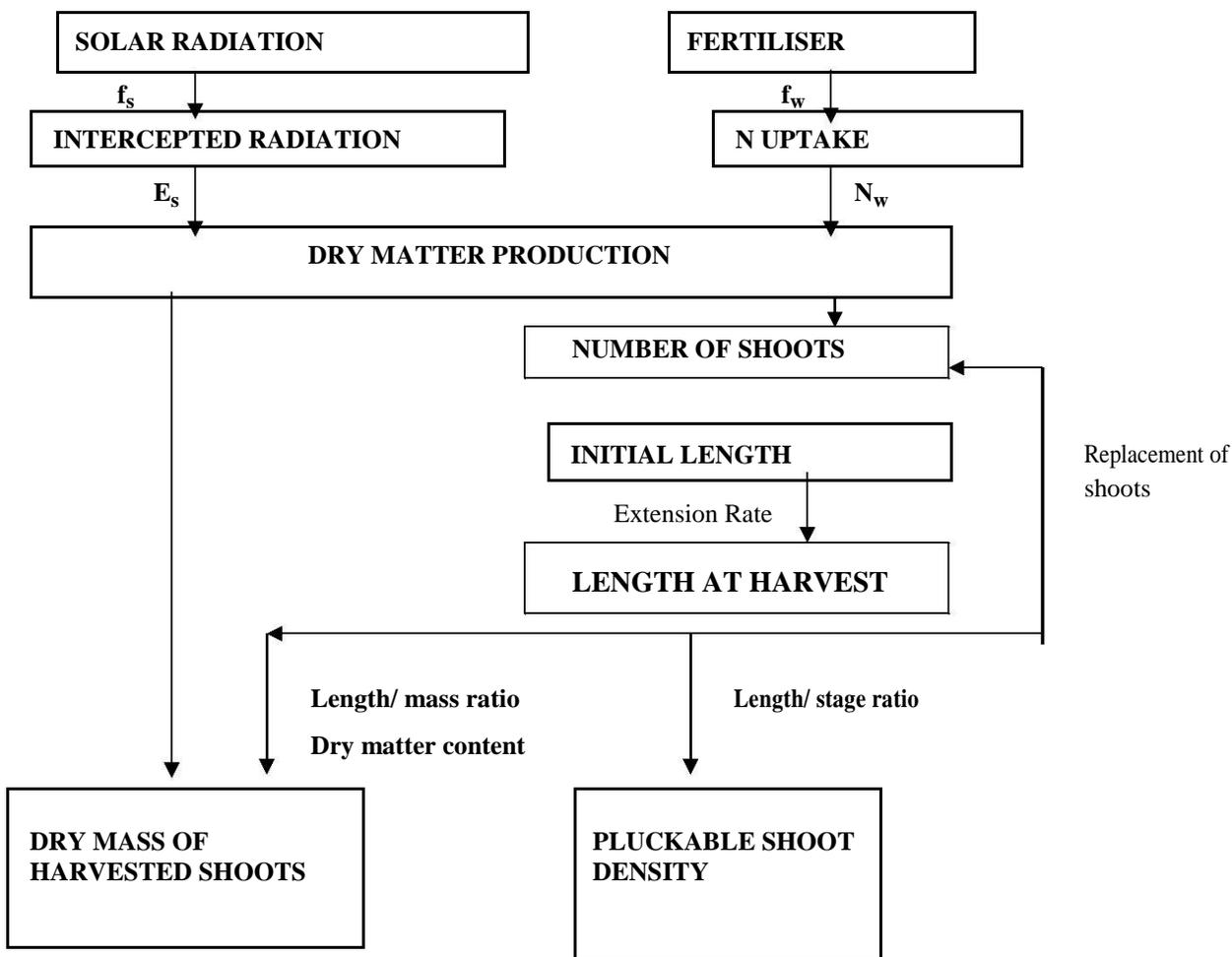
Figure 1: Framework for analyzing effects of climatic factors due to geographical location, genotype and nitrogenous fertiliser in the dry mass and shoot density of harvested shoot. (Source: Burgess, 1992)

CHAPTER TWO

LITERATURE REVIEW

2.1 Tea Botany and Ecology

Tea is a heterogeneous evergreen plant with many overlapping morphological biochemical and physiological characteristics (Purseglove, 1968; Wickremasinghe, 1979; Banerjee, 1988; Bokuchava and Skobelova, 1969). It falls under the *Theacea* family in the *Camellia* genus and is named *Camellia sinesis*, (L) O. Kuntze (Hara *et al.,* 1995). *Camellia sinesis*, consists of two main varieties; var. *sinesis* and var. *assamica* (Hara *et al.,* 1995) known generally as the China and Assam varieties, respectively (Hara *et al.,* 1995; Sealy, 1958). A third variety considered to be a subspecies of *Camellia assamica* named *Camellia senensis* var. *assamica* spp. *Lasiocalyx* (Planch on ex Watt) (Wight, 1962) has semi erect leaves and is classified as an oligophite (leaf 50^o - 70^o) (Banerjee, 1992). It is described as the southern form (Roberts *et al*., 1958) or Cambod race (Kingdon-Ward, 1950). The China varieties (considered shrubs thought originally to have grown in the open) have small erect leaves and are classed as erectophiles (leaf angle $<50^o$) while the Assam varieties (considered small trees thought originally to have grown in the forest) have horizontal and broad leaves and are classified as planophiles (leaf angle $> 70^o$) (Wight, 1962; Banerjee, 1992). Tea can grow into a tree attaining a height of 20-30 m and can have very long life span of more than 1,500 years (Hara *et al*., 1995). The tea plant is extensively commercially exploited (Banerjee, 1992). However, two new varieties *Camellia sinesis* var. *pubilimba* and *Camellia sinesis* var. *Kucha* were recently recognized to have commercial potential in China (Yao *et al.,* 2008).

Commercially, tea grows in a wide range of geographical locations around the world, from latitudes 49^o N in Russia to 33^o S in South Africa (Shoubo, 1989) and from longitudes 150^o E (New Guinea) to 60^o W (Argentina) (Carr, 1972). It grows in altitudes ranging from sea level in Japan and Sri Lanka (Anandacoomaraswamy *et al*., 2000) to 2700m a.m.s.l. in Kenya (Olenguruone) (Anon, 2002a; Owuor *et al.,* 2008) and Rwanda (Gisovu) (Owuor *et al.,* 2008). In East Africa tea is grown in the high

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rainfall highlands of Kenya, Tanzania, Uganda, Burundi and Rwanda at altitudes ranging from 970m a.m.s.l in Southern Tanzania (Kigalu and Rarikiel, 2009) to 2700m a.m.s.l in Olenguruone, Kenya (Anon, 2002a; Owuor *et al.,* 2008) and Gisovu, Rwanda (Owuor *et al.,* 2008). In Kenya, it is grown in the foothills of the Aberdare ranges and Mt. Kenya in the east of the Rift and the Mau ranges, Nandi, Kisii, Kakamega Hills and foothills of Mt. Elgon in the west of the Rift Valley (Owuor *et al.,* 1997; Anon, 2005). These areas lie close to and almost along the equator and shoots are harvested every 7 to 14 days (Eden, 1931) throughout the year.

Rain fed tea requires high well distributed rainfall (Othieno, 1992) of 1150 mm to 2200 mm per year (Carr, 1972; Anon, 2002a) and temperatures ranging from 13^{o}C to 30^{o} with optimum of 18^{o}C to 30^{o} (Carr 1972; Anon, 2002a). Optimal soil temperatures range from 20^{o}C to 25^{o}C (Carr, 1972; Rehm and Epsig, 1991; Anon, 2002a). The crop is grown in a wide range of soil types, but which are highly weathered and leached with pH ranging from $4.0 - 5.6$ (Acland, 1989; Othieno, 1992). Tea needs an acid soil, humid environment and does not tolerate long droughts with the best quality tea being produced at high altitudes (Mahanta *et al.,* 1988; Owuor *et al.,* 1990) that remain free from frost (Acland, 1989).

However, the last four to five decades have seen the development and release of many clones, which have been planted out and produce varying yields in different regions. Under Kenya tea growing conditions, some cultivars with exceptional production in western Kenya performed very poorly in the Eastern Kenya highlands, and *vice versa* (Wachira *et al.,* 2002). Measurable attributes that could be used to predict potential yields of clones in new environments and the development of specific management practices for the different clones in specific locations are however not well established.

2.2 Tea Yields and Components of Yield

Tea is maintained as a low bush, by regular pruning and is maintained in a continuous phase of vegetative growth (Hara *et al.,* 1995; Acland, 1989). The leaves are harvested all year closer to the equator but seasonally further away from the equator (Hara *et al.,* 1995). Although tea crops throughout the year in most tea growing areas, the amount of crop varies considerably both on a weekly and seasonal basis with crop being often low in the coldest weeks of the year (Tanton, 1992) and in the dry season (Carr *et al*., 1987).

The tea as a crop is characterized by close planted bushes, pruned to a convenient height for harvesting thus growing to form a canopy. This causes many branched twigs to develop in the top 20-40 cm of the bush and most of the mature leaves are found in the top 15cm of the canopy. New shoots of two or three leaves and a terminal bud are harvested from the top surface of the bush every 7-21 days after which axils in the top most leaves of remaining butts develop to become the next crop (Tanton, 1992). The weight of shoots in any one harvest therefore depends on the number developing shoots per unit area, their rate of growth and the average weight of shoots at harvest. Yield components of tea have been described as the shoot density, shoot replacement and shoot cycle(rate), shoot extension rate or growth rate (Odhiambo, 1991). These are determined by the dry matter production and partitioning (Stephens *et al.,* 1992).

Seasonal yield variations mainly occur due to differences in shoot density (Kulasegaram and Kaththiravetpillai, 1974). However, shoot growth rate was the major component causing seasonal fluctuation in yield whereas shoot density was the major factor determining yield difference between varieties (Tanton, 1979; Stephens and Carr, 1990). Shoot density and shoot weights may be important in determining yields between clones (Squire, 1979). The size of shoots harvested is potentially an important factor determining yield (Ellis and Grice, 1976), though, shoot size accounted for only 11% of the total

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variation in weekly yield throughout the season, the remaining 89% being accounted for by the number of shoots harvested (Tanton, 1981). Shoot size accounted for differences in the yield between certain clones (Tanton, 1981). However, shoot size was of little importance in determining seasonal changes in yield (Tanton, 1992). These conflicting findings suggest that further studies on growth parameters are necessary for the understanding of how they affect tea yields in different environments and clones. As early as 1979, the lack of knowledge of the mechanisms by which environmental factors influence tea shoot growth fluctuations was reported to have limited development of methods to control these variables (Tanton, 1979). It was observed that, it would be possible to understand causes of yield variations if relationships between yield and its components could be evaluated (Smith *et al.,* 1990). Among the yield components of four clones, shoot density, shoot extension rate, and partly shoot regeneration rates varied with changes in weather parameters while mean shoot weight remained unchanged. Indeed, the effects of individual yield components; shoot extension rates, shoot densities, and shoot regeneration rates varied highly and did not relate with the yield potentials of clonal tea (Tanton, 1979). However, the combined effects of the same parameters had significant relationship with clonal tea yields (Odhiambo, 1991; Odhiambo *et al.,* 1993). In Kenya, tea responded to fertilizer through harvested shoot density and rate of shoot growth (Odhiambo, 1989). The reviewed results were however, from trials conducted in single sites. The relations between yield and yield components and how these vary with environment among clones have not been determined.

The yield of tea crop is not primarily determined by the production of dry matter, but by the proportion of the total dry matter partitioned into the "economic yield" of harvestable shoots, refered to as the harvest index (HI; %) (Tanton, 1979; Squire and Callander, 1981). Partitioning of dry matter to the harvest index can be related to the components of yield which have been identified as shoot extension

rate, fresh mass and the dry matter content of the harvested shoots and the shoot density (Tanton, 1979; Stevens and Carr, 1990). Studies on four clones in four sites around Kericho, revealed variations in dry matter production and partitioning between sites and among clones (Ng'etich and Stephens, 2001a; Ng'etich and Stephens, 2001b). Even within a single site there were clonal variations in dry matter production and partitioning (Magambo, 1983). These studies however, did not relate HI to the yield components.

2.3. Genotype and Yield

Yields are also determined by genotype. While trials enable ranking of clones within a specific environment, the ranking may not be replicated elsewhere since a genotype can respond differently to varying environments. Some tea clones have exhibited a significant genotype–environment interactions in yields across different sites while others did not respond (Wickramaratne, 1981; Ronno *et al.,* 1991; Wachira *et al*., 2002). Although the stability of yield of a range of clones was observed within four regions in Sri-Lanka (Wickramaratne, 1981), the results could not be extrapolated to other regions. The differences in yield could be related to specific environmental variables such as soil water deficit (SWD) and temperature (Burgess, 1992). Shoot density is the major factor determining yield difference between varieties, whereas shoot growth rate is the major component causing seasonal fluctuation in yield (Tanton, 1979). Evaluation of clonal differences in shoot growth patterns could give an indication of varietal differences which could be exploited to alleviate seasonal differences (Tanton, 1982a). Clonal differences in yield response under irrigated and unirrigated conditions in Malawi (Nyirenda, (1988) were not fully quantified (Burghess, 1992). High yielding clones partition more dry matter (DM) above ground than low yielind clones (Magambo, 1983; Magambo and Canell, 1981), demonstrating clonal differences in dry matter partitioning. Differences in base temperatures for shoot extension among clones have been reported (Ng'etich, (1995). Indeed, base temperature differences between clones could explain why

clones selected in hot climate do not always do well in cooler climates and *vice versa* (Tanton, 1992). From past experiments most clones performed best at their sites of selection though some were widely adaptable (Wachira *et al.,* 2002) and many clones continued to be developed, most of which were tested only in Kericho with their performance in other environments not ascertained (Wachira and Mamati, 2002). Variations in clonal performance with sites have also been recorded Kenya (Kamunya, 2008; Wachira *et al.,* 2012). Different tea clones, selected from two different climates (Malawi and Kenya) had variable dry matter content and shoot growth rates (Smith *et al.,* 1990). In Tanzania, different tea genotypes gave varied annual yields mainly due to shoot density while shoot growth rate caused seasonal yield variations (Stephens and Carr, 1990).

The study of varietal differences in shoot growth patterns could give an indication of varietal differences which could be exploited to alleviate seasonal yield differences (Tanton, 1982a). Although it is possible to quantify yield responses of particular clones to quantified drought, the genotypic traits resulting in high yield and/or drought resistance may only be identified from a systematic analysis of the physiological processes, which determine yield (Burgess, 1992). The reviewed texts above indicate that yield variation among clones is due to the variation in responses of yield and growth parameters of individual clones to the environmental variables. There is however lack of information on how or whether the responses of yield and growth parameters of individual clones to the environmental variables changes with the tea growing location. Evaluation of effects of environment on yield components of clonal tea in Kenya could therefore establish how genotypes respond to environmental factors and how yield components affect the yield potential and seasonal yield distribution of different clones.

2.4 Effect Geographic Location on Tea Yields and Growth

Geographical location as herein described, refers to the longitude, latitude and altitude of a particular land area. This determines the prevailing climate and weather of the location. Climate is commonly defined as the weather averaged over a long period of time (AMS, 2010). The standard averaging period is 30 years (Met office, 2010), but other periods may be used depending on the purpose. Weather refers to the annual, seasonal and day to day climate variations (Carr and Stephens, 1992). The yield potential of any crop genotype under any given level of agronomic inputs is determined by climate and weather. Climate determines where a crop is grown and its potential yield; the actual yield depend on the prevailing weather (Carr and Stephens, 1992). The important weather variables are; solar radiation (sunshine), temperature, air humidity and rainfall (Carr and Stephens, 1992). Air humidity and rainfall determine saturation deficit of the air and available soil water, respectively. The crop physiological growth processes affected by these variables are: expansion of leaves shoots and roots; production of dry matter and partitioning of the dry matter between the various plant organs (leaves, stems, shoots, flowers, fruits, roots) (Carr and Stephens, 1992). Yield of tea is determined by rate and duration of these processes (Carr and Stephens, 1992). Within specific regions yields are also affected by hail damage (Stephens *et al.,* 1992), wind (Carr, 1985) and soil temperature (Othieno, 1982). The soil environment can also affect growth and yield of tea through its water holding capacity, nutrient status and pH (Green, 1971a; Othieno, 1992).

Some of the environment factors can be removed or moderated by management. For example, effects of soil water deficits (SWD) can be removed by irrigation (Carr 1974; Stephens and Carr, 1991) while effects of vapour pressure deficits (VPD) can be ameliorated by misting (Tanton, 1982b). Soil temperatures can be altered by mulching (Othieno, 1982) and mean air temperatures below 17-18^{0}C can

be increased by using wind breaks (Carr, 1985). Small differences in environment resulted in large variations in dry matter production and yield between sites and clones among four clones evaluated in four sites at different altitudes in Kericho, Kenya (Ng'etich, 1995; Ng'etich *at al.,* 1995a; Ng'etich *at al.,* 1995c; Ng'etich *at al.,* 1995c; Ng'etich and Stephens, 2001a; Ng'etich and Stephens, 2001b). The differences in clonal dry matter production and yield were attributed partially and mainly to ambient temperatures respectively, with differences in measured and derived environmental variables between sites also being observed. Most of the investigations in environment influence on tea have concentrated on a single clone in a single site or effect of individual environmental parameters on one or two growth parameters at a time. There is paucity of information on the interactive effects of environmental parameters on the tea growth and yield parameters.

2.4.1 Ambient Temperature
Temperature is a major factor determining the natural distribution of plants and the success and timing of agricultural crops (Lange *et al*., 1981). Higher plants are normally unable to maintain their cells and tissues at a constant optimum temperature and therefore their leaves, stems and branches are normally within a few degrees of the surrounding air and soil temperatures, thus the growth and metabolism of plants are profoundly affected by changes in environmental temperature (Fitter and Hay, 1981). Tea yields were positively related to air temperature up to about 25^0C (Squire, 1979; Tanton, 1982a). Indeed, there is a linear relationship between shoot extension rate and mean air temperature over a range of 17-25^0C (Squire, 1979; Carr and Stephens 1992). The base temperature (T_b) for shoot extension of clone SFS 150 for example, was between 12-13^{0}C (Tanton, 1982a). The shoot replacement cycle ((SRC) - duration between removal of a pluckable shoot and development of the bud into harvestable shoot) between 4 sites in East Africa ranged from 42 days during the main growing season to 70-80 days during the cool winter

months in Malawi (Carr and Stephens, 1992) and between 60-70 days at 1500-1800m to around 120 days at 2200m m.a.s.l., in Kenya (Mwakha, 1985; Carr and Stephens, 1992). At high altitudes a 1^0C difference in temperature due topography or aspect shelter can have a big effect at such low temperatures (Stephen and Carr, 1992). These seasonal differences in shoot replacement cycles explain the variability in yield distribution at sites away from the equator (Tanton, 1982a; Carr and Stephens, 1992). These "crop flow" problems can almost entirely by explained by ambient temperature changes in the absence of other limiting factors (e.g. poor nutrition, soil water deficits or excessive leaf temperature) (Carr and Stephens, 1992). Studies on growth rate model based on temperature response in Malawi allowed accurate prediction of growth rate of clone SFS 204 for 9 months of the year (Tanton, 1982a). In the remaining 3 months of hot dry season, very high saturation water vapour pressure deficits in the air restricted shoots extension. This temperature response is applicable in several geographical locations (Tanton, 1992). Rapid decline in growth rate with decreasing temperature and the relatively high temperature at which growth stops indicates that the temperature is a major climatic variable limiting yields in most tea growing areas of the world and is a major factor causing low yields in cold season in Malawi (Tanton, 1992). Discrepancy in yield between Kenya (at 0^022'S 35°21 'E and 2178m a..m.s.l) and Malawi (at 16^0 05'S, 35^0 35' E and 630m a.m.s.l) is due to variability in yield distribution (crop flow problem) (Tanton, 1992; Tanton, 1982a). Whereas in Kenya shoots take 10-14 weeks to grow to harvestable size (and there is always a good supply of shoots reaching harvestable size) in Malawi they develop in 5-6 weeks in the rains and 10-14 weeks in the cool season. The changes in season occur over about a month, thus a delay while shoots which started development at the beginning of the cool season reach harvestable size. This delay accounts for the low crop in July in Malawi (Tanton, 1992; Tanton, 1982a) and explain the crop difference between Malawi and Kenya where temperatures are similar at this time of the year (Tanton,

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1992). Poor yields during some seasons were associated with number of days with temperatures below 21^0C or above 36^0C in Malawi (Green, 1971). The mechanisms for seasonal crop differences between different tea growing regions regions have not been well documented Kenya.

Temperature response has two distinct phases, a base temperature and a linear phase (Tanton, 1992). Base temperatures, below which plants do not grow, have been found in many crops (Landsberg, 1975). It has been postulated that growth stops due to temperature induced phase changes in membrane lipids (Raison, 1974). It is therefore possible that tea clones with lower base temperatures or which can adapt to lower temperature can be found (Tanton, 1992; Ng'etich *et al*., 1995c; Ng'etich *et al*,. 2001b; Ng'etich, 2003) since both these traits have been found in other species (Noggle and Fites, 1974; Wu *et al.,* 1974). Base temperature differences between clones could explain why clones selected in hot climate do not always do well in cooler climates and *vice versa* (Tanton, 1992). However, certain clones yield relatively well in all weather (Tanton, 1992; Ng'etich, 2003). These observations could be explained if there were independent varietal differences in both base temperature and temperature response (Tanton, 1992; Ng'etich *et al*., 1995c; Ng'etich *et al*,. 2001b; Ng'etich, 2003). It is therefore possible that temperature response could be a component of varietal difference in yield. There is inadequate information on clonal responses to temperature in different tea growing regions in Kenya.

Yields from 21 individual estates in Kericho, Kenya tended to decline with increasing altitude above 1700m a.m.s.l. especially at 2200m a.m.s.l. (Carr and Stephens, 1992). This altitude influence can be interpreted through its effect on temperature and hence on the number of shoot replacement cycles (SRCs) which can be expected in a year. For each 100m increase in altitude with a lapse rate of 0.6^0C the length of shoot replacement cycles increased from 60-70 days at between 1500 1800m to around 120 days at 2200m m.a.s.l. where mean air temperature was only 4^0C above base temperature (Carr and Stephens,

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1992). These difference were sufficient to explain the 200kgha^{-1} reduction in yield in 1984/85 for each 100m rise in altitude from 1500m-2000m and even more at altitudes above this (Carr and Stephens, 1992; Othieno *et al*., 1992). In Mufundi, Tanzania however, where the range of altitude was only 120 m the main variable was decline in rainfall from 1700 to 1100mm and increase in length of dry season from 25-28 weeks with distance from the Uzungwe escarpment (Stephens *et al.,* 1988). A yield decline of 10% per every 1^{0}C drop in temperature in clone S15/10 at high altitude was noted while clone TN14-3 did not change systematically with altitude at four sites within 10 km in Kericho, Kenya (Obaga *et al.*, 1989; Squire *et al.,* 1993). Shoot growth cycle increased with altitude while shoot extension rate declined, mainly due to temperature differences between four sites in western Kenya with the response being significant for clone AHP S15/10 but not for clone TN 14-3 (Squire *et al*., 1993). Ambient temperatures were more closely associated with the yield differences recorded although yield response to temperature was complicated by soil water deficits and saturation deficits on four clones in Kenya (Ng'etich *et al*., 2001). Similarly, in southern Tanzania, relative shoot extension rates, internode lengths and shoot development rates of six clones varied linearly with changes in temperature across the seasons (Burgess and Carr, 1997). In Malawi large clonal differences among seven clones were observed, in the response of exponential relative shoot extension rate (ERSER) to temperature within 18-23^{0}C. Two Kenyan clones, BB 35 and TRFK 6/8 did not grow well at 18^{0}C, which is normal for growth in Kenya but coincides with period of short day length (less than 12 hours) in Malawi (Smith *et al.*, 1993). The results from Malawi and Tanzania were from seasonal temperature variations in single sites, whereas those from Kenya are only from a few clones tested in tea growing regions in the west of the Rift Valley. So far there have been no studies in tea response to temperature variations in the east and west of the Rift Valley in Kenya.

2.4.2 Saturation Deficit (SD) (Vapour Pressure deficit (VPD)) and Shoot Water Potential (SWP)

Atmospheric humidity is inversely related to vapour pressure deficits. Tea does best in humid atmosphere (Acland 1989; Bonhuere, 1990) particularly in areas of low rainfall and during the dry season. Tea yields decline when soil water deficits (SWD) exceed 40mm (Stephens and Carr, 1989) or the vapour pressure deficit exceeds 2.3 kPa (Tanton 1982b; Carr *et al.,* 1987). Several studies have reported an inverse linear relationship between VPD and SWP in tea (Williams, 1971; Squire, 1979; Tanton 1982b). However, the relationship was true only up to a VPD of 20 mbars (2 kPa) above which SWP remained at -16 bars (-1.6 MPa) and stayed low long after the VPD of the atmosphere had fallen (Squire, 1979). The SWP of tea shoots were therefore more closely related to VPD than to soil moisture. The lag in rise of SWP when VPD drops is due to disruption of the transpiration stream resulting in accumulated water deficit long after VPD has fallen (Tanton, 1992). A critical midday SD value of about 2.0 kPa above which yields declined was deduced (Carr, 1972; Carr and Stephens, 1992). The sensitivity of shoot extension rates to SD of the air over a range of 1 to 3 kPa and SWP down to -16 bars (-1.6 MPa) observed on tea shoots in Malawi retarded growth (Squire, 1979). The apparent critical SD value above which shoot growth rates reduced was 2.3 kPa, at ambient temperature of 25^0C or 30^0C which corresponds to relative humidity (RH) of 28% or 45%, respectively (Tanton, 1982b). However, high temperatures inhibit tea growth in North India and since high vapour pressure deficits are associated with high temperature (Hadfield, 1968). Iit is important that the two effects are separated and effect of VPD qualified. Within a narrow range of temperature (12.5 - 13^0C) and at VPD of not more than 2 kPa shoot growth rates varied inversely with VPD suggesting that seasonality of shoot growth in tea can be explained largely by the independent effects of temperature and humidity (Squire, 1979).

Dry air surrounding the crop leads to high transpiration rates which can result in minimum shoot

water potential as low as -0.6 to -1.4 MPa in the middle of the day even when soil water content is close to field capacity (Carr and Stephens, 1992). Influence of large saturation deficits of air are closely linked to the adverse effect of high temperature ($>30^0$-35^0C) on shoot growth rate and photosynthesis (Hadfield, 1968; Carr and Stephens, 1992). Low shoot water potential causes metabolism imbalances in plant cells with cell elongation being the most sensitive (Slatyer, 1967; Hsiao and Acevedo, 1975). Shoot water potential link directly to shoot extension rates through effects on cell turgor (Carr and Stephens, 1992).

September to November is hot and dry season in the tea growing areas of Malawi and yields are negligible in the latter half of this period. Irrigation during this period increases yields but not to levels attained in the wet season or to yields obtained by irrigation in Tanzania (Carr, 1971; Dale, 1971). Growth of irrigated tea at this time of the year is also much slower than is predicted by a linear model of shoot extension based on temperature (Tanton, 1981a). Up to a daily maximum VPD of 2.3kPa the internal water deficit only stops growth for a few hours a day and does not significantly limit growth until VPD rises high enough to cause internal water deficit to remain long after the VPD has fallen (Tanton, 1992). A 10^0C leaf to air temperature difference when air temperatures are 35^0C, increases leaf to air SD from 1.55 to 5.5 kPa during the monsoon season in Assam, and from 3.0 to 7.0 kPa during the hot, dry season in Malawi (Squire and Callander, 1981). Experimental evidence shows that shoot extension rates are restricted to a base SD of air of 2.3 kPa, declining by 75% at an SD of 4.0 kPa (Tanton, 1982b). Stomatal conductance may also be reduced by large SD values (Carr and Stephens, 1992). With moist air, shoot growth rate is directly proportional to shoot temperature from about 12 - 36^0C but high VPD above 23 mbars (2.3MPa) is a major factor in decreasing crop yield in hot dry weather (Tanton, 1992). This explains why irrigation is more effective in increasing yield in Tanzania where VPDs are lower than in

Malawi in the dry season.

Varied reduction in yield, shoot growth rates, shoot densities and SWP due to high VPD were recorded amongst clonal teas in Kericho (Odhiambo *et al.,* 1993). Large differences in VPD (0.5 kPa) and evapotranspiration (1mm d^{-1}) across four sites in Kericho, Kenya have also been recorded (Ng'etich, 1995). The differences in VPD explained the differences in yield and yield components observed across the sites amongst the four clones evaluated within Kericho. However, the variations in the relationships between yields, yield components, temperature and VPD, between clones and between the varied tea growing locations in the east and west of the Rift Valley in Kenya is not documented.

2.4.3. Solar Radiation

The annual receipt of total shortwave radiation received at any site is determined by the latitude and local climate. Within tea growing regions of eastern Africa, the main receipt of solar radiation varies from 6500-6700 (MJm^{-2}y^{-1}) at Mufindi, southern Tanzania ($8^0$36'S, 35^0 21'E) and Kericho, Kenya, ($0^0$22'S 35^0 21'E) to 7400 MJm^{-2}y^{-1} at Mulanje, Malawi ($16^0$05'S, $36^0$36'E) (Carr and Stephens, 1992). Since the annual incidence of solar radiation decreases with increasing latitude the lower receipts in Mufindi than Mulanje are probably due to cloud cover (Charles-Edwards, 1982). Within the year, there are also seasonal variations in solar radiation. For example, in Mufindi the mean monthly solar radiation increases from 16 MJm^{-2}d^{-1} in the wet season to 23 MJ m^{-2}d^{-1} in the dry season (Carr, 1974). Incident solar radiation at especially high altitudes can exceed 1000Wm^{-2}, with local peak values sometimes much higher due to additional radiation reflection by clouds. Of this, 20% is reflected by the crop surface and a similar amount is re-emitted as long wave radiation (Carr and Stephens, 1992). This results in a net available energy at the surface of a tea canopy reaching 100Wm^{-2} (Squire and Callander, 1981). Most of this short wave radiation is interrupted by leaves in the top 0.3m of the canopy regardless of the geometry below 0.1m (Hadfield, 1974b). In India, there is a reduction of radiation by 99% within 30 cm of the

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plucking table for a range of clones (Hadfield, 1974a) while in Malawi only 5% of incoming radiation was reported to reach the ground (Green, 1971a). In Kenya, net sum of energy fluxes below the canopy was 4% of net radiation (Callander and Woodhead, 1981). Differences in total light penetration occur among tea varieties (Obaga, 1986). There are differences in ground cover, total dry matter and dry matter partitioning between clones and between sites attributed to differences in daily intercepted solar radiation which differed by as much as 30% between sites (Ng'etich and Stephens, 2001b). However, of the four sites evaluated, light interception was measured in only two sites and calculated for the other two using measurements of GC and LAI. Each of the two sites where interception was estimated is 5km away from a site light interception was measured. The actual differences in daily intercepted solar radiation between studied tea growing locations in Kenya were not established.

Photosynthesis of single leaf of tea in the field is saturated at $350Wm^{-2}$ (Sakai, 1975; Squire, 1977) while whole tea canopies become saturated at $700Wm^{-2}$ (Squire and Callander, 1981). A very small proportional of the net available energy is therefore used in photosynthesis, with most being dissipated as latent heat (through evaporation) and sensible heat (heating the air) (Carr and Stephens, 1992). These concepts bear directly onto the effects of sunshine on leaf temperatures, on leaf to air temperature differences and as the corresponding saturation deficit (SD) between leaf and air. In the rainy season the surface leaf temperature is warmer (0.3^0C) than the air for each $100Wm^{-2}$ of solar radiation up to a maximum of 3^0C but up to 6^0C in the dry season or up to 12^0C if the stomata were closed (Squire and Callander, 1981). These differences have large effect on leaf to air SDs hence on shoot extension rates and therefore yields. Dry matter (DM) production is dependent upon the conversion efficiency (*e*) which is the proportion of solar radiation intercepted by the leaves $S_{(i)}$ that is converted into DM (Equation 1.0; Squire, 1985).

$$DM = S_{(i)} \text{ x } e. \qquad\qquad 1.0$$

Where *e* is the amount of dry matter produced (in grams) per mega joule of solar radiation intercepted by

the leaves (g^{-1} mj^{-1}).The crop yield therefore is determined by the amount of DM partitioned into the harvestable organs, the harvest Index (HI) (Carr and Stephens, 1992). Rate and duration of expansion is largely controlled by temperature when other factors (e.g. humidity and moisture) are not limiting. The yield of tea therefore is determined by the shoot density, their rate of growth and their average dry weight at harvest. In many cropping systems the interception and efficient use of radiation to produce dry matter defines the potential yield. Therefore the DM production (gm^{-2}) of tea, or any crop can be determined from incoming solar radiation (S; MJm^{-2}), the proportion of radiation intercepted by the canopy (f_s) and the dry matter/light conversion ratio or conversion efficiency (E_s; g MJ^{-1}) (also termed the Radiation Use Efficiency-RUE) (Squire, 1985) using the formula 2.0 below

$$DM = S \text{ X } f_s \text{ X } E_s \qquad\qquad 2.0$$

Estimate of conversion efficiency (Es) for tea in Kericho, Kenya were substantially lower (0.25 g MJ^{-1}) than for most temperate (1.3-1.6 g MJ^{-1}) and tropical annual crops (0.6-0.8 g MJ^{-1}), being closest to natural rainforest (0.20 g MJ^{-1}) (Burgess, 1992). In a high altitude site in Southern Tanzania (Ngwazi Tea Research Unit at $8^0$32'S, $35^0$10'E, 1840m a.m.s.l) higher conversion efficiency values were recorded on four contrasting tea clones (0.40 to 0.60 g MJ^{-1}) which corresponded closely to other woody tropical plants (Burgess and Carr, 1996). It has not been established whether there are clonal and locational differences in conversion efficiency values of tea in Kenya. The proportion of solar radiation intercepted (f_s) by a discontinuous canopy like young tea depends on ground cover (GC), the leaf area fraction of area of ground covered (LAI) and the extinction coefficient for light (k) as expressed in Equation 3.0 (Jackson and Palmer, 1979)

$$f_s = GC \text{ }(1\text{-}e^{(-kLAI)}) \qquad\qquad 3.0$$

At commercial planting densities of 10,000 to 14,000 plants ha^{-1} full ground cover is not achieved until at least two years after planting in East Africa (Burgess, 1992). Before complete ground cover is established, clones with a large bush area usually produce higher yields than clones with less ground cover (Nyirenda,

1988). Extinction coefficient (k) values for other crops range from 0.8 for planophiles (flat) leaved canopies to 0.3 for erectophile canopies (Goudriaan and Monteith, 1990). For a given leaf area, clones with horizontal leaves are therefore likely to intercept a greater proportion of light than erect leaved clones (Burgess, 1992). However, at full ground cover plants with erect leaves may compensate for this by having higher leaf area indices (LAI). The value of LAI at full ground cover ranged from 4 for Assam type clones with horizontal leaf orientation to 8 for the erect leaved China types (Hadfield, 1974a). Canopy cover values used for deriving radiation use efficiency have not been determined for tea clones grown in Kenya. Subsequently, the variations in light interception and resultatnt RUEs have not been determined for the different clones in the different tea growing regions of Kenya.

2.5. Tea Response to Fertilizers

The response of tea to fertilizer in terms of growth and yield is influenced by factors such as climate, soil, plant genotype and management practices. These factors vary widely between regions and sites such that plant responses to fertilizer regimes differ between regions and growing sites (Hettierachchi *et al*., 2003; Msomba *et al.,* 2014). A number of studies have demonstrated yield responses to nitrogen (Bonheure, and Willson, 1992) even in Kenya (Owuor and Othieno, 1996; Owuor *et al.,* 1994; Owuor and Wanyoko, 1996; Owuor *et al.,* 2008b; Odhiambo, 1989; Kamau *et al.,* 2008). Variations in yields responses to fertiliser have been reported, on clone TRFK 6/8 across 8 sites in 3 East Africa countries (Msomba *et al.,* 2014), clone BBK 35 across multiple sites (Owuor *et al*., 1994; Kamau *et al*., 2003; Owuor *et al.,* 2013), and on clone Ejulu (Anon, 2002b) in two sites, in Kenya. These findings demonstrate that clonal yields may not always be stable across different environments, even within Kenya. Also the extent and rate of yield response to nitrogen fertilizer to vary with location of production, even for a single clone subjected to same agronomic inputs (Msomba *et al* 2014,; Owuor *et al.,* 2010a). Tea response to fertilizer can be related to the yield and growth factors. Tea responds to fertilizer through

harvested shoot density and rate of shoot growth (Odhiambo, 1989). Variations in shoot growth rates response of clone Ejulu to fertilizer across two different sites in Kenya have also been recorded (Anon, 2002b). Nitrogen deficiency increases stomatal resistance and reduces transpiration (Mohotti *et al*., 2003) by increasing the sensitivity of the transpiration and resistance to water stress (Nagarajah, 1981). Increased application of both N and K increased the chlorophyll content in both flush and mature leaves (Krishnapillai and Ediriweera, 1986). Nitrogen applied at twice the recommended dose, increased bud activity (Kulasegaram and Kathiravetpillai, 1980). Most growth parameters were affectedby doubling the recommended dose but not half or zero. Evaluation of the responses of tea growth parameters' response to nitrogen rates across different environments, particularly in East Africa has not been documented.

The variability of clones to extract nutrients differently in different locations has also been demonstrated. In Kenya, across two sites variations in leaf nutrient content of clone Ejulu at different fertilizer rates were recorded (Anon, 2002b). There were large differences in mature leaf nutrient contents of clone BBK 35 across four sites in Kenya (Kamau *et al*., 2005). This suggests that environmental factors could affect nutrient uptake. During bud break, the uptake of nitrogen was shown to increase. An increase in nitrogen supply improves growth up to a point beyond which nitrogen absorbed is not used for growth of shoots but rather accumulated as soluble compounds in the leaves (Mohotti *et al*., 2003). Application of fertiliser has been shown to stimulate photosynthates accumulation in the whole bush (Shen *et al.,* 1990). The relationships between fertiliser application, nutrient uptake and environmental factors in tea have however not been demonstrated.

The question of which physiological and morphological features of plants serve as adaptations to nitrogen deficient environments and which features lead to high fitness in nitrogen rich environments can only be answered by defining the parameters that measure efficiency of uptake, allocation residence time

and final use of nitrogen from the soil. Nitrogen use efficiency (NUE) was developed as such a parameter (Berendse and Aerts, 1987). As such NUE has a number of definitions that relate to plant dry matter accumulated, stored or lost per unit of nitrogen applied (Berendse and Aerts, 1987). It can also refer to the unit of harvest per unit of nitrogen applied. NUE has also been reported to decreases with increasing abundance of nitrogen as the plants lose their ability to mine and utilize nitrogen more efficiently (Vituosek, 1982; Birk and Vituosek, 1986; Berendse and Aerts, 1987) especially under dry conditions (Gauer *et al*., 1992). Plants in nitrogen poor environments have also been reported to develop the ability to mine and utilise the scarce nitrogen more efficiently (Berendse and Aerts, 1987). There is no information on nitrogen use efficiency in tea and none more so has been found relating the nitrogen use efficiency of tea to actual harvestable crop.

MATERIALS AND METHODS

3.1. Experimental Treatments and Design

3.1.1: Genotype x Environment Trial

The trials were started in 2012 in three different tea growing geographic locations (sites) namely; Kangaita, Timbilil and Kipkebe, varying in proximity by between 45 and 245 Km and altitudinal range differences of between 78 and 435m, (Table 1). Slopes at all the sites were gentle to slightly sloping (0% - 15%).

Table 1: Geographic location and altitude of Genotype x Environment trial study sites.

Site	Location	Latitude	Longitude	Altitude (m amsl)	Mean Annual Rainfall(mm)	Mean Annual T^oC_{Min}	Mean Annual T^oC_{Max}	Mean Annual RH (%)	Soil description*
Timbilil	TRFK, Timbilil, Kericho	0° 22'S	35° 21'E	2180	2154	8.8	23.3	62.4	Volcanic dark red (10R 3/2), deep friable clays with a dusky red (2.5YR 3/6) top soil (0-0.1m), with Kaolinite as the predominant , classified as humic nitosols
Kangaita	KTDA Kangaita Tea Farm, Kirinyaga	0°30'S	37°16'E	2100	2016	10.9	20.2	76.7	Volcanic reddish brown to dark brown, extremely deep, friable and slightly smeary clay with acid humic top soils, classed as ando-humic nitosols
Kipkebe	Kipkebe Tea Company, Sotik, Nyamira	0° 39'S	35° 02'E	1800	1623	13.9	25.0	71.4	Dark reddish brown (2.5YR 3/4), deep to very deep, with friable and slightly smeary top soils, which were developed on acid igneous rock, classed as andoluvic phaeozems

*Soil description after Jaetzold and Schmidt, (2010)

The trials were superimposed on plots of mature clonal tea selection trial of the same age set up earlier and planted in 1991 in performance tests comprising twenty clones namely; TRFK 6/8, TRFK 31/8, AHP S15/10, EPK TN14-3, BBK 35, TRFK 54/40, TRFK12/12, TRFK 12/19, TRFK 31/27, TRFK 11/26, TRFK 57/15, TRFK 7/3, TRFK 7/9, TRFK 56/89, STCK 5/3, TRFK 303/259, TRFK 303/577, TRFK

303/999, TRFK 303/1199 and TRFK 2X1/4. set in randomized complete block design (CRBD) replicated three times at each site (Wachira *et al*., 2002). The clones consisted of selected popular genotypes which are cultivated widely in Kenya. Each plot comprised of 20 bushes spaced at 1.22 x 0.66 m. The tea was managed under standard management practices in Kenya (Anon, 2002), were skiffed to 12 inches in October 2010 and yield uniformity plucking conducted in 2011, prior to data collection in 2012. The yield components recorded were shoot density, dry weight, growth rate and water potential, for one year. The experiment was analysed as a 20×3 factorial 2 design with clones and sites (locations) the factors (Appendix I).

3.1.2. Fertiliser x Location Response Trial

The trials were set up in 2012 in three major tea growing geographic locations (Timbilil, Changoi and Arroket) in the west of the Rift Valley at different altitudes and within a maximum of about 42 km radius apart (Table 2). The slope at all the sites was gentle to slightly sloping (0-15%).

Table 2: Geographic location and altitude of Fertiliser x location response trial study sites

Site	Location	Latitude	Longitude	Altitude (m amsl)	Mean Annual Rainfall(mm)	Mean Annual T^oC_{Min}	Mean Annual T^oC_{Max}	Mean Annual RH (%)	Soil description*
Timbilil	TRFK, Timbilil, Kericho	0^o 22'S	35^o 21'E	2180	2154	8.8	23.3	62.4	Volcanic dark red (10R 3/2), deep friable clays with a dusky red (2.5YR 3/6) top soil (0-0.1m), with Kaolinite as the predominant , classified as humic nitosols
Changoi	George Williamsons Ltd., Changoi Estate, Kericho	0^o 30'S	35^o 13'E	1860	1655	11.4	26.8	90.9	volcanic derived, deep, free draining, dark red (2.5 YR 3/6) with a dark reddish brown (2.5YR 3/4) top soil (0-0.1m), classified as nitosols
Arroket	Sotik Tea Company, Arroket Estate, Sotik, Bomet	0^o 36'S	35^o 04'E	1800	1506	12.2	28.1	71.4	Dark reddish brown (2.5YR 3/4), moderately deep, firm clay loam with humic top soils on, classed as chromoluvic phaeozems

*Soil description after Jaetzold and Schmidt, (2010)

The experiment was superimposed on a fertilizer rate x plucking interval trial set up in 2008 in mature tea of clone TRFK 6/8 planted in 1986 (Timbilil), 1974 (Changoi) and 1972 (Arroket) and laid out in RCBD and replicated three times (Kebeney *et. al.*, 2010). In this trial, the recommended 7-day plucking interval plots were used for data collection and monitoring. It was set in factorial two design with sites and nitrogen rates: 0, 75, 150, 225 and 300 kg ha^{-1} year^{-1} as the factors (Appendix II). Fertilisers were applied once annually in April as N:P:K:S 25:5:5:5. The clone TRFK 6/8 is one of the standard high black tea quality clones in most yield and quality performance evaluation trials in Kenya (Kamunya *et al.,* 2012) and was also used in the G x E study in this study. It is also a popular widely planted, high black tea quality clone in East Africa and constitutes 30% and 80% of commercial clonal plantings in Kenya and Rwanda, respectively (Kwach *et al.,* 2016, 14 Owuor e*t al.,* 2013). Prior to the experiments, the tea was was under standard management practices (Anon, 2002) and the bushes at all sites were pruned in 2007, before the start of the trial.

3.2. Data Sampling, Recording, Analytical methods and derivations
3.2.1. Soil Characteristics
Disturbed soil samples were collected at the beginning of the trials in the dry season between January and March, from two sites from each trial location in approximate diagonal line across the experiment. Samples were collected using a Jarret auger, at depths of 0 -20, 20 - 40, 40 - 60 (Cooper, 1979; TRFK, 2005). These were subjected to full chemical (pH and nutrients) analysis and physical (soil texture) analysis for site characterization.

3.2.2. Soil Chemical and Physical Analysis
Soil pH was determined by making a soil/distilled water suspension (1ml water:1gm soil) of fresh (un-dried) soil sub samples and reading the pH of the suspension off a Jenway 3305 pH meter Soil nitrogen content was determined using the Kjeldahl method. For mineral nutrient analysis, the soils were air dried, ground and sieved through a 2 mm. sieve. The ground samples were then extracted using the

Mehlich III method (Mehlich, 1984) then analysed for nutrients K, P, Ca, Mg, Mn, Na, Cu, Fe and Zn using a plasma atomic emission spectrophotometer (ICPE-9000, Shimandzu). Sub samples from the disturbed soil samples were subjected to particle size analysis using the pipette method (Gee and Baader, 1986), taking 63 μm as the sand/silt boundary.

3.2.3. Site Weather Characteristics

Rainfall and temperature data was recorded from weather stations located at each trial site and accompanying meteorological data derived as follows; Rainfall was recorded daily using a standard rain gauge. Maximum, minimum, wet and dry bulb temperatures were recorded everyday at 09.00 h and 15.00 h local time using mercury in glass thermometers (Cassella (London) Ltd., UK). The relative humidity (RH%) was derived from the wet and dry bulb temperature readings using relevant tables (Mwebesa, 1978). The wet and dry thermometer readings recorded as described above were used to derive saturated vapour pressure deficit (SVPD) using the formula:

$$SVPD = ew - e' \text{ (List, 1949)}$$

Where:

e' = air vapour pressure (mb) at t' (Table 94),

ew = air vapour pressure (mb) at t (Table 94),

t' = dry bulb temperature (˚C),

t = wet bulb temperature (˚C).

3.2.4. Tea Yields

Green leaf comprising of mostly two leaves and a bud were plucked every 7 - 10 days and converted to made tea (mt) by multiplying by a factor of 0.225 (Anon, 2002a).

3.2.5. Shoot Density (SD), and Shoot Dry Weight (SDWT)

Shoot density was determined by recording the mean of the number of mature harvestable shoots (two leaves and a bud) captured within a 0.25 m^2 grid randomly thrown on to the plucking tables (Squire *et al.,* 1981; Odhiambo, 1989; Odhiambo, 1991, Odhiambo *et al*., 1993) of five randomly selected bushes at every plucking round. Shoots falling within the grid were plucked, weighed and counted then oven dried at 105°C for 48 hours and reweighed. The SDWT was determined by dividing the dry weight by the number of shoots harvested (Squire *et al.,* 1981; Odhiambo *et al*., 1993).

3.2.6. Shoot Growth Rate (SGR)

The rate of shoot growth (millimetres per day (mmd^{-1})) was determined by tagging five shoots from each of three randomly selected bushes per plot. Growth was monitored by measuring the length from the tip of the auxiliary bud to the base every three days until the new shoot developed into a mature harvestable two leaves and a bud. The total length measured at each interval was divided by the number of days between two successive measurements to determine the growth rate (mmd−1) (Ng'etich, 1995).

3.2.7. Shoot/Xylem Water Potential (SWP)

The xylem water potential of pluckable shoots was measured between 11.00 am and 2.00 pm, using the pressure chamber technique (Scholander *et al*., 1965; Odhiambo, 1991; Odhiambo *et al*., 1993). Three shoots each from five randomly selected bushes per plot were cut and measured one by one on. The cut shoots were transferred to the site of the pressure chamber where one centimetre was cut off the stalk and the shoot immediately inserted into the gas chamber. The key of the compressed nitrogen gas was turned on until the first gas bubbles were released from the cut shoot stalk surface and the pressure reading taken (Squire, 1979; Squire *et al*., 1981; Odhiambo, 1991, Odhiambo *et al*., 1993. Measurements were taken twice a season and averaged to get the season mean.

3.2.8. Leaf Area Index (LAI)

The twelve plants comprising four each of mean high, medium and low yielding clones, determined from 2012 yields of the 20 clones in this study were selected for LAI determination. A sample of 200 undamaged leaves from the top bottom, middle and bottom of the canopy of the 12 selected clones were randomly detatched from the bush. The leaves were weighed, the length and breadth (l x w) recorded (Magambo, 1976; Ng'etich and Wachira, 1992) then bagged and transported to the laboratory for drying. The leaves were oven dried at $105^{o}C$ for 48 hours to obtain constant dry weight and was then used to determine the leaf area per unit dry weight i.e. specific leaf area (SLA). The leaf area was determined by applying the formula:

$A = l^{2} \, x \, 0.24$ (Anon, 1982)   *(1)*

Where:

l = length of leaf along the leaf midrib.

At the end of the trial period, the selected plants had all pluckable shoots removed and weighed then cut at the base of the stem, stripped of all leaves and the leaves weighed to determine the fresh weight. The leaves were then oven dried as describe for the samples above. The specific leaf area as determined above, for each clone, was then used to determine the leaf area of the leaves from the whole bush. The LAI was then determined by dividing the total leaf area by the canopy ground cover (area of the spacing $0.6x1.21m^{2}$) (Ng'etich, 1995).

3.2.9. Radiation Use Efficiency (RUE)

Radiation use efficiency was estimated as the amount of radiation required to produce 1 g dry weight of harvestable shoots (Squire, 1985). The total annual green leaf dry weight was used to estimate the radiation use efficiency in yield production. The Harvest Index Radiation Use Efficiency (HIRUE) as opposed to the RUE involved in dry matter accumulation. HIRUE of the twelve selected clones was determined using the formula (Squire, 1985):

$$DM = S \: X \: fs \: X \: Es \qquad\qquad\qquad (2)$$

where:

DM = Green Leaf dry weight

S = incoming solar radiation (MJm^{-2}),

fs = the proportion of radiation intercepted by the canopy

Es = the dry matter/light conversion ratio, conversion efficiency or (RUE) (g MJ^{-1}).

The proportion of solar radiation intercepted (f_s) by a discontinuous canopy like young tea depends on ground cover (GC), the leaf area fraction of area of ground covered (LAI) and the extinction coefficient for light (k) as expressed by the equation:

$$fs = GC \: (1-e^{(-kLAI)}) \text{ (Jackson and Palmer, 1979)} \qquad (3)$$

where:

GC = ground area covered by the canopy

LAI = leaf area index as described above

k = extinction coefficient;

The extinction coefficient was determined using the formular:

$$k = [log_e \: (l/l_o)]/LAI \text{ (Sheehy \& Cooper, 1973)} \qquad (4)$$

Where:

l_o = radiation on top of canopy

l = radiation at ground level under the canopy.

The radiation (S) in MJm^{-2} was determined from R (Wm^{-2}) below using the formula:

$$MJm^{-2} = Wm^{-2} \: (3.6 \: KJW^{-1})/10^3 \text{ (radconvert.html:, 2014)} \qquad (5)$$

Where:

MJm^{-2} = Radiation Energy in Megajoules per unit area

Wm^{-2} = Radiative Power in Watts per unit area

KJW^{-1} = Energy/power conversion factor Radiation

3.2.10. Incident and Intercepted Radiation.

Incident and intercepted radiation were measured from four randomly selected plants and tagged in each plot by measuring light intercepted at the top and the bottom of each plant's canopy using a Kipp solarimeter and read in millivolts (mV) off a multimeter. The intercepted radiation (I_{Rad}) was determined by subtracting the bottom reading from the top reading and expressed as a proportion of incident radiation by dividing the sum by the incident radiation as per the formula below.

$$I_{Rad} = \frac{IRT - IRB}{IRT} \; x \; 100$$

Where:

I_{RT} = Incident radiation measured at top of canopy

I_{RB} = Incident radiation measured at bottom of canopy

The radiation measurements as recorded in millivolts were converted into radiation energy using the formula *(6)* below:

$$R = [(r*cf)mV*1000/11.7mV] \; Wm^{-2} \qquad\qquad (6)$$

Where:

R = Radiation in Watts/m^2

r = Kipp's solarimeter reading (as recorded)

cf = conversion factor of solarimeter

$11.7mV$ = Kipp's solarimeter conversion factor to 1.0.

3.2.11. Shoot nitrogen content

To determine the nitrogen content in the pluckablebe shoots, a sample of 300g of fresh harvestable two leaves and a bud shoots taken twice every quarter (season), starting January to December 2012. These

were transferred to the laboratory, dried in an oven at 105°C for 48 hours, allowed to cool then milled to powder. The shoot Nitrogen content was then determined using the Kjeldahl method.

3.2.12. Nitrogen Use Efficiency (NUE)

The NUE was estimated by determining the amount of dry matter produced (yield) per unit of nitrogen fertilizer applied after (Nielsen, 2006). i.e

NUE = *[(Yield at Yi – Yield at Y0)/i]*

where:

Yi is the rate of nitrogen at rate i

Y0 is the control at 0kg N ha^{-1} year^{-1}

The yield dry matter was determined by applying the ratio of dry weight to fresh weight as determined from dry matter of a sample of 300g of fresh harvestable two leaves and a bud shoots sampled twice every quarter (season), starting January 2012. The shoot dry matter was determined by drying the 300 gm sample of fresh harvestable shoots in an oven at 105°C for 48 hours and then weighing. Quantity of nutrients harvested with crop due to nitrogen rate was determined as yield due the nitrogen rate x harvestable leaf nutrient content.

3.2.13. Leaf Nutrient Content

One hundred mature leaf (Figure 2) samples were collected randomly from each plot in April, during the long rain season April-June, and put in labeled paper envelopes. The samples were thereafter oven dried at 105^{0}C for 48 hours and then milled to powder form. The powdered samples were analysed for nitrogen (N) using the Kjeldahl method.and the other major nutrients (K, P, Ca, Mg, Mn, Na, Cu and Zn) by standard methods (Owuor *et al*., 1990a; Wanyoko *et al.*, 1990) modified from IITA, (1979) using: an Atomic Absorption Spectrophotometer (mode: Spect. AA. 30) to determine Ca, Mg Mn, Cu and Zn; a flame photometer (model: Corning 400 flame photometer) to determine K and Na: colorimetric method

using a spectrophotometer (model: CE3 Digitalgrating) to determine P. The leaf nutrient content was used to estimate the quantity of nutrients removed with crop.
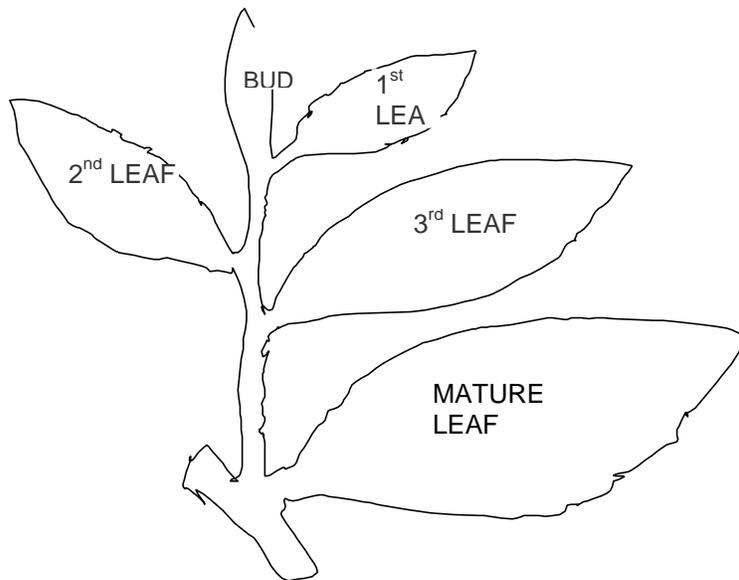
Figure 2: Diagramatic representation of a tea shoot

3.3. Data Analysis

The data collected was subjected to analysis of variance (ANOVA) using MSTAT-C (Version 2.10) statistical package, as a factorial two design, with clone (genotype) as the main factor and location as the second factor. The data was analysed as three factor RCBD with clone (genotype) as the main factor, location (site) as the second factor and season forming the third factor. For fertiliser response effects the data was analysed as RCBD, factorial two design, with location as the main factor and fertilizer rates as the sub factors. For NUE the factorial analysis allowed comparison of the rates omitting the control. Significant means were separated using Duncan's Multiple Range Test (DMRT). Correlations and testing of relationships for significance and strength were done using SPSS (Version 17.0) statistical package.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Response of Growth Parameters and Yield of Clonal Tea to Weather Parameters in Different Geographic Locations East and West of the Rift Valley.

4.1.1 Soil Properties and Weather Variations with Geographic Locations East and West of the Rift Valley

4.1.1.1 Soil Properties

The soil characteristics of the experimental sites are given in Tables 3 and 4. The textural properties of the soils showed variations, with Kangaita soils having coarser texture than Timbilil and Kipkebe soils. Kangaita had higher sand and lower clay contents than the other two sites, which were similar. The porosity ranged from 38% to 56%, with little variation between the sites. The soils from all the sites were of volcanic origin (Jaetzold *et al*., 2010). Tea is grown in soils of varying texture and in soils with clay content as high as 83% in Kenya and as low as 1.7% in Taiwan (Othieno, 1992). The soils in this study fell within these ranges and were similar to those observed in Kericho (Ng'etich *et al*., 1995a), and sandy loam in Kangaita in Kangaita and Nyambene (Kebeney *et al.,* 2010).

Table 3: Soil physical characteristics of the trial sites, 2012

Location	Depth	%sand	%clay	% silt	Textural class	%porosity	Soil description*
Timbilil	0-20	41.37	49.75	10.96	Clay	37.56	Volcanic dark red (10R 3/2), deep friable clays with a dusky red (2.5YR 3/6) top soil (0-0.1m), with Kaolinite as the predominant , classified as humic nitosols
	20-40	42.15	44.13	13.28	Clay	45.22	
	40-60	38.08	48.36	15.57	Clay	47.00	
Kangaita	0-20	76.20	13.44	10.36	Sandy loam	42.00	Volcanic reddish brown to dark brown, extremely deep, friable and slightly smeary clay with acid humic top soils, classed as ando-humic nitosols
	20-40	71.00	18.11	10.89	Sandy loam	41.00	
	40-60	62.65	24.72	12.63	Sandy loam	55.67	
Kipkebe	0-20	30.62	57.35	14.73	Clay	37.74	Dark reddish brown (2.5YR 3/4), deep to very deep, with friable and slightly smeary top soils, which were developed on acid igneous rock, classed as andoluvic phaeozems
	20-40	47.14	42.63	12.17	Clay	39.63	
	40-60	46.31	38.35	16.01	Clay	46.44	

*Soil description after Jaetzold and Schmidt, (2010)

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These results demonstrate the ability of tea to grow in a wide variety of soil textural types. The pH of the soils from the three sites ranged from 4.0 to 3.4 but were predominantly lower than 4.0 (Table 4). There was very little variation in the soil pH between the sites. Tea grows in soils of optimal pH of 4.0 to 6.0 (Anon, 2002a), but can grow in pH below 4.0 (Othieno, 1992). Indeed, optimal growth of tea had been reported at pH ranges between 3.8 and 5.7 in land newly cleared from primary, secondary forests and tree plantations (Ng'etich *et al.*, 1995a; Kebeney *et al.*,. 2010). The soil mineral contents (Table 4) were within the ranges observed in the major tea growing areas (Othieno, 1992). The soil nitrogen contents were adequate for tea growth. However, site variations were evident with Kangaita recording higher nitrogen levels than the other locations. These soils were all suitable for tea growing (Anon, 2002a; Othieno, 1988). Tea can be successfully and commercially grown in a wide variety of soil types.

Table 4: Soil chemical characteristics of trial sites,2012

Location	Depth .	pH (1:1)*	N (ppm)	P (ppm)	K (ppm)	Ca (ppm)	Mn (ppm)	Mg (ppm)	Na (ppm)	Cu (ppm)	Fe (ppm)	Zn (ppm)
Timbilil	0-20	3.9	57.5	19.1	157.8	264.6	196.9	69.4	67.4	19.0	70.4	32.4
	20-40	3.6	47.5	31.8	187.7	315.1	314.9	73.3	70.1	25.0	96.3	41.9
	40-60	3.8	45.0	23.4	181.4	295.1	243.5	70.9	68.1	19.5	77.7	34.4
Kangaita	0-20	3.6	29.5	27.6	669.6	133.6	27.4	23.4	93.8	2.5	145.0	3.2
	20-40	3.6	33.5	20.2	349.7	120.1	23.3	21.6	94.8	2.4	117.2	3.6
	40-60	3.7	58.5	21.5	235.8	99.8	22.1	19.1	88.3	2.3	113.4	3.5
Kipkebe	0-20	4.0	49.5	12.8	189.1	551.9	530.1	345.1	151.3	7.1	159.2	4.6
	20-40	3.4	43.0	14.7	190.7	520.4	767.2	176.3	138.5	7.1	155.0	7.2
	40-60	3.8	42.5	12.7	198.0	563.7	591.1	281.1	142.9	7.2	155.3	8.0

* 5g soil : 5ml distilled water

The variations in soil types and nutrients in this study could in part potentially contribute to locational yield variations. Similar soil properties differences between sites and even big differences between sites across East Africa tea growing regions had been observed. Soil water deficits and compaction could restrict productivity of tea in different locations (Ng'etich *et al.*, 1995a; Ng'etich *et al.*, 1995b). Indeed, results of soil water potential, which is directly related to plant water status show site variations in this study (Table 6). Though the variations in soil chemical properties cause yield variation

between locations, variations could also be due to the soil physical properties, which affect the plant water status, among other plant physiological properties.

4.1.2. Weather and Geographical Locations

There were noticeable differences between the sites in all the weather parameters measured and derived (rainfall, rain days, ambient temperatures, relative humidity and vapour pressure deficit), in 2012 (Table 5).

4.1.2.1. Temperatures

Mean monthly temperatures generally rose with declining altitude from Timbilil to Kipkebe (Table 1 and Table 5). However, Kipkebe had the highest mean ambient temperatures while mean Kangaita and Timbilil temperatures were similar despite the difference in altitude (Table 1). This was due the close proximity of Kangaita site to the Mt. Kenya, which lowered mean daily temperatures. The mean temperature difference between Kangaita and Timbilil was only 1˚C while between Kipkebe and Timbilil and Kipkebe and Kangaita were 3˚C and 4˚C, respectively. Similar results were obtained earlier (Squire *et al.,* 1993; Ng'etich *et al*., 1995a, Ng'etich *et al*., 1995c) where temperature difference between locations at high altitude (over 2000 m) was lower than those between high and lower altitude (below 2000 m) locations. Therefore, Kangaita and Timbilil, both lying above 2000 m were similar in terms of mean annual temperatures despite their altitudinal difference, but different from the low altitude Kipkebe site (Tables 1 and 5).

4.1.2.2. Rainfall

The rainfall pattern in Kangaita was bimodal with peaks in April-May and October-November, separated by cold and hot dry seasons from June to August and January to March, respectively. Rainfall pattern in Timbilil was unimodal with rains starting in April and continuing up to December. In Kipkebe the rainfall was weakly bimodal with peaks in April to July and in December (Table 5) as had been

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reported earlier (Stephens *et al*., 1992). Total rainfall declined with decreasing altitude from Timbilil to Kipkebe (Tables 1 and Table 5). Timbilil and Kipkebe had more rain days during the year but were drier in the January-March season, with no rain in the month of January. These seasonal variations are likely to impact on total annual yields and groth parameters variations between the sites.

Table 5: Monthly weather parameters at all G x E trial sites, Jan – Dec 2012

	Timbilil (0° 22'S)					Kangaita (0°30'S)					Kipkebe (0° 39'S)				
	Temp (^{o}C)	Rain (mm)	Rdays (d)	Rh (%)	Vpd (kPa)	Temp (^{o}C)	Rain (mm)	Rdays (d)	Rh (%)	Vpd (kPa)	Temp (^{o}C)	Rain (mm)	Rdays (d)	Rh (%)	Vpd (kPa)
Jan	16.7	0.0	0.0	46	10.33	16.3	17.2	3.0	55	8.91	19.9	0.5	0.0	64	7.82
Feb	17.7	26.8	7.0	38	11.41	15.3	19.7	4.0	55	8.56	20.1	82.9	11.0	73	5.97
Mar	18.0	27.7	6.0	48	10.11	17.1	40.3	3.0	55	8.18	19.4	50.1	7.0	73	5.9
Apr	15.3	398.4	25.0	71	5.65	16.2	449.6	23.0	80	3.93	19.5	514.4	26.0	80	3.34
May	16.4	391.1	24.0	80	3.62	16.4	692.0	25.0	80	3.49	19.6	249.4	24.0	80	3.53
Jun	16.0	226.9	20.0	80	3.34	14.8	89.4	16.0	89	1.97	18.6	178.3	20.0	90	2.58
Jul	15.7	160.9	13.0	79	3.38	13.3	49.1	16.0	88	1.39	18.6	122.6	10.0	85	3.07
Aug	16.1	298.9	18.0	70	4.51	13.6	190.5	14.0	78	2.68	18.9	97.7	11.0	80	3.45
Sept	15.7	239.1	24.0	80	4.9	16.5	121.8	8.0	78	3.1	17.8	194.5	17.0	81	3.62
Oct	16.9	269.4	24.0	63	6.63	15.4	325.0	11.0	80	3.58	20.5	99.3	16.0	76	4.96
Nov	16.9	227.6	22.0	62	6.54	15.5	234.1	13.0	80	3.25	19.7	97.1	15.0	80	3.48
Dec	16.4	172.3	15.0	62	6.43	15.1	169.6	17.0	71	4.81	19.7	261.6	17.0	80	3.44
Total		2439	198				2398	153				1948	174		
Mean	16.5			68.3	8.0	15.4			54.8	5.3	19.3			76.5	5.9

Temp = AmbientTemperature; Rain = Rainfall; Rdays = Rin days; Rh = Relative humidity; Vpd = Vapour pressure deficit

4.1.2.3. Relative Humidity (Rh) and Vapour Pressure Deficit (VPD)

Relative humidity (Rh) and vapour pressure deficit (VPD) also showed variations between sites (Table 5). Mean monthly relative humidity increased from high to low altitude (Table 1 and Table 5). The high humidity recorded at Kipkebe was attributed to its closer proximity to the Lake Victoria. Monthly VPD was highest in Timbilil and lowest in Kangaita. Highest VPDs were recorded during the January March period at all sites. This suggests there was a more severe drought in Timbilil than at Kipkebe and Kangaita during the study period. Seasonal variations of the weather parameters within and between sites were also evident. Soil water deficits and similarly, shoot water potential (SWP), are determined by

ambient temperatures and humidity. Atmospheric humidity is inversely related to vapour pressure deficits (Acland, 1989; Bonheure, 1990). An inverse linear relationship between VPD and SWP in tea has been reported (Squire, 1979; Williams, 1971; Tanton, 1982), although the SWP of tea shoots were more closely related to VPD than to soil moisture (Squire, 1979; Ng'etich *et al.,* 2001) reported variations in soil water deficits between sites in Kericho, which could cause yield variations. The recorded variations in RH and VPD, in this study, may explain the locational yield differences observed.

4.1.3. Response of Growth and Yield Parameters of Clonal Tea to Seasonal Weather Changes in Different Geographic Locations.

4.1.3.1. Season Description

The seasons 1 through 4 as described, in this study represent January-March, April May, June-September and October-December periods (Table). Though these do not follow the seasons described (Ng'etich *et al.,* 1995b) for Kericho. The description follow closely the changes in temperature and precipitation patterns while apportioning equal growing periods to each season. It was acknowledged that while Kericho rainfall is unimodal (Ng'etich *et al.,* 1995b; Ng'etich and Stephens, 2001b), Sotik and Kangaita experienced bimodal rainfall pattern (Table 5) (Jaetzold *et al.*, 2010.) The discernible seasonal differences were described from temperature and rainfall patterns as hot dry, cool wet, cold wet, and warm wet respectively (Table 5).

4.1.3..2 Tea Yield Components

New shoots of two or three leaves and a bud are harvested from the top surface of the bush every 7-21 days after which axils in the top most leaves of remaining butts develop to become the next crop (Tanton, 1992). The weight of crop in any one harvest therefore depends on the number of developing shoot per unit area, their rate of growth and the average weight of shoots at harvest. Tea yield components therefore comprise primarily, shoot growth rate (sgr), shoot dry weight (sdwt) and shoot density. The seasonal growth parameters data are presented in Tables 16 - 18.

4.1.3.2.1 Shoot Growth Rate (sgr)

Shoot growth rates (sgr) over the period of study (January-December 2012) showed significant ($p \leq 0.05$) clonal, locational and seasonal differences (Table 6). Clonal differences in shoot growth rates changed between locations and between seasons. Similar results had been reported as significant genotype–environment interactions where some clones exhibited high yields across four sites while others did not (Wickramaratne, 1981; Ronno *et al.,* 1991; Wachira *et al*., 2002.

Mean shoot growth rates varied significantly ($p \leq 0.05$) between locations and in the order Kangaita<Timbili<Kipkebe. These variations followed closely the temperature patterns of the locations (Table 5). Similarly, differences in shoot extension rates between two locations in two countries in eastern Africa (Carr *et al.,* 1987) and between three sites in Kenya (Squire *et al.,* 1993) had been reported. The results of a comparison of the stability of yield of a range of clones within four regions in Sri-Lanka (Wickramaratne, 1981) could not be extrapolated to other regions unless the differences in yield could be related to specific environmental variables such as soil water deficit (SWD) and temperature (Burgess, 1992). The variations in shoot growth rates observed in this study similarly, could be due to differences in environmental variables, which change with location and season (Table 5). The results show that clonal growth responses to environment will vary in magnitude and direction. Indeed, locations x season interactions were also significant ($p \leq 0.05$). Mean shoot growth rates were lowest ($p \leq 0.05$) in Timbilil throughout the four seasons while Kipkebe had the highest mean growth rates except for the April-June season. Similar results, were earlier attributed the variations to differences in temperature due to altitude and response of different clones to temperature (Carr *et al.,* 1987; Ng'etich *et al.,* 1995c; Stephens and Carr, 1990; Ng'etich *et al.,* 2001a). The results suggest that when growing conditions, e.g soil moisture, are not limiting (as during the wet season) plant growth will not vary with the location, implying that seasonal and locational yield differences are caused by the variation in severity of the abiotic stresss limiting the plant growth and not by variation in the viguor of growth.

Table 6: Effect of genotype, location and season on shoot growth rates (mm/day) in 2012

	Jan Mar				Apr Jun				Jul Sept				Oct Dec			
Clone	Kgta	Tmbl	Kpkb	*Cln mean*	Kgta	Tmbl	Kpkb	*Cln mean*	Kgta	Tmbl	Kpkb	*Cln mean*	Kgta	Tmbl	Kpkb	*Cln mean*
TRFK 7/3	0.08	0.03	0.72	*0.27*	0.31	0.06	0.21	*0.19bc*	0.53	0.31	0.95	*0.60e*	0.47	1.40	1.53	*1.13bc*
TRFK 303/577	0.09	0.05	0.67	*0.27*	0.24	0.09	0.30	*0.21a*	0.49	0.78	1.37	*0.88a*	0.60	1.16	1.48	*1.08cd*
EPK TN 14-3	0.06	0.03	0.65	*0.25*	0.23	0.08	0.26	*0.19bc*	0.42	0.59	1.36	*0.79b*	0.43	1.64	2.20	*1.42a*
TRFK 2X1/4	0.05	0.02	0.51	*0.19*	0.12	0.08	0.23	*0.15fg*	0.53	0.52	1.02	*0.69cd*	0.57	1.48	1.61	*1.22b*
STC 5/3	0.07	0.02	0.66	*0.25*	0.29	0.07	0.19	*0.18cd*	0.40	0.70	0.83	*0.64cde*	0.46	1.38	1.12	*0.99def*
TRFK 11/26	0.10	0.03	0.74	*0.29*	0.27	0.07	0.20	*0.18cd*	0.31	0.29	0.68	*0.43a*	0.68	0.99	0.98	*0.88fghi*
TRFK 12/19	0.06	0.02	0.68	*0.25*	0.22	0.07	0.17	*0.16ef*	0.32	0.36	0.68	*0.45fg*	0.46	1.09	0.97	*0.84ghi*
TRFK 56/89	0.06	0.03	0.68	*0.26*	0.05	0.07	0.22	*0.11g*	0.66	0.66	1.08	*0.80b*	0.69	2.18	1.70	*1.52a*
TRFK 12/12	0.06	0.03	0.71	*0.26*	0.30	0.07	0.18	*0.18cd*	0.40	0.27	0.58	*0.42g*	0.52	1.08	0.77	*0.79i*
TRFK 303/999	0.05	0.03	0.67	*0.25*	0.32	0.54	0.24	*0.20bc*	0.62	0.32	0.93	*0.62de*	0.67	1.23	1.23	*1.04cde*
AHP S15/10	0.07	0.02	0.59	*0.26*	0.25	0.07	0.23	*0.18cd*	0.49	0.18	0.83	*0.50f*	0.64	0.87	1.30	*0.94efg*
TRFK 57/15	0.06	0.02	0.76	*0.28*	0.30	0.08	0.19	*0.19bc*	0.33	0.60	1.16	*0.69c*	0.79	0.84	1.58	*1.07cd*
TRFK 31/27	0.09	0.02	0.74	*0.28*	0.26	0.06	0.19	*0.17de*	0.39	0.33	0.81	*0.51f*	0.79	0.78	1.20	*0.92efg*
TRFK 6/8	0.09	0.03	0.66	*0.26*	0.24	0.06	0.19	*0.16ef*	0.55	0.24	0.59	*0.46fg*	0.59	0.97	0.86	*0.81hi*
BBK 35	0.06	0.03	0.64	*0.24*	0.31	0.08	0.22	*0.21a*	0.58	0.49	0.76	*0.61e*	0.64	1.30	1.69	*0.21j*
TRFK 31/8	0.06	0.03	0.69	*0.26*	0.20	0.08	0.23	*0.17de*	0.38	0.56	0.84	*0.60e*	0.45	1.15	1.43	*1.00def*
TRFK 7/9	0.07	0.04	0.69	*0.27*	0.25	0.06	0.18	*0.16ef*	0.38	0.24	0.61	*0.41g*	0.68	1.22	0.92	*0.94efg*
LDS (p≤0.05)303/259	0.05	0.02	0.66	*0.25*	0.11	0.08	0.22	*0.14g*	0.44	0.32	0.88	*0.55fg*	0.68	1.12	1.46	*1.09cd*
TRFK 303/1199	0.08	0.03	0.72	*0.28*	0.21	0.07	0.22	*0.17de*	0.41	0.62	1.00	*0.68cd*	0.56	1.83	1.11	*1.16bc*
TRFK 54/40	0.09	0.03	0.70	*0.27*	0.05	0.09	0.21	*0.12h*	0.41	0.41	0.73	*0.52f*	0.81	0.94	0.96	*0.90fghi*
Ste mean	*0.07y*	*0.03y*	*0.68x*		*0.23x*	*0.07z*	*0.21x*		*0.45y*	*0.44y*	*0.88x*		*0.61y*	*0.23z*	*1.31x*	

SSn mean	0.26		0.17		0.59		1.05
CV%	32.86		27.46		26.69		27.98
LDS (p≤0.05)							
Clone	NS		0.043		0.15		0.27
Site	0.03		0.02		0.06		0.11
CxS	NS		0.078		0.25		0.47

All 4 seasons
CV%   33.97

	Kangaita	Timbilil	Kipkebe				
Site mean	0.34	0.442	0.77				
	Cln	Ste	Ssn	ClnXSt	ClnxSSn	StxSsn	ClnxStexSSn
LDS (p≤0.05)	0.08	0.03	0.04	0.01	0.02	0.06	0.03

Numbers followed by the same letter, down the column *(a,b,c,d,e)* and across the row *(x,y,z)* are not significantly different according to Duncan's Multiple Range Test (DMRT)

The variations in clonal shoot growth rates to location and season indicated that shoot growth rate was mainly environment controlled and its response to weather was determined by the inherent genetic makeup. Tea growth rates will vary with season and different management options will be required to optimize yields of a clone across the seasons in different locations. It has also been suggested that the study of varietal differences in shoot growth patterns could give an indication of varietal differences which could be exploited to alleviate seasonal yield differences (Tanton, 1982a).

4.1.3.2.2 Shoot density (SD/sd))

Shoot densities showed significant ($p \leq 0.05$) clonal differences (Table 7). This had been reported earlier and has been sugetsed to be the reason for yield differences between clones (Squire, 1979; Obaga *et al.,* 1989; Stephens and Carr, 1990; Odhiambo *et al.,* 1993). Mean shoot densities also showed large differences between ($p \leq 0.05$) sites. Indeed, locational variations in shoot density (Obaga *et al.,* 1989) and dry matter partitioning to shoots (Ng'etich and Stephens 2001a) were observed earlier. The observed differences in this study could be attributed to differences in temperature, being the main weather parameter differentiating the sites (Tables 5 and 14).

The clonal differences also varied significantly with location but not season. Previous studies India (Kulasegaram and Kathiravetpillai, 1974) and in Eastern Africa (Carr, 1990; Stephens and Carr, 1990) reported that that seasonal yield variations occurred mainly due to differences in shoot density. However, the clone x location interactions were significant ($p \leq 0.05$) across the seasons an indication that the clones responded differently to location in terms of shoot density, this pattern did not vary with season. This suggests that SD was not significantly affected by seasonal changes in weather but only by the fundamental climatic differences between locations. This could be due to the observed non significant clonal response and clone x site interaction in October-December season.

Table 7: Effect of genotype, location and season on shoot densities (shoots/m^2) in 2012

Clone	Jan Mar Kgta	Tmbl	Cln mean	Apr Jun Kgta	Tmbl	Kpkb	Cln mean	Jul Sept Kgta	Tmbl	Kpkb	Cln mean	Oct Dec Kgta	Tmbl	Kpkb	Cln mean
TRFK 7/3	77.33	18.67	*48.00cd*	105.00	15.00	61.67	*60.56bcd*	87.00	33.33	69.33	*63.22fgh*	115.67	64.33	87.67	*89.22*
TRFK 303/577	97.67	26.00	*58.83a*	141.00	19.67	70.33	*77.00a*	123.67	48.00	72.67	*81.44a*	114.67	86.33	71.33	*90.78*
EPK TN 14-3	73.33	27.00	*50.17bc*	97.33	20.00	57.00	*56.11cdfg*	102.67	34.33	66.67	*69.22bcde*	97.67	75.00	81.33	*84.67*
TRFK 2X1/4	67.67	23.67	*45.67def*	77.67	19.67	64.00	*53.78fghiu*	96.33	34.67	76.67	*69.22bcde*	105.33	65.33	86.00	*85.56*
STC 5/3	62.00	23.33	*42.67fgh*	100.00	16.00	72.67	*62.89b*	114.33	32.33	75.33	*74.00b*	116.00	58.00	91.33	*88.44*
TRFK 11/26	77.00	25.00	*51.00bc*	80.00	16.33	69.33	*55.22defghi*	84.33	37.33	63.00	*61.55gh*	95.67	57.00	81.33	*78.00*
TRFK 12/19	74.33	17.33	*45.83def*	77.00	13.67	60.67	*50.44hi*	81.67	38.33	74.00	*64.67efg*	83.00	59.33	88.67	*77.00*
TRFK 56/89	73.67	34.67	*54.17b*	110.67	22.33	44.33	*59.11bcdef*	81.00	38.33	63.00	*60.78ghi*	68.67	65.33	85.00	*73.00*
TRFK 12/12	70.00	28.67	*49.33cd*	96.67	21.00	58.00	*58.56bcdefg*	67.33	38.00	64.33	*56.56ij*	83.00	64.33	74.00	*73.78*
TRFK 303/999	62.67	23.33	*42.50fgh*	82.00	26.00	55.67	*54.56efghi*	77.33	41.67	70.33	*63.1fgh*	97.67	79.00	79.00	*85.22*
AHP S15/10	62.67	21.33	*42.00fgh*	106.67	16.33	52.00	*58.33bcdefg*	89.00	38.33	66.67	*64.67efg*	102.67	64.33	93.67	*86.89*
TRFK 57/15	65.00	29.67	*47.33cde*	100.67	26.00	57.00	*61.22bc*	105.33	49.33	63.00	*72.56bc*	103.33	71.33	84.00	*86.22*
TRFK 31/27	78.33	23.67	*51.00bc*	94.33	12.33	69.33	*58.67bcdefg*	91.33	37.00	72.67	*67.00def*	93.33	58.00	82.67	*78.00*
TRFK 6/8	61.00	19.00	*40.00ghi*	98.00	18.67	64.00	*60.22bcde*	68.33	27.33	65.33	*53.67j*	97.67	56.00	83.67	*79.11*
BBK 35	58.00	17.67	*37.83i*	76.67	17.33	55.67	*49.89i*	110.33	31.00	74.00	*71.78bcd*	113.33	65.33	83.67	*87.44*
TRFK 31/8	65.00	22.33	*43.67efg*	88.67	17.67	59.33	*55.22dfghi*	82.00	28.33	66.67	*59.00hi*	87.00	126.00	88.67	*100.56*
TRFK 7/9	73.33	27.33	*50.33bc*	94.67	18.67	65.33	*59.56bcdef*	98.67	43.33	71.67	*71.22bc*	106.33	69.33	91.33	*89.00*
TRFK 303/259	67.00	27.00	*47.00cde*	80.67	17.67	63.00	*53.78fghi*	68.33	54.33	63.33	*62.00gh*	86.33	115.00	75.00	*92.11*
TRFK 303/1199	86.67	21.00	*53.83b*	128.33	21.00	69.33	*72.89ghi*	88.67	53.00	72.00	*67.78cdef*	110.33	70.67	79.33	*86.78*
TRFK 54/40	57.00	20.00	*38.50hi*	81.67	16.33	65.33	*54.44efghi*	72.00	46.00	65.33	*60.78ghi*	85.33	56.00	82.67	*74.67*
Ste mean	70.18x	23.78y		95.58x	18.58z	61.70y		89.68x	39.22z	68.23y		98.15x	71.30z	83.52y	
Ssn mean	46.98			58.62				65.71				84.322			
CV%	17.17			22.38				17.69				24.63			
LDS (p≤0.05)															
Clone	9.22			12.12				10.74				NS			
Site	2.92			4.69				4.16				7.43			
CxS	13.04			20.99				18.61				NS			

All seasons

CV%	22.65						
	Kangaita	Timbilil	Kipkebe				
Site mean	94.47	43.03	71.15				
	Cln	Ste	Ssn	ClnXSt	ClnxSSn	StxSsn	ClnxStexSSn
LDS (p≤0.05)	8.4	3.25	3.26	14.56	NS	5.64	NS

Numbers followed by the same letter, down the column *(a,b,c,d,e)* and across the row *(x,y,z)* are not significantly different according to Duncan's Multiple Range Test (DMRT)

The October-December season was warm and wet, conditions conducive for the growth of tea, compared to other seasons which had limitations of high or low temperatures (January-March, April- June and July-August) and saturation deficits (January-March) (Tables 5 and 14) which could have caused expression of tolerance genotypic traits. Indeed correlation of seasonal SD to yield was not significant (Table 20). The temperatures were therefore too high or too low as to encourage initiation of new buds so that clones adapted to these conditions responded by initiating more buds than the rest. In the October-December season however, conditions were not limiting for any clone hence there were no significant variations between clones within any location. These observations suggest that there were differences in conditions that limit growth in some clones more than others rather than conditions that favour growth in some clones more than others.

4.1.3.2.3 Shoot Dry Weight (sdwt)

The effects of genotype, location and season on dry weights are presented in (Table 8). There were significant ($p \leq 0.05$) variations in shoot dry weights (sdwt) due to clones. Similar results were reported in Malawi (Smith *et al*., 1993), Tanzania (Stephens and Carr, 1990) and Kenya (Odhiambo *et al*, 1991), at single sites. In the January-March season, there were no significant ($p \leq 0.05$) differences. This could be attributed to the lack of moisture due to the dry conditions experienced in that season at all the sites. The conditions were too dry in Kipkebe (Tables 5 and 14), growth ceased and no pluckable shoots developed. These findings demonstrate the diversity of clones and sites. The clones x site interactions were also significant throughout the growing period. Similar results were reported for dry matter Ng'etich and Stephens 2001a; Ng'etich *et al.*, 1995c). The findings demonstrate the variations in clonal yield components response to environment. Significant ($p \leq 0.05$) differences in sdwt due to season were also recorded.

Table 8: Effect of genotype, location and season on shoot dry weights (g/shoots) in 2012

Clone	Jan Mar			Apr Jun				Jul Sept				Oct Dec			
	Kgta	Tmbl	*Cln mean*	Kgta	Tmbl	Kpkb	*Cln mean*	Kgta	Tmbl	Kpkb	*Cln mean*	Kgta	Tmbl	Kpkb	*Cln mean*
TRFK 7/3	0.11	0.13	*0.12*	0.10	0.17	0.15	*0.14ab*	0.13	0.32	0.15	*0.20cdef*	0.14	0.36	0.18	*0.22cd*
TRFK 303/577	0.10	0.12	*0.11*	0.04	0.13	0.16	*0.11d*	0.10	0.29	0.13	*0.17fgh*	0.19	0.32	0.16	*0.23bcd*
EPK TN 14-3	0.12	0.12	*0.12*	0.05	0.17	0.16	*0.13bc*	0.12	0.41	0.17	*0.24abcd*	0.17	0.42	0.16	*0.25bcd*
TRFK 2X1/4	0.09	0.12	*0.11*	0.03	0.15	0.14	*0.11d*	0.11	0.28	0.13	*0.17fgh*	0.14	0.37	0.16	*0.22cd*
STC 5/3	0.13	0.10	*0.12*	0.07	0.12	0.12	*0.11d*	0.08	0.32	0.12	*0.17fgh*	0.09	0.37	0.17	*0.21d*
TRFK 11/26	0.13	0.08	*0.10*	0.07	0.12	0.16	*0.11d*	0.11	0.21	0.14	*0.15ghi*	0.19	0.29	0.17	*0.22cd*
TRFK 12/19	0.10	0.11	*0.10*	0.05	0.16	0.15	*0.15a*	0.14	0.19	0.13	*0.16gh*	0.22	0.39	0.17	*0.26bc*
TRFK 56/89	0.07	0.12	*0.10*	0.04	0.16	0.14	*0.11d*	0.17	0.47	0.13	*0.26a*	0.30	0.57	0.17	*0.34a*
TRFK 12/12	0.15	0.09	*0.12*	0.10	0.14	0.19	*0.14ab*	0.16	0.29	0.16	*0.20def*	0.29	0.35	0.18	*0.27b*
TRFK 303/999	0.11	0.15	*0.13*	0.05	0.12	0.19	*0.12cd*	0.10	0.31	0.16	*0.19ghi*	0.20	0.44	0.18	*0.27b*
AHP S15/10	0.13	0.13	*0.13*	0.09	0.17	0.20	*0.15a*	0.14	0.33	0.18	*0.22bcde*	0.18	0.38	0.17	*0.24bcd*
TRFK 57/15	0.09	0.08	*0.09*	0.06	0.10	0.18	*0.11d*	0.09	0.22	0.14	*0.15i*	0.13	0.34	0.18	*0.22cd*
TRFK 31/27	0.11	0.12	*0.12*	0.10	0.19	0.14	*0.14ab*	0.11	0.37	0.14	*0.21cdef*	0.17	0.44	0.16	*0.26bc*
TRFK 6/8	0.10	0.12	*0.11*	0.06	0.13	0.16	*0.11d*	0.18	0.34	0.16	*0.23abcd*	0.20	0.36	0.16	*0.24bcd*
BBK 35	0.14	0.15	*0.15*	0.06	0.17	0.16	*0.13bc*	0.08	0.28	0.15	*0.17fgh*	0.16	0.36	0.17	*0.23bcd*
TRFK 31/8	0.07	0.12	*0.10*	0.07	0.16	0.18	*0.14ab*	0.18	0.39	0.18	*0.25ab*	0.20	0.38	0.16	*0.25bcd*
TRFK 7/9	0.09	0.15	*0.12*	0.06	0.17	0.14	*0.12cd*	0.14	0.38	0.13	*0.22bcde*	0.14	0.49	0.16	*0.26bc*
TRFK 303/259	0.11	0.11	*0.11*	0.08	0.17	0.14	*0.13bc*	0.19	0.35	0.17	*0.24abc*	0.23	0.37	0.18	*0.25bcd*
TRFK 303/1199	0.10	0.16	*0.13*	0.06	0.19	0.14	*0.13bc*	0.10	0.29	0.13	*0.17fgh*	0.15	0.43	0.15	*0.24bcd*
TRFK 54/40	0.11	0.09	*0.10*	0.09	0.11	0.16	*0.12bcd*	0.16	0.16	0.15	*0.16gh*	0.31	0.29	0.16	*0.26bc*
Ste mean	*0.11*	*0.12*		*0.06y*	*0.15x*	*0.16x*		*0.13y*	*0.31x*	*0.15y*		*0.19y*	*0.39x*	*0.17y*	
Ssn mean		0.11			0.13				0.20						0.25	
CV%		23.0			22.7				28.8						19.0	
LDS (p≤0.05)															
Clone		NS			0.026				0.049						0.04	
Site		NS			0.01				0.02						0.02	
CxS		0.04			0.05				0.09						0.08	

All seasons

	CV%						
	23.9						
	Kangaita	Timbilil	Kipkebe				
Site mean	0.01	0.03	0.02				
	Cln	Ste	Ssn	ClnXSt	ClnxSSn	StxSsn	ClnxStexSSn
LDS (p≤0.05)	0.02	0.01	0.01	0.04	0.04	0.03	NS

Numbers followed by the same letter, down the column *(a,b,c,d,e)* and across the row *(x,y,z)* are not significantly different according to Duncan's Multiple Range Test (DMRT)

Site variations were not significant in January- March but shoot dry weights were significantly highest in Timbilil, a factor attributable to the milder weather through the seasons compared to the other two sites which experienced growth limiting extremes of high (Kipkebe) and low (Kangaita) temperatures at some point during the growth period (Table 5). Similar findings have been reported for dry matter with the locational differences being attributed to differences in temperature (Smith *et al*., 1993; Ng'etich and Stephens 2001a; Ng'etich *et al.*, 1995c). The site difference observed in this study could also be attributed to variations in temperature and saturation deficits as earlier (Table 5).

The mean sdwts showed significant ($p \leq 0.05$) variation with location during all growth seasons. Mean shoot dry weighs were significantly lowest in January –March and increased through the seasons to peak in October-December. Similarly, seasonal variation in shoot dry weights among four clones in high altitude area of Tanzania was attributed to reduction due to drought and cold (Burgess and Carr, 1996). The findings from thus study can be related to the weather changes through the seasons, where moisture was limiting in January march, April June being the recovery period, July-September being cold and October December being warm and wet, was conducive for growth. Shoot dry weights showed varied correlation relationships to yields over the seasons (Table 8).

4.1.3.2.4: Shoot Water Potential (SWP)

Shoot water potential was measured only in the 3 seasons of January March, April June and October December. There were no genotypic differences in all locations and in all seasons (Table 9). Similar findings were earlier recorded in Kericho (Odhiambo *et al*., 1993).

Tea plants maintained similar water status regardless of genotype and this did not vary with the location or season. SWP therefore may not an appropriate parameter for modeling clonal yields.

Table 9: Effect of genotype, location and season on clonal shoot water potential (KPa) in 2012

	Jan Mar				Apr Jun				Oct Dec			
	Kgta	Tmbl	Kpkb	*Cln mean*	Kgta	Tmbl	Kpkb	*Cln mean*	Kgta	Tmbl	Kpkb	*Cln mean*
TRFK 7\3	17.7	20.1	16.0	*17.9*	6.3	6.7	5.8	*6.3*	8.6	5.1	9.3	*7.7*
TRFK 303/577	16.0	20.2	15.4	*17.2*	6.8	6.7	5.8	*6.4*	7.7	4.7	9.4	*7.2*
EPK TN 14/3	16.6	20.5	15.7	*17.6*	6.2	6.5	5.8	*6.2*	9.0	5.0	9.1	*7.7*
TRFK 2X1/4	17.4	21.0	16.1	*18.1*	6.0	5.7	5.8	*5.9*	8.5	5.0	8.7	*7.4*
STC5/3	16.8	19.5	14.8	*17.0*	6.8	6.0	5.8	*6.2*	8.9	4.5	9.2	*7.5*
TRFK 11|26	16.4	19.9	15.1	*17.1*	5.4	4.7	5.7	*5.2*	7.7	4.8	8.9	*7.1*
TRFK 56/89	18.1	19.4	16.8	*18.1*	5.8	6.3	5.9	*6.0*	7.9	4.8	7.8	*6.8*
TRFK 12|19	16.6	18.4	16.2	*17.1*	5.3	5.5	5.7	*5.5*	7.8	4.6	8.9	*7.1*
TRFK 12|12	14.9	19.5	15.8	*16.7*	6.3	5.4	6.3	*6.0*	7.7	4.5	9.0	*7.1*
TRFK 303/999	18.0	20.1	17.0	*18.3*	5.8	4.7	6.0	*5.5*	8.6	4.6	8.7	*7.3*
AHP S15/10	17.9	20.3	16.0	*18.0*	6.4	5.3	5.8	*5.8*	9.3	4.9	8.9	*7.7*
TRFK 57/15	18.6	20.3	16.0	*18.3*	6.7	5.6	5.9	*6.1*	8.7	4.7	9.0	*7.5*
TRFK 31/27	16.6	19.7	14.1	*16.8*	6.4	6.6	6.0	*6.3*	8.8	4.2	9.1	*7.4*
TRFK 6|8	18.4	20.6	16.8	*18.6*	6.4	5.3	5.8	*5.9*	9.3	4.6	8.4	*7.4*
BBK 35	16.8	19.8	14.2	*16.9*	6.6	5.9	6.1	*6.2*	8.1	4.6	8.1	*6.9*
TRFK 31\8	18.3	20.6	16.6	*18.5*	5.7	4.6	5.8	*5.4*	8.5	4.2	8.6	*7.1*
TRFK 7\9	16.5	19.4	17.6	*17.8*	5.0	6.0	6.0	*5.7*	8.7	4.3	8.3	*7.1*
TRFK 303/259	17.3	19.0	17.0	*17.8*	6.3	3.9	5.8	*5.3*	8.9	4.3	8.2	*7.1*
TRFK 303/1199	17.2	20.5	15.4	*17.7*	6.2	5.0	5.7	*5.6*	8.7	4.1	83.0	*7.0*
TRFK 54/40	17.6	20.6	14.7	*17.6*	5.4	5.1	5.9	*5.5*	9.3	4.1	8.9	*7.4*
Ste mean	*17.2y*	*20.0x*	*15.9z*		*6.1*	*5.6*	*5.9*		*8.5x*	*4.6*	*8.7x*	
Ssn mean	17.7				5.9				7.3			
CV%	8.7				20.1				7.7			
LSD (p≤0.05)												
Clone	NS				NS				NS			
Site	.06				NS				0.20			
CxS	NS				NS				0.90			
All seasons												
CV%	22.65											

	Kangaita	Timbilil	Kipkebe				
Site mean	10.6	10.1	10.16				
	Cln	Ste	Ssn	ClnXSt	ClnxSSn	StxSsn	ClnxStexSSn
LSD (p≤0.05)	NS	0.3	0.3	0.2	NS	0.4	NS

Numbers followed by the same letter, across the row *(x,y,z)* are not significantly different according to Duncan's Multiple Range Test (DMRT)

Other growth parameters like sgr and sd which are water dependent showed, highly significant (p≤0.05) differences between genotypes and locations (Tables 6 and 7) suggesting therefore that water use efficiency must vary between clones. Differences in locational shoot growth rates were reported to be due to differences in saturation water deficits between locations (Ng'etich *et al.,* 1995). Mean locational SWP showed significant (p≤0.05) differences during the January March and October December seasons but not April June season. Locational environmental effects, most probably SVPD and soil moisture (Table 5 and 14) may have contributed to the location SWP differences when moisture was limiting but did not affect

significantly, plant growth when moisture was in abundance as in April June season. Since SWP is not responsive in conditions of moisture abundance it may therefore not be a good parameter for yield modeling across seasons and locations. Seasonal differences in SWP were significant as were site differences, across the seasons. Similar findings have been recorded in Malawi (Squire, 1979). The interactions clone x site and clone x season were significant (p≤0.05). Though the clonal differences were not significant, the differences in their response to location and season was significant (p≤0.05). Shoot water potential may therefore affect tea yields across different locations and seasons but not individual clonal yields. SWP may determine yields across locations and season but not between individual clones and may therefore have potential for use in modelling tea yields in different environments but not between clones. Inherent genotypic differences in SWP is only expressed in response to different environments but not under the same environment.

4.1.4. Seasonal Yield, Yield Parameters and Weather Interactions

4.1.4.1. Shoot Growth Rates

Shoot growth rates showed significantly (p≤0.05) high correlations to yields throughout the four seasons. These ranged from a low of r = 0.322 in January-March to high of r= 0.822 in April –June season (Tables 20). Correlations of sgr to SD, SWP and sdwt varied with season (Table 10 and 11). Sgr was negatively correlated to sdwt throughout except for Oct-Dec season. Shoot growth cycle increased while shoot extension rate declined, mainly due to temperature differences between four sites in Kenya (Squire *et al*., 1993; Magambo *et al*., 1989). In Kenya ambient temperatures were more closely associated with the yield differences recorded although yield response to temperature was complicated by soil water deficits and saturation deficits (Ng'etich *et al*., 2001).

Table 10: Effect of season and geographical location on correlation coefficients (r) of yield (Yld) and yield parameters: shoot growth rate (Sgr), Shoot density (sd), shoot dry weight (sdwt).

		Kangaita			Timbilil			Kipkebe		
		Sdwt	Sgr	sd	Sdwt	Sgr	Sd	sdwt	Sgr	Sd
Jan Mar	Sgr	0.06			0.3					
	Sd	1***	0.06		1.0***	0.3*				
	Yld	-0.09	0.27	-0.09	0.35	0.45*	0.35		-0.38	
Apr Jun	Sgr	0.23			-0.31			0.20		
	Sd	-0.10	0.07		-0.42	0.51*		-0.50*	-0.07	
	Yld	0.15	0.09	0.64**	-0.04	0.06	0.32	-0.20	0.40	0.23
Jul Sept	Sgr	0.05			0.12			-0.15		
	Sd	-0.75***	-0.06		-0.25	0.13		-0.51*	0.04	
	Yld	-0.27	-0.03	0.44*	0.17	0.52*	0.42	-0.01	0.26	0.19
Oct Dec	Sgr	0.24			0.61**			0.02		
	Sd	-0.83***	-0.19		0.02	0.03		-0.09	-0.03	
	Yld	0.12	0.02	0.18	0.10	0.01	0.14	-0.25	0.37	-0.16

* Significant at 0.05; ** Significant at 0.01; *** Significant at 0.001

These findings illustrate the complexity of the interrelationships between the yield and growth components response to weather and show that that no single component will determine tea yields. Increase in shoot growth rates in response to conducive weather may have been at the detriment of the shoot dry weight during periods in most of the growth period. Correlation of sgr with swp was only significant in January and March season, when moisture was limiting. Shoot water potential effect on plant growth appears to only significantly limit plant growth during periods of water stress. Correlations with weather parameters (temperature and rainfall) remained significant during all the seasons implying that rainfall and temperatures exerted significant effect on plant growth throughout the seasons and therefore, are key in determining the potential plant growth and ultimately yield. Sgr also showed significant correlation to altitude during all the seasons except for October December season when adequate warm temperatures and rainfall were conducive to plant growth and there was little difference in weather between the locations.

Table 11: Effects of seasons on correlation coefficients (r) between mean clonal yields, yield components and weather parameters

	Jan -Mar										Apr Jun									
	SWP	SGR	SD	SDWT	Temp	Rain	RH	VPD	Rad.	Alt.	SWP	SGR	SD	SDWT	Temp	Rain	RH	VPD	Rad	Alt
Yield	-.607**	.882**	-0.152	0.217	.879**	.842**	.587**	-.505**	0.183	-.812**	0.066	.328**	0.191	.371**	.928**	-.574**	.897**	.347**	.509**	-.908**
SWP		.707**	.897**	.103	-.419**	.813**	.116	.890**	.525**	.841**		0.168	.378**	-0.175	.017**	.240**	.164**	-.304**	-.169**	-.150**
SGR			.877**	-0.125	.909**	.969**	.512**	-.677**	.040	-.948**			.562**	-.293*	.244*	0.213	.452**	-.361**	-.245*	-.434**
SD				-0.285	-.952**	.952**	-.952**	-.952**	-.953**	-.952**				-.682**	0.044	.633**	.434**	-.803**	-.610**	-.396**
SDWT					0.237	-0.237	0.237	0.237	0.25	0.237					.512**	-.866**	0.169	.873**	.824**	-0.208
Temp						.801**	.8**	-.327*	.440**	-.750**						-.713**	.909**	.492**	.623**	-.927**
Rain							.311*	-.827**	-0.181	-.997**							-.357**	-.961**	-.919**	.398**
RH								.277*	.874**	-0.232								0.085	.285*	-.999**
VPD									.699**	.870**									.896**	-0.13
Rad.										.260*										-.324**

	Jul Sept										Oct Dec									
	SWP	SGR	SD	SDWT	Temp	Rain	RH	VPD	Rad.	Alt.	SWP	SGR	SD	SDWT	Temp	Rain	RH	VPD	Rad.	Alt.
Yield	.ᵃ	.786**	0.135	-.319*	.860**	-.341**	.659**	.425**	.801**	-.860**	0.19	.547**	-0.182	-0.127	.760**	-.749**	.763**	0.163	.671**	-.548**
SWP		.ᵃ	.ᵃ	.ᵃ	.ᵃ	.ᵃ	.ᵃ	.ᵃ	.ᵃ	.ᵃ		-0.031	0.063	-.290*	0.22	-0.242	0.181	-0.214	0.018	-.322*
SGR			0.093	-.275*	.712**	-.300*	.538**	.340**	.646**	-.723**			-.403**	.319*	.585**	-.541**	.645**	.505**	.708**	-0.185
SD				-.815**	-0.224	-.861**	-.552**	-.744**	-.350**	-.402**				-.548**	-0.222	0.165	-.311*	-.619**	-.503**	-0.196
SDWT					-0.063	.857**	.285*	.524**	0.095	.611**					-.278*	.356**	-0.145	.814**	0.242	.745**
Temp						-0.021	.917**	.745**	.969**	-.752**						-.996**	.988**	0.111	.780**	-.785**
Rain							.381**	.651**	0.137	.674**							-.970**	-0.018	-.728**	.839**
RH								.950**	.951**	-.426**								.261*	.851**	-.681**
VPD									.827**	-0.122									.608**	.529**
Rad.										-.625**										-.287*

n=20 ᵃ data not available; ** Significant at 0.01; *** Significant at 0.001

The locations differences are therefore described by the variations in local weather patterns resulting in the plant growth and yield variations between the locations. The variation in the correlation between the plant growth components may be attributed to the genetic variation in plant response to weather.

Sgr response to temperature across seasons also varied significantly. This was clear indication of temperature regulation of sgr. Indeed, the correlations were greatest and lowest in the hot and the cold seasons of January March and July September respectively. These months correspond to the periods of hot and cold stress and therefore reiterate the earlier observation that yield differences may be due to variations in severity of the abiotic stresss on limiting the plant growth. Therefore sgr is important in determining yields and should therefore be considered in any yield model for tea.

Stepwise regression with weather parameters indicated that temperature was not always the main determining factor of sgr (Table 11). Similar findings have been reported earlier (Ng'etich *et al.*, 2001). Regressions carried out on only the parameters that returned significant correlations showed that in the cold and warm wet seasons of April June and October December, relative humidity (RH) was the most closely related weather parameters to sgr with the correlations r=0.452 to 0.205 and r =0.645 to 0.416, respectively. Consequently the slopes of the regression also varied 0.006 mmd^{-1} %RH^{-1} and 0.047 mmd^{-1} %RH^{-1}. In the hot and cold seasons of January March and July September, temperature featured as the most weather limiting parameter to sgr (r=0.994 to 0.987 and r= 0.712 to 0.506, respectively) (Table 21). Though SVPD significantly correlated to sgr, regression analysis showed that it was only significant in determining sgr during the wet seasons; however, not independently but in combination with temperature in July September season. Similar saturation deficit, temperature relationships and their influence on tea shoot growth had been reported earlier (Hadfield, 1968; Hadfield, 1979; Tanton, 1982b; Carr and Stephens, 1992). These relationships suggest that the plant shoot growth rate response to weather across the seasons was determined by varying weather parameters. Indeed, it has been reported that that seasonal

variation in yield of seedling tea at high altitude in Kenya was due to variation in weight and growth of rate of shoots (Mwakha, 1981).

Stepwise regression showed that in the hot season, the locational variation in sgr was attributed to the combination of temperature and rainfall, though rainfall was the most limiting (r=0.969 to 0.939) (Table 11). The relationship of sgr and temperature varied from 0.075mmd^{-1} ^{0}C^{-1} in the hot season (Jan/Mar) to 0.116 mmd^{-1} ^{0}C^{-1} in the cold wet season (Jul/Sept) and 0.5 mmd^{-1} ^{0}C^{-1} in the warm wet season (Oct/Dec). Temperature rainfall relationships influence on yields have been reported in Malawi (Tanton, 1982a; Tanton, 1992;). This reveals the significant effects of season on shoot growth rate hence yields. The results suggest that for drought avoidance or quick recovery after drought in January March, management interventions that would. Such interventions include mulching, skiffing or compensatory sprinkler irrigation which also humidifies the air reducing the svpd. Such interventions have been suggested before as a means of overcoming the effects of weather on tea yields (Carr 1974; Stephens and Carr, 1991; Tanton, 1982b).

4.1.4.2. Shoot Density
Shoot density did not show significant correlation with temperature throughout the seasons, except for hot dry January March season (Table 11). This explained the lack of significant seasonal variations However, in Tanzania, shoot densities varied with seasons (Stephens and Carr, 1990). Seasonal variation in yield of seedling tea at high altitude in Kenya was due to variation in weight and growth rate of shoots (Mwakha, 1981), contradicting other observations (Herd and Squire, 1976; Tanton, 1981) that seasonal yield variation depended on the variation in rate of shoot extension rather than the shoot density and shoot weight, while yield variation between genotypes was primarily due to differences in shoot density. Those results concur with, the significant (p≤0.05) clonal differences and clone x location interactions, findings of this study. The locational variations in SD (Table 7) observed are therefore most likely due to the

variations in genotype response to environment. Shoot density showed significant positive correlations to SWP (Table 12). Good plant water status is favourable to generation of buds. Shoot density was not significantly correlated to yield in all but April June and July September seasons, and only in Kangaita. However, during these seasons multiple regressions excluded sd from the yield model showing the insignificant contribution to yield during the wet flush periods. Shoot population nevertheless had significant correlations to all weather parameters and radiation. When all seasons were considered, sd was significantly poorly correlated to yield (r=0.192 n=60) (Table 12). These results do not concur with observations by Kulasegaram and Kathiravetpillai, (1974) that seasonal yield variations occured mainly due to differences in shoot density, but rather are similar to the observations by Squire, (1979), that shoot density and shoot weights may be important in determining yield differnces between clones. These differences may be due to the interrelations of temperature and saturation deficits. These relationships also highlight the difficulty in applying them into a model to simulate yields in different locations. Clones should therefore be tested in new locations prior to release.

4.1.4.3. Shoot Dry Weight

Correlations of sdwt to yield were significant in April June and July September seasons (Tables 10 and 21), both being periods of well distributed rainfall (Tables 5). This suggests that sdwt contribution to yield was significant only during periods of continued adequate moisture availability. Consequently, clones selected for high yields will express their genetic potential only under growth favouring environments. Tea yield realization is a process of shoot expansion and elongation (Tanton, 1992). Therefore, a minimum level of moisture should be available for not less than some given amount of time for the yield to be realized. Indeed, tea requires well-distributed rainfall (Othieno, 1992) and does not tolerate long droughts (Acland, 1989).

The correlations of sdwt to yield and sgr were weak (< 0.5) but correlation with sd was strong (> 0.8) but negative (Table 21). Shoots became lighter as shoot density increased, due to the increased

number of sinks that shared the dry matter. This could be the basis for the variation in individual clonal response to environment. However, stepwise regression showed that sdwt was not significant in contributing to yield (Tables 10 and 11). Shoot dry weight response to weather was not significant in Jan/Mar but showed significant correlations to rainfall, temperature, radiation and SVPD in all other seasons, and was most closely related to rain with the correlation varying from r= -0.866 in Apr/Jun where there was most rain to r=0.356 in Oct/Dec where there was least rain (Table 11). There appeared to be a linear correlation between sdwt and rain across the seasons. In Apr/Jun season, sdwt had significantly (p≤0.05) high negative correlation to rainfall and SVPD, r= -0.866 and -0.873, respectively. The relationships imply that while high rainfall may be conducive to shoot flushing, there may be profuse production of shoots but less accumulation of dry matter. Indeed, it had been reported that dry matter partitioning to shoots was reduced during periods of high rainfall (Ng'etich and Stephens 2001a; Ng'etich *et al.*, 1995c). Shoot dry weight contribution to yield varies with location and season. Nevertheless, sdwt on its own does not significantly contiribute to tea yields.

4.1.4.5. Shoot Water potential
Shoot water potential showed significant but weak positive correlations to sd, sgr and sdwt (Table 12). It has been suggested that it would be possible to understand causes of yield variations if relationships between yield and its components could be evaluated (Smith *et al.,* 1990).

Table 12: Correlation coefficients (r) between mean annual yield, yield components and plant water status (SWP)

	Shoot Water Pot	Shoot gwth rate	Shoot density	Shoot dry wt
annual yield	-0.032	0.487[**]	0.192[**]	0.080
Shoot Water Pot		-0.160[*]	-0.172[*]	-0.278[**]
Shoot gwth rate			0.364[**]	0.497[**]
Shoot density				-0.151[*]

n=60 * Significant at 0.05; ** Significant at 0.01

The lack of knowledge of the mechanisms by which environmental factors influence tea shoot growth fluctuations has severely limited the development of methods to control these variables (Tanton, 1979). In this study, correlations between tea yields and the yield parameters showed that when all the seasons were considered sgr and sd were significantly correlated to yields but sdwt was not (Table 12). The correlations were however mild for sgr ($r=0.487$) and weak for sd ($r=0.192$). Shoot water potential (SWP) is a determinant of yield through its influence on the yield parameter sgr (Odhiambo *et al.,* 1993). Shoot water potential determines the cell turgidity, which allows cell expansion, the phenomenon expressed as tissue growth. The swp was not significantly correlated to yield but was significantly ($p \leq 0.05$) correlated to the yield parameters. It may therefore be a good factor for modelling tea yields. Management practices must therefore be site and season specific for maximization of yields. Management practices should thus be geared towards maximization of sgr and sdwt which, though are temperature dependent, can be manipulated through interventions such as choice of clone, irrigation, mulching in young tea and microclimate modification e.g. planting of shade trees and windbreaks. Stepwise regression showed sd to have non significant correlation to yields. Results also showed sdwt to reduce with increase in shoot density (Table 12). For high yields, it may be more appropriate therefore, to select clones with higher sdwt rather than for sd. Yield is realised through a complex interrelation of many plant and weather parameters both of which vary seasonally even within any one location. Similar findings were reported from trials conducted in Kericho (Odhiambo, 1991; Odhiambo *et al.,* 1993). Few (three sites only) may limit the linear regression analysis and be less accurate in using the relation between the various parameters to predict yields. Similar limitations due to few sites were been reported to limit plant responses to weather parameters (Ng'etich and Stephens 2001a).

4.1.5. Tea Yields and Yield Components seasonal variations

The size of tea crop varies considerably both on a weekly and seasonal basis with crop being often low in the coldest weeks of the year (Tanton, 1992) and reduced in the dry season (Carr *et al*., 1987). Indeed, clonal seasonal yields showed significant ($p \leq 0.05$) variation between location and seasons (Table 23). The clonal yields varied ($p \leq 0.05$) within and between seasons. The clonal response to geographical location also showed variations ($p \leq 0.05$) in any one season. The clone x location x season interactions were significant ($p \leq 0.05$). Clonal yield levels varyied significantly with location and season. Measurement of growth parameters was affected at Timbilil due to the effect of frost and the following drought. Usually, frost and drought significantly affect yields in Kericho (Ng'etich *et al.* 2001). Yield components of tea have been described as the shoot density, shoot replacement and shoot cycle/rate, shoot extension rate (growth rate). These are determined by the dry matter production and partitioning (Stephens *et al.,* 1992). Odhiambo, (1991) reported that among tea yield components, clonal shoot density, shoot extension rate, and partly shoot regeneration rates varied with changes in weather while mean shoot weight remained unchanged. The effects of individual yield components; shoot extension rates, shoot densities, and shoot regeneration rates varied highly and did not relate with the yield potentials of clonal tea (Odhiambo, 1991). However, the combined effects of the same parameters had significant relationship with clonal tea yields. Correlation analysis in this study showed correlations between yield and yield parameters to vary with season (Table 20). Shoot growth rate was consistently positively significantly correlated to yield across the seasons. Shoot density (Sd) and shoot dry weight (Sdwt) to yield correlations appeared to be season related. Indeed, analysis across the seasons showed all yield components tested to be significantly correlated to yield. Shoot growth rates varied significantly across sites and seasons except for January March season when growth ceased during most of the season due to limiting rainfall and high temperatures (Tables 5 and 20). The significant yield and yield components correlations (Table 19) are strong indications of yield components contribution to tea yields

4.1.6. Tea Yields
4.1.6.1. Yields and Seasonal Yield Distribution
Mean clonal yields varied significantly (p≤0.05) in all seasons (Table 23). Yield variations between locations were highly significant across all seasons but in January March and July September yields from Kerugoya and Timbilil were not significantly (p≤0.05) different. Yields were consistently highest in Kipkebe and lowest in Kangaita over the seasons except for the April June season when yields in Timbilil were affected by the early year drought, which also necessitated pruning bushes to ensure their survival. The pruning led to the loss of yield in July September season. Mean clonal yield patterns followed the mean ambient temperature patterns across the locations (Tables 5 and 24). However, in the cold wet season of July September the mean yields between Kangaita and Timbilil were not significantly different. The temperature difference between the two locations during the period was only 1.4^0C, compared to the 2.8^0C between Timbilil and Kipkebe during the same period. The variation in seasonal yield distribution between locations also varied with rainfall (Tables 5 and 24). The seasonal mean clonal yields (Table 23) were also significantly p≤0.05) different, with the cold wet season giving the highest the yields. This was attributed to the effect of January March drought depressing the potential yields of the cool wet season of Apr July. From long term yield data in Timbilil, early year drought led to yield decline followed recovery in the April May period (Carr and Stephens, 1992). Kipkebe and Kangaita saw significant decline in yield in the warm wet (Oct Dec) season while Timbilil registered a significant yield increase. The yield decline in the two locations is attributable to the poorer rainfall distribution starting in the previous quarter and extending into the October December season, which had a 20 day rain day difference between Kangaita and Timbilil (Tables 5 and 24). This is also an example of how unfavourable weather in the preceding season affects the yields of the following season.

Table 13: Effect of genotype, location and season on tea yields, 2012

	Jan Mar				Apr Jun				Jul Sept				Oct Dec			
	Kgta	Tmbl	Kpkb	Cln mean	Kgta	Tmbl	Kpkb	Cln mean	Kgta	Tmbl	Kpkb	Cln mean	Kgta	Tmbl	Kpkb	Cln mean
TRFK 7/3	175	172	474	274h	162	58	887	369bcdefg	235	161	1417	604dfgh	223	255	983	487ghi
TRFK 303/577	522	444	641	536a	454	131	1584	723a	621	961	1720	1103ac	734	1433	1106	1091a
EPK TN 14-3	244	262	862	456bc	211	125	1224	520bc	524	363	1421	769j	356	598	1101	685bc
TRFK 2X1/4	161	227	782	390def	120	34	830	328jk	260	195	1063	506hij	241	277	859	459hi
TRFK STC 5/3	164	189	822	392def	172	88	1357	539b	286	207	1156	550ij	239	542	762	514fghi
TRFK 11/26	205	184	696	362efg	170	91	801	354ijk	297	267	990	51fgh	226	371	696	431i
TRFK 12/19	207	290	719	405de	139	61	893	364hijk	248	383	1173	601de	264	525	659	483ghi
TRFK 56/89	163	313	736	404de	167	84	873	375fghijk	375	613	1300	763cde	329	545	757	544efg
TRFK 12/12	247	230	549	342g	352	115	901	456bcdef	331	303	1202	612j	308	454	676	479ghi
TRFK 303/999	218	298	635	384defg	181	106	774	353ijk	372	481	1219	691chij	343	775	728	615bcde
AHP S15/10	191	229	671	364efg	169	45	1134	450cdefg	405	295	1411	704fghi	264	547	984	599cdef
TRFK 57/15	228	192	631	350fg	226	121	850	399efghij	467	232	825	508cd	275	473	588	445i
TRFK 31/27	299	298	590	396def	310	103	812	409efghij	431	297	970	566ghij	313	779	638	577defg
TRF 6/8	124	282	615	341g	161	80	1021	421defghi	296	204	1283	594fghi	267	379	794	480ghi
BBK 35	173	348	1004	408de	146	105	1247	499bcd	298	417	1536	750cd	293	363	1225	644bcd
TRFK 31/8	228	313	611	384defg	250	110	971	444bcd	392	250	1087	576ghij	302	353	684	446hi
TRFK 7/9	221	234	570	342g	178	129	1247	518cdefgh	295	287	1311	631efg	310	492	1064	622bcde
TRFK 303/259	213	396	817	475b	170	106	1146	474bc	308	310	1352	657ef	338	443	1187	656bcd
TRFK 303/1199	355	401	862	539a	310	174	1252	578bcde	527	746	1736	1003b	417	723	982	707b
TRFK 54/40	224	325	741	43cdc	249	140	495	294bcde	247	141	1381	590fghi	291	442	984	572defg
Ste mean	228y	281y	701x		215y	100y	1015x		361yy	356y	1278x		317z	538y	875x	
Mean season		404				443				665				577		
CV%		24.3				34.6				24.8				27.0		
LSD(p≤0.05)																
Clone(C)		91				142				152				144		
Site(S)		32				55				59				56		
CxS		157				245				264				249		
All 4 seasons																
CV%	28.71															

	Kgta	Tmbl	Kpk				
Site mean	280	319	967				

	Clone (C)	Site (S)	Sean (Ssn)	CxS	CxSsn	SxSsn	CxSxSsn
LSD(p≤0.05)	69	27	31	120	139	54	240

Numbers followed by the same letter, down the column *(a,b,c,d,e)* and across the row *(x,y,z)* are not significantly different according to Duncan's Multiple Range Test (DMRT)

These demonstrate the variations in clonal response to environment even under similar management. The results also suggest that for maximization of yield, clonal management will have to be site specific.

Table 14: **Seasonal mean weather parameters at G x E trial sites, 2012.**

	KANGAITA					TIMBILIL					KIPKEBE				
	Temp	Rain	Rdays	Rh	Vpd	Temp	Rain	Rdays	Rh	Vpd	Temp	Rain	Rdays	Rh	Vpd
Jan Mar	16.2	77	10	34.3	10.6	17.5	55	13	60.0	14.9	19.8	134	18	62.3	9.6
Apr Jun	15.8	1231	64	75.7	3.9	15.9	1016	69	71.0	4.5	19.2	942	70	82.7	4.5
Jul Sept	14.4	361	38	44.0	4.0	15.8	699	55	70.7	5.4	18.4	415	38	81.3	5.4
Oct Dec	15.3	729	41	65.3	2.9	16.7	669	61	71.7	7.1	19.9	458	48	79.7	4.3

Seasonal yield (expressed as % of annual yield) distribution was uniform in all locations except Timbilil. Drought and frost early in the year (Tables 5 and 24) accounted for the marked drop in yield in April-June to achieve only 8% of the total annual yield in the season (Table 25). Further, in Timbilil, October December season, the seasonal yield proportion was 100% higher than that of Kipkebe (Sotik) and Kangaita (Kirinyaga). This could also be attributed to better rainfall distribution in Kericho, having 20 rain-days more than the other two locations during the same period. This may have had the effect of evening out any potential yield limiting soil water deficits. Seasonal yield distribution between the locations also varied with seasons.

Table 15: Seasonal yield distribution across three trial sites, 2012

	Proportion of yield (% of annual yield)		
Season	Kangaita	Timbilil	Kipkebe
Jan Mar	*20*	*22*	*18*
Apr Jun	*19*	*8*	*26*
Jul Sept	*32*	*28*	*33*
Oct Dec	*28*	*42*	*23*

The genotype yield response to geographical location showed significant variations throughout all seasons leading to significant ($p \leq 0.05$) clonal yields and season interactions (Table 23). The interactions of clone and location also varied significantly within and across the seasons. The rate and extent of yields

variation between clones changed with location and from one season to the next. Indeed, the clonal yields varied across locations and seasons. The clone x location x season interactions were also highly significant (p≤0.05). This indicated significant influence of geographical location and seasons on the clonal yields. In Kericho analysis of long term data showed the annual seasonal yield variability to arise mainly in January June period which includes most of the dry period and the bush recovery period which follows the start of the rains (Carr and Stephens, 1992). The clonal yield performance (ranking) varied significantly across sites and seasons. When yields are ranked, in Kipkebe particularly, no single clone retained the position through the four seasons. In Kangaita and Timbilil however, Clone TRFK 303/577 retained the top position throughout three of the four seasons. Clone TRFK 2X1/4 retained the lowest position in two seasons in Kangaita. These observations illustrate the variation in clonal response to environment and influence of environment on clone yields and growth as also shown in the variation in yield and yield components correlations with seasons. This phenomenon is further illustrated by the variation in weather parameters across seasons (Table 24) and significant correlations between weather and yield parameters in the same period (Table 21).

Further investigations into yield responses to weather using regression analysis revealed that though correlation showed significant (p≤0.05) responses to all weather parameters, there were varying influence of the weather parameters on yield, across the seasons (Table 11). Stepwise regression showed that yield was significantly (p≤0.05) correlated to the combined effect of temperature and rainfall (r = 909 to 0.826) though temperature was the stronger determinant. Further regressions indicated that temperature relation to yield between locations varied from a slope of 90kg mt^{0}C^{-1} in January March to 459.6kg mt^{0}C^{-1} in July September. In October December temperature was not a yield determinant but relative humidity appeared to be the main yield determinant having the greatest correlation (r=0.763 to 0.583). Soil moisture deficits are major factor determining yields. However, though soil moisture deficits were not measured in this study, the effects of soil moisture deficits were estimated from SVPD. SWP of tea shoots

were more closely related to SVPD than to soil moisture (Squire, 1979). Indeed results showed SVPD and yield to have better correlation when soil moisture and rainfall were most limiting in January March season.

Earlier studies of seasonal yield variability between estates in Kericho area of Kenya showed the variability to be larger in some estates than others. The yield potential was observed to be sustainably more at lower altitudes below 2000m (Carr and Stephens, 1992). Similar analyses conducted for Mufindi, Southern Tanzania showed the main variable determining yield variability to be decline in rainfall from 1700-1000m and increase in the length of the dry season, since the altitude difference was only 150m. In Malawi climate was influenced by proximity to Mulange Mountain and the major variable was also decline in rainfall. Kericho had the most even yield distribution, attributed to seasonal temperature changes and development of large soil water deficits during the dry seasons. Contrastingly, Mufindi, Tanzania and Mulanje, Malawi showed marked seasonal variations in yield distributions (Carr and Stephens, 1992). There were considerable variation of yield seasonal distribution between Kenya, Tanzania and Malawi from analysis of long-term yields Carr and Stephens, (1992). Similar findings were reported in India (Kulasegaram and Kaththiravetpillai, 1974). These findings were similar to the findings of this study, where yields were higher at low altitude (Sotik) than at the two high altitude locations, Timbilil and Kangaita. Management options for optimization of yields will have to be site specific. Clones should be tested in new areas before release. The varied effect of the interactions of weather parameters on plant response makes it more difficult to develop a universal model for estimating tea yields.

4.1.7. Conclusions

Seasonal and locational yield differences are caused by the variation in severity of the abiotic stresss limiting the plant growth and not by variation in the viguor of growth There are differences in conditions that limit growth in some clones more than others rather than conditions that favour growth in some

clones more than others. Shoot density is affected, not by seasonal changes in weather, but only by the fundamental climatic differences between locations. Shoot water potential may determine yields across locations and season but not between individual clones and may therefore have potential for use in modelling tea yields in different environments but not between clones. Inherent genotypic differences in SWP is only expressed in response to different environments but not under the same environment.

Though no single component will determine tea yields, shoot density and shoot weights may be important in determining yields between clones with the differences arising due to the responses to the interrelations of temperature and saturation deficits.

Unfavourable weather in the preceding season may significantly affect the yields of the following season. Management options for optimization of yields will have to be site specific and clones should be tested in new areas before release. The varied effect of the interactions of weather parameters on plant response makes it more difficult to develop a universal model for estimating tea yields.

4.1.8. Variations in annual Yield Components
The shoot growth rates, shoot dry weights, shoot densities and shoot water potentials and their rankings, as recorded in 2012 are shown in Table 6 and Table 7.

4..1.8..1. Shoot Growth Rate
The shoot growth rates (Table 6) in Kangaita and Timbilil were similar, but lower (p≤0.05) than that of Kipkebe. Plant growth rate patterns at the two sites followed the locational temperature patterns (Table 5). This agrees with earlier reports that temperature is a major determinant of growth (Obaga *et al*., 1988; Squire *et al.,* 1993). Clonal variations in shoot growth rates varied both within and across locations. Variations in clonal growth rates were not consistent across all sites as the shoot growth rate rankings showed variation with location (Table 7).

Table 16: Effect of geographical location and genotype on yield components, Jan – Dec 2012

Clone	Shoot growth rate (mm/day)				Shoot dry weight (g/shoot)				Shoot density (shoots/m^2)				Shoot water potential (KPa)			
	Tmbl	Kgta	Kpkb	Clone mean	Tmbl	Kgta	Kpkb	Clone mean	Tmbl	Kgta	Kpkb	Clone mean	Tmbl	Kgta	Kpkb	Clone mean
TRFK 7/3	0.45	0.35	0.85	0.55	0.25	0.12	0.16	0.17	32.83	96.25	72.89	67.32	-9.92	-10.06	-10.61	-10.20
TRFK 303/577	0.52	0.35	0.96	0.61	0.22	0.11	0.15	0.16	45.00	119.25	71.44	78.56	-9.09	-10.83	-10.32	-10.08
EPK TN 14-3	0.59	0.28	1.12	0.66	0.28	0.12	0.16	0.19	39.08	92.75	68.33	66.72	-9.89	-10.69	-9.80	-10.13
TRFK 2X1/4	0.53	0.32	0.84	0.56	0.23	0.09	0.14	0.15	35.83	86.75	75.56	66.05	-9.94	-10.77	-9.82	-10.18
STC 5/3	0.54	0.30	0.70	0.52	0.23	0.09	0.14	0.15	32.42	98.08	79.78	70.09	-9.80	-10.83	-10.33	-10.32
TRFK 11/26	0.35	0.34	0.65	0.44	0.18	0.12	0.16	0.15	33.92	84.25	71.22	63.13	-10.10	-10.52	-9.48	-10.03
TRFK 12/19	0.39	0.27	0.62	0.42	0.21	0.13	0.15	0.16	32.16	79.00	74.44	61.87	-10.18	-11.37	-10.32	-10.62
TRFK 56/89	0.73	0.37	0.92	0.67	0.33	0.14	0.14	0.21	40.16	83.50	64.11	62.59	-10.17	-10.60	-9.73	-10.17
TRFK 12/12	0.36	0.32	0.56	0.41	0.22	0.17	0.17	0.19	38.00	79.25	65.44	60.90	-9.81	-9.63	-10.34	-9.93
TRFK 303/999	0.53	0.42	0.77	0.57	0.26	0.12	0.17	0.18	42.50	79.92	68.33	63.58	-9.79	-10.80	-10.58	-10.39
AHP S 15/10	0.29	0.36	0.74	0.46	0.25	0.13	0.18	0.19	35.08	90.25	70.78	65.37	-10.13	-11.22	-10.22	-10.53
TRFK 57/15	0.38	0.37	0.92	0.56	0.18	0.09	0.17	0.15	44.08	93.58	68.00	68.55	-10.20	-11.31	-10.32	-10.61
31/27	0.30	0.38	0.73	0.47	0.28	0.12	0.15	0.18	32.75	89.33	74.89	65.66	-10.19	-10.59	-10.19	-10.32
TRFK 6/8	0.32	0.37	0.58	0.42	0.24	0.13	0.16	0.18	30.25	81.25	71.00	60.83	-9.51	-9.91	-10.26	-9.89
BB 35	0.48	0.40	0.83	0.57	0.24	0.11	0.16	0.17	32.83	89.58	71.11	64.51	-9.80	-9.80	-9.90	-9.83
TRFK 31/8	0.45	0.28	0.80	0.51	0.26	0.13	0.18	0.19	48.58	80.67	71.55	66.93	-10.00	-10.82	-9.96	-10.26
TRFK 7/9	0.39	0.34	0.60	0.44	0.30	0.11	0.14	0.18	39.66	93.25	76.11	69.67	-10.62	-10.87	-10.38	-10.62
TRFK 303/259	0.39	0.32	0.80	0.50	0.25	0.15	0.16	0.19	53.50	75.58	67.11	65.40	-10.53	-10.16	-10.19	-10.29
TRFK 303/1199	0.64	0.31	0.76	0.57	0.27	0.10	0.14	0.17	41.42	103.50	73.55	72.82	-10.64	-10.61	-10.21	-10.49
TRFK 54/40	0.36	0.34	0.65	0.45	0.16	0.17	0.16	0.16	34.58	74.00	71.11	59.90	-10.58	-10.62	-10.19	-10.46
Site mean	0.44	0.34	0.77		0.24	0.12	0.16		43.03	94.47	71.15		-10.04	-10.60	-10.16	
CV%	33.97				23.9				22.65				22.65			
	Cl	St	ClxSt		Cl	St	ClxSt		Cl	St	ClxSt		Cl	St	ClxSt	
LSD$_{(P<0.05)}$	0.08	0.31	0.14		0.024	0.01	0.04		8.40	3.25	14.56		NS	0.25	14.56	

Cl = clone; St. = site

The differences between the highest and lowest clonal growth rates also varied with location with the highest (0.56 mm/day) in Kipkebe and the lowest in Kangaita (0.15 mm/day). Similar results were reported in earlier findings of clonal variation within one location (Obaga and Ng'etich. 1989; Burgess and Carr, 1997) across seasons (Stephens and Carr , 1990) and across locations (Obaga *et al.,* 1988; Squire *et al.,* 1993; Wachira *et al.,* 2002). Shoot growth rate will vary with genotype and the genotypic

variation will also vary from one location to the other. Changes in shoot growth rates could be explained by the inherent effects of temperature and relative humidity, which varied across seasons (Squire, 1979).

Table 17: Effects of geographical location on ranking of genotype yield and components in 2012

	Annual yields			Shoot growth rate			Shoot dry weight			Shoot density			Shoot water potential		
	Tmbl	Kgta	Kpkb	Tmbl	Kgta	Kpkb	Tmbl	Kgta	Kpkb	Tmbl	Kgta	Kpkb	Tmbl	Kgta	Kpkb
TRFK 7/3	20	20	16	9	8	5	8	9	6	15	4	7	8	4	20
TRFK 303/577	2	1	2	7	9	2	15	14	13	3	1	9	1	15	13
EPK TN 14-3	4	2	4	3	18	1	3	10	7	9	7	15	7	11	3
TRFK 2X1/4	7	14	6	5	13	6	13	18	16	11	11	33	9	12	4
STC 5/3	17	18	10	4	17	14	14	19	17	18	3	1	4	16	16
TRFK 11/26	19	11	15	17	10	15	18	11	8	14	12	10	11	6	1
TRFK 12/19	6	15	8	11	20	17	17	5	14	19	18	5	14	20	14
TRFK 56/89	9	13	9	1	4	3	1	4	18	7	13	20	13	8	2
TRFK 12/12	10	6	17	15	14	20	16	1	3	10	17	19	6	1	17
TRFK 303/999	11	9	19	6	1	10	6	12	4	5	16	16	3	13	19
AHP S 15/10	5	16	12	20	7	12	9	6	1	12	8	14	12	18	11
TRFK 57/15	16	8	11	14	5	4	19	20	5	4	5	17	16	19	15
TRFK 31/27	13	4	20	19	3	13	4	13	15	17	10	4	15	7	7
TRFK 6/8	18	17[+]	18	18	6	19	11	7	9	20	14	13	2	3	12
BB 35	3	19	7	8	2	7	12	15	10	16	9	11	5	2	5
TRFK 31/8	14	7	5	10	19	8	7	8	2	2	15	8	10	14	6
TRFK 7/9	15	12	13	12	11	18	2	16	19	8	6	2	19	17	18
TRFK 303/259	12	10	3	13	15	9	10	3	11	1	19	18	17	5	8
TRFK 303/1199	1	3	1	2	16	11	5	17	20	6	2	6	20	9	10
TRFK 54/40	8	5	14	16	12	16	20	2	12	13	20	12	18	10	9

Temperature and relative humidity indeed, determine the prevailing vapour pressure deficits in any one location. The findings by Squire, (1979) therefore explain the relations between shoot growth rates and saturated vapour pressure deficits observed in this study. Indeed, the clonal variations in shoot growth rate between locations could possibly be explained by the variations in temperature and vapour pressure deficits (Table 5) between the locations. Vapour pressure deficits are therefore a major weather parameter other than temperature that determines the shoot growth rate of the tea plant. Tea clones responded to vapour pressure deficits and temperature differently from one location to the next and this may be key

plant physiological properties determining yield differences between locations. Shoot growth rates could therefore be considered as a yield indicator during selection of planting material for different tea growing locations.

4.1.8.2. Shoot Dry Weight and Shoot Density

Shoot densities showed significant ($p \leq 0.05$) variations due to genotype and location. The genotype x location interactions was also significant ($p \leq 0.05$). Whereas shoot dry weights varied ($p \leq 0.05$) between locations there was no apparent relationship to temperature or vapour pressure deficit (Tables 6 and Table 7). The shoot densities also showed variation ($p \leq 0.05$) due to location and appeared to change in the same pattern as with vapour pressure deficits but not temperature, across the sites (Tables 6 and Table 7). The highest mean shoot density was recorded in Kangaita (119 shoots m^{-2}) and lowest at Timbilil (32 shoots m^{-2}). Obaga *et al.*, (1988) reported varying clonal response of shoot density with altitude. Both shoot dry weights and shoot densities showed significant clonal differences within each of the three locations. Similar results were reported for dry matter in four locations around Kericho (Ng'etich and Stephens 2001a; Ng'etich and Stephens 2001b). These differences varied between locations causing significant ($p \leq 0.05$) genotype x location interactions. The paucity of information on the two parameters indicates that they may not have been given as much attention as other tea yield components such as shoot growth rates. The findings of this study however, show that significance of these parameters. They are thus important to consider when determining yields of different genotypes in different locations.

4.1.9. Annual Yields

There were significant ($p \leq 0.05$) genotypic and site differences in annual yields (Table 8). The clones x site interactions were also significant ($p \leq 0.05$). Clonal mean yields were lowest ($p \leq 0.05$) in Timbilil and highest in Kipkebe. This yield trend mimicked the locational temperature patterns (Table 5) and altitudes (Table 1). The differences between the three geographical locations can be explained in terms of the weather differences (Table 5), as had been observed in earlier studies (Squire *et al.,* 1993;

Ng'etich *et al.,* 2001b). The earlier studies however, involved sites around Kericho, within a radius of 20 Km (Obaga *et al.,* 1989) and only two sites, with different weather patterns (Kericho and Kangaita) (Wachira *et al.,* 2002). The findings from this study replicate findings reported from single sites and also from multiple sites. Yield variations due to genotype were also significant ($p \leq 0.05$). The genotypic variations occurred in all locations but the extent of the variations differed from location to location (Table 8). This indicated that clones respond differently in different environments and was manifested in significant clones and sites interaction as illustrated in the variations in clonal yield rankings between sites (Table 7). Clone TRFK 303/1199 recorded highest yield (5162 kg mt ha^{-1}), at Kipkebe while TRFK 7/3 recorded the lowest yield (763 kg mt ha^{-1}) at Timbilil. All clones recorded highest yields at Kipkebe. Yield differences between the highest and lowest yielding clones also varied between sites. These differences were highest in Timbilil at 2410 kg and lowest in Kipkebe at 1473 kg. This phenomenon elucidated the variation in genotype yield response to different environments. Clonal yield rankings showed clonal yield stability across only two environments in clones, TRFK 12/19, TRFK 12/12 AHP S15/10 and TRFK 54/40. Some clones showed consistent good yield performance across all environments, falling in the 1st quartile in all locations (TRFK 303/1199, TRFK 303/577 and EPK TN 14-3). However, consistent inferior yield performance (4th quartile) across all three locations was exhibited by only two clones (TRFK 7/3 and 6/8). Similarly, consistent poor performance under low temperature conditions (Kangaita and Timbilil) was exhibited by only one clone (STC 5/3). One clone, TRFK 11/26 showed consistent poor performance across two temperature regimes of Timbilil and Kipkebe. Majority of the clones did not show any consistent yield response to locations.

Table 18: Effects of geographical location and genotype on annual yields (kg ha-1) and their rankings in 2012

	Yields				Yield ranking		
	Timbilil	Kangaita	Kipkebe	Mean	Timbilil	Kangaita	Kipkebe
TRFK 7/3	1520	935	3349	1934	20[+]	20[+]	16[+]
TRFK 303/577	3244	2408	4583	3412	2*	1*	2*
EPK TN 14-3	2663	1950	4037	2883	4*	2*	4*
TRFK 2X1/4	2083	1218	3932	2411	7	14	6
STC 5/3	1754	1003	3431	2063	17[#]	18[#]	10
TRFK 11/26	1596	1272	3352	2073	19[#]	11	15[#]
TRFK 12/19	2278	1181	3689	2383	6	15	8
TRFK 56/89	2054	1234	3468	2252	9	13	9
TRFK 12/12	2051	1504	3304	2286	10	6	17
TRFK 303/999	2014	1306	3077	2132	11	9	19
AHP S15/10	2413	1179	3400	2331	5	16	12
TRFK 57/15	1851	1434	3410	2232	16	8	11
TRFK 31/27	1958	1536	2752	2082	13	4	20
TRFK 6/8	1710	1045	3087	1947	18[+]	17[+]	18[+]
BBK 35	2685	942	3863	2497	3	19	7
TRFK 31/8	1878	1444	3989	2437	14	7	5
TRFK 7/9	1856	1242	3399	2166	15	12	13
TRFK 303/259	1981	1277	4234	2497	12	10	3
TRFK 303/1199	3671	1903	5162	3579	1*	3*	1*
TRFK 54/40	2060	1510	3369	2313	8	5	14
Ste Mean	2166*y*	1376*z*	3644*x*				
CV%	14.77						
	Clone	Site	CxS				
LSD(0.05)	654	253	1134				

*Consistent superior performance (1st quartile) across all three locations
[#] consistent poor performance (4th quartile) across two locations
[+] consistent poor performance (4th quartile) across all three locations

These results demonstrate the variability in clonal yield response to environment as earlier reported in Kenya (Ng'etich and Stephens, 2001a; Squire *et al.,* 1993; Wachira *et al.,* 2002), Tanzania (Stephens and Carr, 1990), across East Africa region (Kamunya *et al.,* 2012) in Sri Lanka (Wickramaratne, 1981) and on precursor quality parameters of black tea (mainly catechins) (Cherotich *et al*., 2013; Cherotich *et al*., 2014; Kwach *et al.,* 2016). However, the results of Stephens and Carr (1990) could not be extrapolated to other regions unless the differences in yield were related to specific environmental variables such as soil water deficit (SWD) and temperature (Burgess, 1992). Clonal yield variations were observed to occur

under different weather patterns (Kericho and Kangaita) and different temperature regimes (Kericho/Kangaita and Sotik). Therefore, despite close similarities in weather parameters between locations, tea genotypes will respond differently in the locations. Hence, different clones with similar performance under the same management in one site will require different management options to optimize yields in a separate location. Similar observation had been made in previous studies (Ng'etich *et al.*, 1995b; Ng'etich *et al.*, 2001, Ng'etich and Stephens, 2001a; Wachira *et al.,* 2002). Therefore, importing clones selected for high yield in a given location may not optimise yields a different. Clones should thus not be grown without pre-testing in new areas.

4.1.10. Shoot Components and Annual Yield Interactions

Correlations between yield components' and yield at different sites are presented in Table 9.

Table 19: Relationship (r) between yields and yield components at different geographical location

Location		Sgr	Sd	Sdwt.	Swp
Kangaita	Yield	0.001	0.652[**]	-0.065	0.115
Kipkebe	Yield	0.384	-0.072	0.029	-0.137
Timbilil	Yield	0.476[*]	0.396	0.231	-0.219

N = 20** Correlation is significant at the 0.01 level; * Correlation is significant at the 0.05 level
Sgr = Shoot growth rate; Sd = Shoot density; Sdwt = Shoot dry weight; Swp = Shoot water potential

The magnitude of the correlation varied with locations. Similar variations have previously been reported in Malawi (Squire, 1979). The correlations showed that different yield components may be important in determining yields in varying locations. The magnitude of the correlations between yields and growth components varied with locations. Significant relationship between shoot growth rate and yield was observed in Timbilil (r = 0.476, p ≤ 0.05) but not at Kipkebe (r = 0.384) and Kangaita (r = 0.001) while shoot density showed significant relationship in Kangaita (r = 0.652, p ≤ 0.05) (Table 9). Previous observations that shoot density and shoot weights were important in determining yields between clones (Squire, 1979) concur with this study's observation from Timbilil only. Shoot dry weights and

shoot water potentials showed no significant correlation to yield. Thus, these relationships were not universal in all environments. Yield selection using yield components may be genotype specific and therefore weighting of the components may need to be considered during genotype selection.

For Kipkebe, the regression were not significant, suggesting that at Kipkebe all yield components may combine equally to determine potential yields. Similar results were reported (Odhiambo, 1991) from 4 clones in Timbilil in Kericho and further that effects of individual components were highly varied and did not relate with potential clonal tea yields. A relationship between shoot sizes and shoot mass had also been shown (Squire *et al.,* 1993). The size of shoots harvested is an important factor in determining yield (Burgess, 1992; Ellis and Grice, 1976). The regression models indicate the importance of shoot weight in yield determination. However, Tanton, (1981) reported that shoot size contributed only 11% of the total seasonal yield variation, the remaining 89% being accounted for by the number of shoots. Seasonal yield variations mainly occur due to differences in shoot density (Kulasegaram. and Kathiravetpillai, 1974). Later investigations (Odhiambo *et al*., 1993; Stephens. and Carr, 1990) hypothesized that shoot growth rate was the major component causing seasonal fluctuation in yield while shoot density was the major factor determining yield difference between varieties. In this study the genotype and environment interactions showed that the yield components contribution to yield in any environment varied with the genotype.

In Kangaita, all yield components in the model were additive to yield (Equation (1)). In Kipkebe and Timbilil however, the high temperatures resulted in low plant shoot water potentials thereby reducing potential yields (Equations (2) and (3)). The negative shoot water potential was attributed to the prolonged droughts experienced in the two locations during the one year period of the study.

$$Y_{Kangaita} = -4618 + 10140S + 33.66D + 10140W + 134.7P \quad (R=0.809; R^2=0.655)………..(1)$$

$$Y_{Kipkebe} = 2181 + 2204S + 18.78D + 4758W - 167.87P \quad (R=0.395; R^2=0.156)……..…(2)$$

$$Y_{Timbilil} = 3428 + 2117S - 38.71D + 370W - 438.78P……(R=0.605; R^2=0.366)…..…... (3)$$

where:

S = Shoot growth rate (sgr),

D = Shoot density (sd),

W = Shoot dry weight (sdwt),

P = Shoot water potential (swp).

These relationships are similar to those derived in Sri Lanka (Wijeratne, 2001), where shoot density and mean shoot weight were considered to be the components of predicting tea yields. Shoot density is the major factor determining tea yield, accounting for more than 80 per cent of the variation in tea yield (Wijeratne, 2001). In Kenya, shoot densities and shoot dry weights of two clones showed varied clonal response with altitude in four sites around Kericho (Obaga *et al.,* 1989).

In this study, yield components' contribution to yield varied with genotype within the same environment and between environments (Table 9). Similar results had been reported (Ng'etich and Stephens, 2001a; Squire *et al.,* 1993) illustrating the variations in clonal growth response to temperatures across four sites within the Kericho region. Findings from this study indicate that variations in tea response to weather parameters may apply even across locations with different climatic regimes. The results therefore suggest that not all yield components can be used for yield selection in all environments. Indeed, in Kangaita clonal yield selection would best be done using shoot density as a yield indicator while in Timbilil shoot growth rate would be the best selection indicator. Variation in clonal yield components' response to environments explains the variability clonal tea yield responses in different environments. The interaction and the dominant component response determine the actual clonal yields realised in every location. Yield optimisation should therefore be targeted at the management practices that reduces the yield limiting factors and maximises the dominant responsive component. Such interventions could inlude sprinkler irrigation during periods of moisture stress to reduce soil water

deficits (Carr 1974; Stephens and Carr, 1991) and raising the relative humidity hence lowering the SVPD (Tanton, 1982b) which is the main factor limiting growth in such conditions. Clonal selections should therefore be location specific. Clonal selection for universal planting will not always optimise yields across all locations. Yield modelling even for a single clone across all sites will at best, be estimate not accurate. Perhaps this would explain the difficulty in modelling of yield predictions encountered in past works.

4.1.11. Yield and Yield Components' Response to Weather

All yield components studied (shoot growth rates, shoot dry weights and shoot densities), showed significant clonal variations in their sensitivity to the different environments. Generally, shoot growth rate increased with temperature across the locations while shoot dry weights varied significantly ($p \leq 0.05$) between sites but showed no response to temperature or vapour pressure deficit. All yield components gave significant ($p \leq 0.05$) genotypic variations in their responses to the environment (Table 10). Weather trends and yield components presented in Tables 5 Table 6, respectively indicate general linear responses of yield components to weather parameters from low to high altitude locations (Table 1). Shoot dry weights and shoot densities showed no response to temperatures across the sites. Across the three trial sites the temperatures tended to drop with increased rainfall leading to yield depression at Kangaita and Timbilil where ambient temperatures were low. At Kipkebe however, the low rainfall that was well distributed did not depress yields as the temperatures remained warmer.

Correlation analysis however, showed that the yield and individual yield component response to weather parameters varied significantly ($p \leq 0.05$) between locations (Table 10). Similar observations were made, where shoot dry weight of two clones to varied with altitude (Obaga *et al.,* 1989) and where dry matter partitioning by clones varied with location (Ng'etich and Stephens, 2001b). These correlations explain the locational variation in the yield models above (Table 9). The data demonstrate the difficulty in using yield components and weather parameters to develop an accurate yield prediction model. It is

therefore necessary that clones are evaluated in the environment of intended commercial exploitation before widespread cultivation.

Table 20: Relationships (r) between yield, yield components and weather parameters across three geographical regions of tea production in 2012

Location		Temp	Rain	Rh	Rdays	Svpd	Tir
Kangaita	Yield	-.499**	-.147	-.106	-.452**	-.270*	-.330**
	Swp	.718**	-.962**	-.990**	-.386**	.938**	.954**
	Sgr	-.669**	.201	.325**	-.555**	-.751**	-.456**
	Sd	-.293**	.495**	.528**	.047	-.603**	-.358**
	Sdwt	-.305**	-.210	-.063	-.661**	-.239*	.038
Kipkebe	Yield	-.665**	.281*	.543**	.268*	-.421**	-.516**
	Swp	.343**	-.404**	-.341**	-.390**	.301*	.173
	Sgr	.217	-.471**	.009	-.317**	-.118	-.025
	Sd	.526**	-.590**	-.836**	-.432**	-.272*	.217
	Sdwt	.407**	.047	-.211	.140	-.382**	.323*
Timbilil	Yield	.208	-.163	.124	-.008	.060	-.025
	Swp	.808**	-.909**	-.997**	-.978**	.950**	.924**
	Sgr	.000	.189	.517**	.389**	-.273*	-.286**
	Sd	.087	.064	.407**	.266*	-.163	-.219
	Sdwt	-.222*	.268*	.602**	.448**	-.412**	-.499**

* significant at 0.05; ** significant at 0.01; Yld= Annual yield; Sgr=shoot growth rate; Sd= Shoot density; Sdwt=shoot dry weight; Swp=shoot water potential; Temp=ambient temperature; Rain=annual rainfall; Rh=relative humidity; Rdays=rain days; Svpd=saturated vapour pressure deficit; Tir=total incident radiation;

4.1.12. Conclusion

Soil chemical and physical parameters varied between sites, but were suitable for tea growing. Yield components contribution to yield varied with location. The response of tea yield components to weather factors also varied with location. Genotype, yield and yield components varied significantly in their response to environment, variations in correlations between yield and yield components indicate that no single component can be used to predict tea yields in all locations. Shoot density and shoot growth rates were more closely related to yields only in Kangaita and Timbilil, and may therefore be used as yield selection indicators in the respective locations. Genotypes selected in any one location may not

perform optimally in another location. However, in terms of yield optimization, clones TRFK 303/1199, TRFK 303/577 and EPK TN 14-3 are recommended for planting on all three locations while clones TRFK 7/3 and TRFK 6/8 are not recommended for planting in any of the three locations. Selected clones should therefore be subjected to testing before adoption for commercial planting in new locations.

4.2. Effects of Genotype and Geographic Locations on Radiation Use Efficiency (RUE) of Clonal Tea

4.2.1. Incident Radiation (Wm^{-2})

Incident radiation varied significantly (p≤0.05) with location and seasons (Table 11). Kipkebe recorded the highest (p≤0.05) amount of incident radiation but there was no significant difference in incident radiation between Timbilil and Kangaita (Table 11). Similar results had been reported for three countries in east Africa (Carr and Stephens, 1992) and within Kenya (Ng'etich and Stephens, 2001b)

Table 21: Effect of location (site) and season on Incident radiation (Wm^{-2}) in 2012

	Kangaita (0^{o}30'S, 37^{o}16'E; 2100m amsl)	Timbilil (0^o 22'S, 35^o 21'E; 2180m amsl)	Kipkebe (0^o 39'S, 35^o 02'E; 1800m amsl)	Mean
Jan Mar	11105	12522	10672	11433
Apr Jun	8572	8982	9634	9063
Jul Sept	7495	6637	8954	7696
Oct Dec	9399	8559	9913	9290
Mean	9143	9175	9794	
CV%	6.4			
	Site	Season	SitexSsn	
LDS(p≤0.05)	107	124	215	

The annual receipt of total shortwave radiation received at any site is determined by the latitude and local climate (Carr and Stephens, 1992). Since the mean annual incidence of solar radiation decreases with increasing latitude, the locational variations in incident radiation observed may be due to cloud cover

as had been reported earlier for locations in Malawi and Tanzania (Charles-Edwards, 1982). These locations were close to the equator (Table 1). The observations from Timbilil and Kangaita concur with the findings that incident solar radiation was unlikely to vary so much between locations (Squire, 1985) at high altitude, but altitude of Kipkebe was much lower. Indeed differences by as much as 30% between sites within 10 kms radius at varying altitudes have been recorded in Kenya (Ng'etich and Stephens, 2001b). The mean seasonal radiation also varied ($p \leq 0.05$) across the four seasons, similar to earlier findings (Carr, 1974; Carr and Stephens, 1992). The site and season interactions effects were also significant ($p \leq 0.05$) with the seasonal differences varying between locations. These interactions were demonstrated by the observations that though Kipkebe recorded the highest mean incident radiation (11433 Wm^{-2}), Timbilil received the highest radiation (12522 Wm^{-2}) during January March season and also the least radiation (6637 $Wm^{-2)}$ in July September. The findings contradict prediction (Squire, 1985) that in Kenya tea growing areas, incident solar radiation was unlikely to vary so much as to noticeably affect the yields of tea. These figures recorded were much higher than the 1000 Wm^{-2} earlier predicted for the high altitude areas (Carr and Stephens, 1992). A very small proportional of the net available energy is in photosynthesis, most being dissipated as latent heat (through evaporation) and sensible heat (heating the air) (Carr and Stephens, 1992). These concepts bear directly onto the effects of sunshine on leaf temperatures, on leaf to air temperature differences and as the corresponding saturation deficit (SD) between leaf and air. In the rainy season the surface leaf temperature is warmer (0.3^0C) than the air for each 100Wm^{-2} of solar radiation up to a maximum of 3^0C but up to 6^0C in the dry season or up to 12^0C if the stomata were closed (Squire and Callander, 1981). These differences have large effect on leaf to air SDs hence on shoot extension rates and therefore yields. Seasonal yield variations and the locational variations as reported earlier (Ng'etich and Stephens, 2001b; Carr, 1974; Carr and Stephens, 1992) can thus be attributed to the prevailing patterns of solar radiation observed. Due to these variations incident solar radiation can be higher than those previously measured. For purposes of yield estimation it is

therefore advisable to use means of values measured over a long period. This may necessitate the installation of radiation measuring equipment in various tea growing areas for more accurate data and modeling.

4.2.2. Intercepted Radiation (I_{Rad})

The intercepted radiation (I_{Rad}) showed significant ($p \le 0.05$) differences due to genotype, location and season (Table 12). Mean clonal differences in I_{Rad} were significant. The clonal differences varied from location to location as demonstrated by the significant genotype x location interactions. Similar observations were made earlier on four clones in four locations (Ng'etich and Stephens, 2001b). The abilities of clones to capture solar radiation are related to their canopy architecture (Magambo and Cannell, 1981). However, characteristic changes from location to location could be attributed to variations in plant growth responses to environment.

Variations in intercepted radiation with locations were observed, with Timbilil and Kipkebe recording higher ($p \le 0.05$) I_{Rad} than Kangaita. Such findings were earlier reported within a 10 km radius in Kericho (Ng'etich and Stephens, 2001b). Nevertheless, the actual differences in daily intercepted solar radiation between studied tea growing locations in Kenya are reported herein (Table 12) for the first time. Such variations in intercepted solar radiation with clone and location have been reported in other tea growing countries. For example, in India 99% of radiation was intercepted by a range of clones (Hadfield, 1974a), in Malawi 95% was intercepted (Green, 1971a) and in Kenya 96% was recorded (Callander and Woodhead, 1981) in single locations. Differences in total light penetration occur among tea varieties (Obaga, 1986). The findings of this study therefore confirm that provided leaf canopy architecture are different or environmental growth factors vary, the amount of intercepted radiation in tea growing areas of Kenya will vary. This in part accounts for differences in growth parameters and yields observed in different clones or even the same clone grown in different locations. .

Table 22: Effect of genotype, location and season on intercepted radiation (measured as % of total incident radiation) in 2012.

	Jan Mar				Apr Jun				Jul Sept				Oct Dec			
	Kgta	Tmbl	Kpkb	Cln mean	Kgta	Tmbl	Kpkb	Cln mean	Kgta	Tmbl	Kpkb	Cln mean	Kgta	Tmbl	Kpkb	Cln mean
TRFK 7/3	59.87	88.87	87.93	78.89g	60.17	82.23	90.03	77.48m	63.13	93.67	88.23	81.68abc	61.57	97.17	89.33	82.69
TRFK 303/577	59.67	93.03	89.07	80.58a b	64.07	95.70	90.17	83.31a	62.27	96.20	89.03	82.50a	65.33	97.83	77.00	80.06
EPK TN 14-3	61.33	91.87	87.77	80.26abcd	64.97	93.73	88.00	82.23ab	60.87	95.50	89.10	81.82ab	62.97	97.87	89.57	83.47
TRFK 2X1/4	59.63	87.80	89.37	78.93g	64.10	74.30	88.70	75.70l	61.67	73.07	88.60	74.44g	62.17	90.40	88.60	80.39
STC 5/3	61.00	92.10	88.27	80.46ab	64.23	93.57	86.73	81.51bcd	62.03	95.43	87.27	81.58abcd	63.40	96.57	87.57	82.51
TRFK 11/26	59.83	92.30	88.00	80.04bcde	64.40	88.60	87.60	80.20defg	60.30	94.57	87.20	80.69bcdef	62.50	97.23	88.17	82.63
TRFK 12/19	60.50	91.00	87.63	79.71adef	64.10	88.23	90.00	80.78cde	60.00	93.30	88.67	80.66bcdef	61.50	97.03	89.20	82.58
TRFK 56/89	59.47	92.00	87.53	79.67ef	63.33	94.83	88.27	82.14abc	60.03	95.57	88.83	81.48abcd	63.60	96.30	89.37	83.09
TRFK 12/12	59.60	90.47	87.97	79.34def	64.30	85.83	89.07	79.73efghi	60.13	94.27	88.20	80.87bcde	62.50	97.07	89.60	83.06
TRFK 303/999	60.30	90.13	88.97	79.80ef	63.30	85.20	88.73	79.08ghij	60.47	95.33	87.63	81.14bcde	62.43	96.97	90.23	83.21
AHP S15/10	60.50	89.23	89.73	79.82fg	63.87	83.17	87.90	78.31ijk	60.13	91.43	89.47	80.34cef	63.13	95.73	89.33	82.73
TRFK 57/15	60.63	88.60	88.17	79.13def	63.57	86.23	87.67	79.19fghij	56.90	93.90	87.50	79.43f	62.80	99.67	88.33	83.60
TRFK 31/27	60.53	91.77	89.64	80.64def	64.70	88.27	88.63	80.53defg	60.60	93.93	88.57	81.03bcde	61.53	97.00	88.50	82.34
TRFK 6/8	60.87	89.07	86.90	78.94g	61.90	86.33	88.87	79.03hij	58.70	92.93	88.37	80.00def	60.40	96.30	89.97	82.22
BBK 35	60.17	91.97	87.53	79.89a	61.50	83.27	87.93	77.57k	60.67	94.03	88.23	80.98bcde	60.57	97.43	90.80	82.93
TRFK 31/8	59.67	89.73	87.87	79.09g	64.23	80.73	89.57	78.18jk	58.97	93.94	88.17	80.37cdef	63.13	94.73	89.97	82.61
TRFK 7/9	60.23	91.30	89.77	80.43cdef	63.23	90.77	87.97	80.66def	60.33	94.90	87.23	80.82bcde	62.60	96.87	88.33	82.60
TRFK 303/259	60.53	90.60	88.50	79.88g	65.23	89.50	87.00	80.58def	59.97	94.27	89.10	81.11bcde	62.30	96.90	87.43	82.21
TRFK 303/1199	60.17	93.07	87.97	80.40abc	65.13	94.37	87.57	82.3ab	58.63	95.40	87.53	80.52bcdef	62.80	97.37	88.40	82.86
TRFK 54/40	60.90	89.03	89.10	79.68ef	64.13	84.50	89.73	79.46efghij	59.33	93.20	88.90	80.68bcdef	63.90	95.30	89.07	82.76
Ste mean	60.26	90.70x	88.38x		63.72y	87.47x	88.51x		60.29y	93.24x	88.29x		62.56z	96.59x	88.44y	
	CV%	1.65			CV%	4.27			CV%	3.65			CV%	4.13		
	Clone	Site	CxS		Clone	Site	CxS		Clone	Site	CxS		Clone	Site	CxS	
LSD(0.05)	1.22	0.47	2.11		3.16	1.22	5.47		2.72	1.05	4.712		N S	1.22	NS	

ALL 4 SEASONS

CV% 3.64

	Kangaita	**Timbilil**	**Kipkebe**	
Site mean	61.707	91.999	88.406	
	Jan Mar	**Apr Jun**	**Jul Sept**	**Oct Dec**
SSn Mean	79.78	79.901	80.607	82.527

	Clone	**Site**	**Season**	**ClnXSte**	**ClnxSSn**	**StexSsn**	**CxSxSSn**
LDS (p<0.05)	0.36	0.53	0.61	2.35	NS	2.72	1.05

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Mean seasonal intercepted radiation varied significantly between seasons. However, in January March season there was no significant difference between clones in intercepted radiation. This was probably due to the drought effect in reducing the canopy foliage on all tea bushes during this season.

The clones x site interactions were significant in each season as seen for the variation in clonal I_{Rad} values between locations. This was attributed to locational variations in plant canopy growth response to seasonal weather patterns (Table 5). Indeed, the leaf area indices (LAI) showed clonal and locational variations ($p \leq 0.05$) (Table 13). Intercepted radiation varied by between 3% (Kericho and Sotik) and 30% (Kericho and Kirinyaga) between locations. Earlier (Ng'etich and Stephens, 2001b) daily intercepted solar radiation differed by as much as 30% between sites in Kericho that were within a 10 km radius. Radiation intercepted by the clonal teas varied significantly between sites and across the seasons. Interactions were also significant with the clonal radiation intercepted by individual clones varying with locations and seasons. This varied from 97.87% in clone EPK TN 14-3 in Timbilil in Oct-Dec season to 56.9% in clone TRFK 57/15 in Kangaita in Jul-Sept season. In Kenya tea growing areas (Squire , 1985) intercepted radiation had been posited to be uniform in except following hail damage and therefore most yield variation between fields and clones would be due to the conversion efficiency and dry matter (DM) partitioning to Harvest Index (HI). This study's findings indicate that radiation is not intercepted uniformly across seasons and locations in tea growing areas in Kenya as earlier postulated. The variations can also be much larger than that previously recorded at 30%. These findings demonstrate that the interaction of the three factors of genotypes, locations and season in determining yields and may also explain the large yield variations observed between genotypes, locations and season.

4.2.3. Proportion of Photosynthetically Active Radiation (PAR) Intercepted by Canopy (fs)

The photosynthetically active radiation intercepted by the canopy (*fs)* showed significant (p≤0.05) clonal and locational differences (Table 13). These observations are contrary to the observations made earlier that across tea growing areas in Kenya *fs* is unlikely to vary significantly as to affect tea yields after attaining of full canopy (Squire, 1985).

Interception of PAR by a crop canopy is strongly related to total leaf area. A crop will thus intercept more PAR and hence grow faster if it develops leaf area rapidly. This principle applies to both annual crops which are usually planted at the beginning of a growing season and perennial crops which resume growth after a dormant season (Plantsinaction, 2014). The findings show that though these differences between clones may not be large, locational differences can be quite large as seen in the differences between Kangaita in the east of the Rift Valley and Timbilil and Kipkebe in the west of the Rift Valley in *fs* values, between clones. This may lead to quite large yield differences (Table 8). It is therefore important that clones be tested in new areas prior to release for commercial exploitation in new areas.

Table 23: Effect of genotype, and site on the proportion of PAR intercepted by canopy (fs), canopy extinction coefficient (k) and Leaf area index (LAI) in 2012

	f_s				k				LAI			
	Kgta	Tmbl	Kpkb	*Cln mean*	Kgta	Tmbl	Kpkb	*Cln mean*	Kgta	Tmbl	Kpkb	*Cln mean*
TRFK 303/577	0.44	0.67	0.64	*0.58b*	0.27	2.02	1.16	*1.15cd*	4.38	1.32	1.74	*2.48a*
TRFK 303/1199	0.47	0.73	0.68	*0.62a*	0.49	6.66	2.73	*3.2ab*	2.05	0.66	0.96	*1.22bc*
BBK 35	0.46	0.71	0.66	*0.61ab*	0.76	5.26	2.13	*2.72bc*	1.34	2.31	1.2	*1.03bc*
EPK TN 14-3	0.45	0.57	0.66	*0.56bc*	0.41	1.72	1.57	*1.23*	2.31	1.2	1.56	*1.66bc*
TRFK 12/12	0.45	0.69	0.67	*0.6ab*	2.23	2.26	1.17	*1.89bc*	0.47	1.19	2.23	*1.3bc*
TRFK 56/89	0.56	0.69	0.68	*0.61a*	0.84	3.56	1.45	*1.95bc*	1.33	0.87	1.84	*1.35bc*
TRFK 31/27	0.46	0.67	0.69	*0.61a*	0.55	3.11	2.44	*2.03bc*	1.77	0.95	1.18	*1.3bc*
TRFK 7/9	0.54	0.66	0.63	*0.58b*	0.54	4.3	1.69	*2.18bc*	1.84	0.66	1.12	*1.2bc*
TRFK 2x1/4	0.46	0.69	0.65	*0.6ab*	1.11	6.89	2.99	*3.66a*	0.94	0.4	0.73	*0.69bc*
TRFK 6/8	0.46	0.69	0.64	*0.6ab*	0.6	2.09	0.83	*1.18cd*	1.61	1.45	2.51	*1.86ab*
TRFK 57/15	0.46	0.68	0.65	*0.6ab*	1.41	4.02	1.07	*2.17bc*	1.36	0.68	2	*1.34bc*
TRFK 7/3	0.47	0.68	0.67	*0.6ab*	0.92	2.28	1.22	*1.48cd*	1.56	1.42	1.95	*1.64bc*
Site mean	0.45*z*	0.68*x*	0.66*y*		0.85*xy*	2.02*x*	1.71*xy*		1.75*x*	0.95*z*	1.57*xy*	
CV%		0.18				46.44				48.53		
	Clone	Site	CxS		Clone	Site	CxS		Clone	Site	CxS	
LSD$_{(0.05)}$	0.0011	0.0006	0.0017		0.91	0.45	1.58		0.65	0.33	1.13	

C= clone; S= site (location)

4.2.4. Extinction Coefficient (k) and Leaf Area Index (LAI)

The canopy extinction coefficient (k) is an expression of the power of a canopy to capture light. Extinction coefficients showed significant ($p \leq 0.05$) differences due to genotype and location (Table 23). The recorded values ranged from 6.89 in clone TRFK 2x1/4 in Timbilil to 0.27 in clone TRFK 303/577 in Kangaita. Extinction coefficient (k) values for other crops range from 0.8 for planophiles (flat) leaved canopies to 0.3 for erectophile canopies (Goudriaan and Monteith, 1990). The clones studied included chinary varieties e.g. TRFK 303/577 which represent erectophile canopies, and Assamica variety such as TRFK 2x1/4 representing planophiles leaved canopies. These findings were therefore similar to but wider in range than those earlier reported for tea (Goudriaan and Monteith, 1990). The larger values obtained in this study could be attributed partly to the heterogeneity of tea and its overlapping morphological characteristics (Purseglove, 1968; Wickremasinghe, 1979; Banerjee, 1988; Bokuchava and Skobelova, 1969) which would result in a wide range of leaf areas (Table 13), even within the same plant and partly to the fact that this study was conducted on mature tea with well developed deeper canopies that capture light more rapidly than young canopies as those reported (Goudriaan and Monteith, 1990). For a given leaf area, clones with horizontal leaves are therefore likely to intercept a greater proportion of light than erect leaved clones (Burgess, 1992). However, at full ground cover plants with erect leaves may compensate for this by having higher leaf area indices (LAI). In this study, all the canopies were fully developed and had attained full ground cover. The LAI also showed significant ($p \leq 0.05$) clonal and locational variations. The clones x location interactions were also significant with the clonal differences varying between locations. The observed variations in LAI are an indication, in this instance, of variability in canopy depth as opposed to the extent, which was restricted by the plant spacing. The recorded values varied from 4.38 on clone TRFK 303/577 in Kangaita to 0.40 in clone TRFK 2x1/4 in Timbilil. The value of LAI at full ground cover was reported in North India to range from 4 for Assam type clones with horizontal leaf orientation to 8 for the erect leaved China types (Hadfield, 1974a). LAI

values obtained in this study ranged far lower than those obtained in India (Hadfield, 1974b). This could an indication of locational and clonal differences. However, variations of between 5.2 to 6.1 in two, four year old clones in two geographical regions were reported in Kenya (Ng'etich, 1995), which were also higher than but closer to the values obtained in this study. The differences between the earlier findings in Kenya and those of this study could be due to the age of the teas while those from India could be due to the difference in climatic and environmental conditions. LAI showed significant (p≤0.05) variations with geographical area of production, a factor once again attributed to canopy growth response to climate. The variations in LAI values obtained in this study and North India (Hadfield, 1974a; Hadfield, 1974b) could also be attributed to fact that the LAI determination in the different studies used different methods. Indeed, it had been reported that LAI values will depend on method used (Ng'etich, 1995). In this study LAI was estimated using a rapid leaf area determination formula (Magambo, 1976). However the observed variations in LAI with geographical area of production is sufficient indication that canopy development will vary with area and season of production. Leaf area index is related to crop biomass and radiation use efficiency which is a key factor in determining crop yield (Miranzadeh *et al.,* 2011). LAI has direct bearing on tea yields and therefore crop management in diverse environments cannot be uniform and still attain the same level of yields.

4.2.5. Specific Leaf Area (SLA)

Specific leaf area (SLA) is the leaf area per unit dry weight. The specific leaf area method is a rapid way of estimating leaf area, following length and breadth measurements (Ng'etich and Wachira, 1992), of crops like tea which bear leaves profusely as compared to maize, for example. The SLA varied (p≤0.05) with clones and location (Table 14), similar to the intercepted radiation and components of the radiation use efficiency (Table 13). Clonal variations in SLA had been reported before (Magambo, 1982). Clones with higher specific leaf areas had lighter leaves with higher rate of growth and development and

more surface area for photosynthesis (Magambo, 1982). Site differences in specific leaf area were also significant. These parameters are precursors of yield differences. Their variations are therefore indications of variations of yield with genotype and location, respectively. The significant ($p \leq 0.05$) clone and location interactions demonstrate the variations of clonal response to location. These results further emphasize the tea plant's genetic variability and variability in individual plant's response to environment. As such clones may not be expected to behave the same in all environments and may therefore not be adopted for commercialization prior to testing.

Table 24: Effect of genotype, and location on specific leaf area (SLA), and Radiation use efficiency (E_s)

	SLA (Cm^2g^{-1})			Cln mean	E_s (gMJ^{-1})			Cln mean
	Kgta	Tmbl	Kpkb		Kgta	Tmbl	Kpkb	
TRFK 303/577	106.99	27.8	41.39	58.72ab	21.29	27.74	27.53	25.52
TRFK 303/1199	96.8	18.4	30.4	48.56bc	16.41	18.44	23.43	19.43
BBK 35	84.69	26.79	47.33	52.93bc	7.97	12.27	18.67	12.97
EPK TN 14-3	124.3	33.72	37.07	65.03a	12.71	18.87	17.97	16.52
TRFK 12/12	112.51	27.75	54.46	64.90ab	12.89	8.83	19	13.58
TRFK 56/89	108.34	23.16	45.33	58.94ab	9.18	11.44	18.18	12.93
TRFK 31/27	94.43	22.33	37.96	51.57bc	11.94	11.83	14.11	12.63
TRFK 7/9	111.95	20.93	35.29	56.06ab	9.81	8.95	18.29	12.35
TRFK 2x1/4	96.59	23.56	38.42	52.79bc	7.97	5.43	22.88	12.09
TRFK 6/8	92.79	26.14	46.72	55.22ab	8.14	6.45	15.55	10.13
TRFK 57/15	94.55	18.53	47.77	53.62bc	11.49	6.74	22.28	13.50
TRFK 7/3	77.15	25.66	48.06	50.28bc	8.43	5.65	19.7	11.26
Site mean	100.09x	24.55z	42.52y		11.52yz	11.9y	19.8x	
CV%	19.46					22.99		
	Clone	Site	CxS			Clone	Site	CxS
LSD(0.05)	10.22	5.11	17.71			3.12	1.56	5.41

4.2.6. Radiation Use Efficiency (Es)

The tea crop yield is determined by the amount of DM partitioned into the harvestable organs, the harvest Index (HI) (Carr and Stephens, 1992). The radiation use efficiency (RUE) (also termed conversion efficiency (Es; g MJ^{-1}) was estimated as the amount of radiation utilised in producing dry matter (DM) in the two leaves and a bud green leaf harvested in a year as opposed to the total plant dry matter as used in

other studies in tea (Magambo, 1983; Ng'etich *et al.,* 2001). This is referred to herein as the "harvest index radiation use efficiency (HIRUE)". There was significant (≤ 0.05) differences due to clons and site in HIRUE (Table 14). The values from 12 clones ranged from 27.74 gMJ^{-1} in clone TRFK 3203/577 to 5.34 gMJ^{-1} in clone TRFK 2x1/4 both in Timbilil (Table 14). Much lower conversion efficiency (Es) (x100) were recorded tea in Kericho (0.25 g MJ^{-1}) (Burgess, 1992), (0.1-0.56 g MJ^{-1}) (Ng'etich and Stephens 2001a) and Tanzania (0.40 to 0.60 g MJ^{-1}) (Burgess and Carr, 1996). These differences could be explained by the different parameters used in calculation of the conversion efficiency in this study. Whereas this study estimated conversion efficiency based on annual yield, the studies mentioned above estimated Es from whole the harvest index at the time of sampling of the whole plant for dry matter determination. Nevertheless, Es expressed as the weight of dry matter produced per unit of radiation intercepted can be used to compare performance of canopies of very different structure and leaf area indices growing in different climates (Squire, 1985).

Significant ($p \leq 0.05$) clonal conversion efficiency (Es) and locational differences were recorded. Similar findings had been reported by in Kericho (Ng'etich and Stephens 2001a) and Tanzania (Burgess and Carr, 1996). The HIRUE results showed that conversion efficiency varied with the geographical area of production. In a high altitude site in Mufindi Southern Tanzania (Ngwazi Tea Research Unit at 8032'S,35010'E, 1840m a.m.s.l), much higher conversion efficiency values on four contrasting tea clones (0.40 to 0.60 g MJ^{-1}) were observed (Burgess and Carr, 1996) than those recorded in high altitude area of Kericho, Kenya. This study however recorded significantly lower mean conversion efficiencies for 12 clones at high altitudes (11.52 and 11.90 g MJ^{1}) in Kangaita and Timbilil, respectively), above 2000m a.m.s.l. than at low altitude (19.70 g MJ^{-1}). This is could be due to the lower temperatures associated with the high altitudes in tea growing areas in Kenya compared to those of Southern Tanzania.

Small differences in solar radiation between sites gave rise to large differences in ground cover and harvest indices which were the main contributors to yield variations between sites and clones

(Ng'etich *et al*., 2001). It had been proposed that yield improvements in tea would be obtained from an increase in RUE or HI (Squire, 1985). However, other studies suggested that RUE varied little with temperature (Ng'etich and Stephens, 2001b) thereby implying that yield differences between sites were due to HI and ground cover (Ng'etich *et al*., 2001). Incident radiation may not be limiting to Es so long as a critical level of radiation is achieved (Squire, 1985). This could explain the lack of significant differences in Es between the two sites at high altitude which received lower incident radiation. The results indicate that while RUE is genetically determined, the potential RUE will vary with the environment under which the clone is grown. The response to this environment varies with clone as demonstrated by the significant ($p \leq 0.05$) genotype and location interactions. Tea plants have different efficiency potentials to exploit solar radiation. This potential is further modified by the influence of environment on the plant growth responses, the Genotype x Environment interaction effect. Conversion efficiency (RUE) can therefore be used to compare the potential performance of clones in different environments as has also been posited earlier (Squire, 1985). RUE will vary with genotype and environment thereby affecting yields similarly. This therefore calls for testing or accurately modeling varieties for potential yields before release into new environments.

4.2.7. Radiation and Yield Interactions

The mean locational HIRUE (Es) correlated positively to the annual yields. (Table 15). Incident radiation and conversion efficiency and its components and ambient temperature gave significant positive correlations with yield but significantly negative correlations to altitude. This relationship supports and explains the findings that tea yields decline with altitude (Mwakha, 1985; Obaga *et al.,* 1988; Othieno *et al*., 1992; Squire *et al.,* 1993; Balasuriya, 1999; Anandacoomaraswamy *et al.*, 2000) but contradicts the findings that suggested that RUE varied little with temperature (Ng'etich and Stephens, 2001b) thereby implying that yield differences between sites were due to HI and ground cover (Ng'etich *et al*., 2001). This difference in findings could be attributed to the parameters used in deriving RUE as indicated above.

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Since this study used the biomass of actual annual tea yields it is reasonable to expect that the RUE will follow the yield pattern response to temperatures. As tea yields decline due to reduced shoot growth rate with increase in altitude so does the efficiency of conversion of radiation decline.

Table 25: Correlation coefficients (r) of yields, RUE components and weather and location parameters

	fs	I_{Rad}	Es	k	Temp	Alt
Yld	.430***	.614***	.541***	-.093NS	.872***	-.863***
fs		.944***	.218*	.568***	.638***	-.276**
I_{Rad}			.382***	.398***	.815***	-.501***
Es		.		-.120NS	.557***	-.558***
k					.024***	.249**
temp						-.910***

NS= not significant. ; Yld=annual yield; I_{Rad}=Intercepted radiation; Es=Conversion efficiency (radiation use efficiency); k=canopy extinction coefficient, fs=photosythetically active radiation intercepted by canopy, Temp=temperature, Alt=altitude

Multiple regression showed that the factors Es, fs, k, Incident radiation and temperature combined were highly strongly correlated to yield (R=0.889, R^2= 0.790). Individually however, only altitude had significant correlation to yield (r=0.558, r^2= 0.312). Stepwise regression however showed that only altitude was a significant determinant of conversion efficiency (Es) though it accounted for only 31% of the variation. The data indicates that though the efficiency of conversion will vary with location it only responds to the overall locational parameters that determine yield, the strongest determinant being temperature, other factors (like soil moisture) not limiting. Harvest index radiation use efficiency can therefore be used as a yield predictor in clonal selection or for comparison of potential performance of different clones in varied environments.

4.2.8. Conclusions

Altitude is a significant determinant of radiation conversion efficiency due to its effect on ambient temperatures. RUE should therefore be considered as a key yield predictor in breeding programmes and clonal selection for commercialisation.

4.3. Influence of Geographic Locations on Response of Yields and Yield Components of Clone TRFK 6/8 to Nitrogen Fertiliser rates

4.3.1. Soil properties and weather variations with geographic locations in Kericho and Sotik, West of the rift

4.3.1.1 Soil Properties

The soil characteristics of the experimental sites are presented in Tables 26 and 27. The textural properties of the soils showed variations, with Timbilil soils having coarser texture than Changoi and Arroket soils (Table 26). Timbilil soils had the highest sand content while Changoi soils recorded highest clay content. The porosity ranged from 38% to 51%, but with little variation between the sites. Arroket had the highest porosity (averaging 45.77%) due to the higher silt content. The soils from all the sites were of volcanic origin Jaetzold, *et al.,* 2010. Tea is grown in soils of varying texture and also grows in soils with clay content as high as 83% in Kericho, Kenya and as low as 1.7% in Taiwan[60] Othieno, 1992. The soils in this study fell within these ranges and were similar those observed in Kericho Ng'etich, *et al.,* 1995a. These results demonstrate the suitability of these soils to grow tea despite their variability. The pH of the soils from the three sites ranged from 5.0 to 3.8. Arroket soils had the highest mean pH at 4.7 (Table 27). However, tea grows in soils of optimal pH of 4.0 to 6.0 (Anon, 2002a), but can grow in soils with pH below 4.0 Othieno, 1992. Indeed, optimal growth of tea had been reported at pH ranges between 3.8 and 5.7 in land newly cleared from primary, secondary forests and tree plantations (Ng'etich, *et. al.,* 1995a). The soil mineral contents (Table 26) were within the ranges observed in the major tea growing

areas (Othieno, 1992). The successful growing of tea in a wide variety of soils makes it difficult to put tea soils into any general classification.

Table 26: Soil physical characteristics of the trial sites, 2012

Location	Depth	%sand	%clay	% silt	Textural class	%porosity	Soil description*
Timbilil	0-20	41.37	49.75	10.96	Clay	37.56	Volcanic dark red (10R 3/2), deep friable clays with a dusky red (2.5YR 3/6) top soil (0-0.1m), with Kaolinite as the predominant , classified as humic nitosols
	20-40	42.15	44.13	13.28	Clay	45.22	
	40-60	38.08	48.36	15.57	Clay	47.00	
Changoi	0-20	23.75	70.79	11.52	Clay	43.33	volcanic derived, deep, free draining, dark red (2.5 YR 3/6) with a dark reddish brown (2.5YR 3/4) top soil (0-0.1m), classified as nitosols
	20-40	22.28	72.08	11.67	Clay	31.67	
	40-60	23.07	70.32	12.86	Clay	31.67	
Arroket	0-20	29.84	48.59	21.57	Clay	51.33	Dark reddish brown (2.5YR 3/4), moderately deep, firm clay loam with humic top soils on, classed as chromoluvic phaeozems
	20-40	27.84	49.59	22.57	Clay	42.00	
	40-60	28.20	50.23	21.57	Clay	44.00	

*Soil description after Jaetzold *et al.,* 2010.

Table 27**: Soil chemical characteristics of trial sites, 2012**

Location	Depth.	pH (1:1)*	N (ppm)	P (ppm)	K (ppm)	Ca (ppm)	Mn (ppm)	Mg (ppm)	Na (ppm)	Cu (ppm)	Fe (ppm)	Zn (ppm)
Timbilil	0-20	3.94	53.5	8.7	239.3	297	86.3	179.7	1.0	1.0	84.7	2.3
	20-40	3.92	78.0	7.7	256.0	336	87.0	155.0	1.0	1.0	84.7	2.0
	40-60	3.96	58.5	5.3	148.3	295	94.3	103.7	1.0	1.0	74.7	2.0
Changoi	0-20	3.82	22.9	10.7	212.0	516	130.0	145.7	1.0	1.0	74.7	3.0
	20-40	3.69	52.4	6.0	70.3	249	86.0	105.7	1.0	1.0	76.0	3.0
	40-60	3.95	57.0	10.7	63.3	269	83.7	124.7	1.0	1.0	79.0	3.0
Arroket	0-20	4.44	34.0	11.3	579.3	1290	152.7	213.0	1.0	1.0	127.0	3.3
	20-40	5.02	33.5	10.7	407.3	1807	196.7	195.3	1.0	1.0	119.3	3.0
	40-60	4.85	24.5	9.3	450.3	1317	234.7	193.7	1.0	1.0	101.0	3.0

* 5g soil : 5ml distilled water

In Kenya, tea is grown mostly on volcanic soils (Scott, 1962; Othieno, 1992; Carr, 1974) which are classified as nitosols in the FAO-UNESCO classification system(Othieno, 1992) but there are also pockets of acrisols and ferralsols. Site variations in the soil nitrogen contents were evident. However, the soil nitrogen levels were adequate for tea growth despite the higher nitrogen levels recorded in Timbilil. The results demonstrate that the soils were suitable for tea growing. These results demonstrate that though tea can be successfully commercially grown in a wide variety of soil types, the variations in soil types

could contribute significantly to locational yield variations. Soil differences between sites and even significantly big differences between sites across East Africa tea growing regions have been recorded. In addition, soil water deficits, compaction and soil water deficits could restrict productivity of tea in different locations (Ng'etich, *et. al*., 1995a; Ng'etich, *et. al*., 1995c). The noticeable differences in clay content in Changoi and pH and base elements in Arroket are likely to contribute to differences in yields and yield responses bwteen the sites. Similar findings of differences in clay content have been reported to contribute to yield differences (Ng'etich, *et. al*., 1995c).

4.3.2 Weather and Geographical Locations

The weather components from the three trial locations during the duration of the trial are as shown in Table 28. There were differences between the sites in all the weather parameters measured and derived (rainfall, rain days, ambient temperatures, relative humidity and vapour pressure deficit).

4.3.2.1 Temperatures

Mean monthly temperatures generally rose with declining altitude from Timbilil to Arroket (Table 2 and Table 28). The monthly and the monthly mean temperatures were in the order Arroket >Chamgoi>Timbilil (Table 28). Whereas temperatures in Timbilil and Changoi dropped with the onset of the April rains, temperatures in Arroket the rose with the onset of the April rains. This could be ascribed to the influence proximity of Timbilil and Changoi to the Mau forest complex which may have contributed to lowering of ambient temperatures. Sites in Timbilil and Changoi were reported to have been previously under natural forest (Ngetich *et al.*, 1995a). The mean temperature difference between Timbilil and Changoi was 1.8˚C while between Changoi and Arroket and Timbilil and Arrroket were 1.9˚C and 3.7˚C, respectively. These results were similar to those obtained earlier(Squire et al., 1993) where temperature difference between locations at high altitude (over 2000 m) was lower than those

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between high and lower altitude (below 2000 m) locations. It was noted that the temperature difference between Changoi and Arroket was similar to that between Timboilil and Changoi though the difference in altitude between the former was only 60 m as compared to the over 300 m differences between Timbilil and Changoi and Timbilil and Arroket. Location differences due to temperature have been earlier observd (Ng'etich, *et. al*., 1995a,b; Ngetich *et al.,* 2001a; Ngetich and Stephens 2001a)

4.3.2.2 Rainfall

Rainfall pattern in Timbilil was unimodal with rains starting in April and continuing up to December. In Changoi and Arroket Kipkebe the rainfall was weakly bimodal with peaks in April to July and in December (Table 4) as had been reported earlier for Kericho (Stephens *et al*., 1992). Total rainfall declined with decreasing altitude from Timbilil to Arroket (Tables 1 and 4). However, these relationships were not significant. Timbilil and Arroket had more rain days in the January- March season but received less rain than Changoi. The seasonal variations are likely to influence the total annual yields variations between the sites as has also been reported earlier (Ng'etich, 1995, Ng'etich *et al.*, 1995c).

4.3.2.3 Relative humidity (Rh) and Vapour pressure deficit (vpd)

Relative humidity (Rh) and vapour pressure deficit (VPD) also showed variations between sites. Mean monthly relative humidity did not follow any altitudinal pattern. Changoi recorded the lowest VPD. The Highest VPDs were recorded during the January March period in Timbilil and Arroket but was highest at Timbili. This suggests more severe drought in Timbilil than at the other locations. Similar weather effects, with more severe drought at higher altitude has been recorded before (Ng'etich *et al.*, 1995c). Such droughts have been also recorded to generate high soil water deficits, and occurs around Kericho area on average once every three years (Ng'etich, 1995, Ng'etich *et al.*, 1995c). Seasonal variations of the weather parameters within and between sites were also evident. Ambient temperatures and humidity determine soil water deficits, similar to shoot water potential (SWP). Atmospheric humidity

is inversely related to vapour pressure deficits (Acland, 1989; Bonhuere, 1990). An inverse linear relationship between VPD and SWP in tea has been reported (Tanton,1992; Williams, 1971; Tanton, 1982) although SWP of tea shoots were more closely related to VPD than to soil moisture (Williams, 1971). Variations in soil water deficits between sites in Kericho, affected the difference in yield variations (Ng'etich and Stephens, 2001a). While these may explain yield difference, they may not explain the variations in response to nitrogenous fertiliser observed.

Table 28: Monthly weather parameters at three study locations, Jan – Dec 2012

	Timbilil							Changoi							Arroket						
	Temp(°C)			Rain (mm)	Rdays (d)	Rh(%)	Svpd (KPa)	Temp(°C)			Rain	Rdays (d)	Rh(%)	Svpd (KPa)	Temp(°C)			Rain	Rdays (d)	Rh(%)	Svpd (KPa)
	Max	Min	Mean					Max	Min	Mean					Max	Min	Mean				
Jan	25.7	7.7	16.7	0.0	0	62	15.14	27	11	19.0	0.4	0	88	1.5	27.8	11.2	19.5	2.5	1	62	11.05
Feb	26.3	9.1	17.7	26.8	7	55	15.52	28	11	19.5	26.4	3	86	1.9	29.1	9.9	19.5	31.6	8	67	12.90
Mar	27.5	8.5	18.0	27.7	6	63	14.08	27	11	19.0	76.3	6	86	1.9	28.6	10.0	19.3	56.9	7	70	9.67
Apr	23.3	7.2	15.3	398.4	25	62	5.43	26	11	18.5	423.3	17	88	1.6	29	11.0	20.0	337.7	26	74	5.93
May	22.9	9.8	16.4	391.1	24	71	3.61	25	10	17.5	429.0	21	85	1.7	28.2	13.5	20.9	236.0	23	69	6.08
Jun	22.2	9.7	16.0	226.9	20	80	4.37	25	10	17.5	231.2	20	85	1.7	26.8	12.8	19.8	153.8	20	74	4.88
Jul	21.7	9.7	15.7	160.9	13	70	5.14	25	10	17.5	140.9	13	82	2.1	25.8	13.4	19.6	82.2	9	76	5.50
Aug	22.8	9.4	16.1	298.9	18	71	5.14	25	10	17.5	35.0	3	79	2.2	27.8	13.8	20.8	78.0	12	72	6.59
Sept	22.7	8.7	15.7	239.1	24	71	6	25.4	10.2	17.8	152.5	6	74	3.2	27.6	13.5	20.6	135.5	16	72	6.58
Oct	23.7	10.0	16.9	269.4	24	73	7.39	25.3	10.4	17.9	78.9	4	94	0.6	29.6	12.6	21.1	74.0	14	74	6.33
Nov	24.1	9.7	16.9	227.6	22	80	6.56	26	11.4	18.7	139.3	8	94	0.6	27.7	12.8	20.3	87.0	19	75	5.14
Dec	22.9	9.9	16.4	172.3	15	62	7.44	26.9	10.4	18.7	185.1	11	94	0.7	29.3	12.2	20.8	230.8	17	72	5.46
Total				**2439**	**198**						**1918**	**112**						**1506**	**172**		
Mean	**23.8**	**9.1**	**16.5**			**68.3**	**8.0**	**26.0**	**10.5**	**18.3**			**86.3**	**1.6**	**28.1**	**12.2**	**20.2**			**71.4**	**7.2**

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4.4. Influence of Nitrogen Fertilizer Rates and Variations in Nitrogen Use Efficiency of clone TRFK 6/8 with Geographic Locations

4.4.1 Yields

Application of nitrogen increased yields significantly (p≤0.05) over the control but further increments above 75 kg N ha^{-1} year^{-1} did not significantly increase yields (Table 29). The response of tea to nitrogen has been widely reported (Bonheure, and Willson, 1992) even in Kenya (Owuor and Othieno, 1996; Owuor *et al.,* 1994; Owuor and Wanyoko, 1996; Owuor *et al.,* 2008b; Odhiambo, 1989; Kamau *et al.,* 2008). The mean yield response to nitrogen application varied significantly between locations, in the order Timbilil<Arroket<Changoi. The rates x site interactions were, significant (p≤0.05). In Timbilil, application of nitrogen had no effect on yields, but in Changoi nitrogen application significantly (p≤0.05) increased yields above the control though further increments did not affect the yields. In Arroket, fertilizer application gave significantly (p≤0.05) higher yields up to 300 kg N ha^{-1} year^{-1}. There was therefore better yield response to nitrogen fertilizer rate in Arroket than the other sites.

Table 29: Effect of location and nitrogen rates on annual yields (Kg mt ha^{-1} year^{-1}ha), yield rankings and actual response to nitrogen (Kg mt ha^{-1} year^{-1}) (yields due to nitrogen application (Y_T-.Y_0)) , 2012

N Rate (kg N ha^{-1} year$^{-1)}$)	Timbilil	Changoi	Arroket	Rate mean	Actual response to N			
					Timbilil	Changoi	Arroket	Rate mean
0	1906*(4)*	3446*(5)*	2225*(5)*	2526	-	-	-	-
75	1867*(5)*	4044*(2)*	2834*(4)*	2915	-38	597	609	390
150	1944*(3)*	4288*(1)*	3339*(2)*	3190	38	842	1114	665
225	2173*(1)*	4020*(3)*	3235*(3)*	3142	267	574	1010	617
300	1978*(2)*	4009*(4)*	3596*(1)*	3195	73	563	1371	669
Site mean	1974	3961	3046		85	644	1026	
CV%	9.95							
	N Rate	Site	RatexSite					
LSD0.05	281	218	483					

Yield rankings are in parentheses; (Y_T-.Y_0) = Yield at rate T ; Y_0– Yield at control

The yield response to nitrogen application varied significantly (p≤0.05) between each of the three locations. These results sugest that the currently recommended fertilizer rates in Kenya of 150 kg N [ha-1]

year[-1] (Anon 2002a; Othieno, 1988) may be appropriate in all locations. Indeed, rankings of yield increase due to nitrogen application also varied with site. In Tanzania, linear responses of tea yields to nitrogen up to a maximum of 375 and 300 kg N ha[-1] year[-1] in irrigated and unirrigated tea, respectively, were reported (Williams and Carr, 1991). In Kenya, however, seedling tea yields increased with application of nitrogenous fertilizer up to a maximum rate of 470 kg N ha[-1]year[-1] (Owuor and Othieno, 1996). The response of tea to fertilizer in terms of growth and yield is nonetheless influenced by aspects such as climatic, edaphic, genotypic and managerial factors[71] (Mohotti et al., 2003). These factors vary widely between regions and sites such that plant responses to fertilizer regimes differ between regions and growing sites in an unpredictable manner. These were demonstrated in clone BBK 35 across five sites in Kenya (Owuor et al., 1994; Owuor et al., 2010a), in four clones across different seasons in Malawi (Malenga, 1996) and across East Africa (Owuor et al., 2013; Msomba et al., 2014). Thus, clonal tea yields may not be stable across different environments, even within Kenya. Similar observations were recorded in this study. These observations imply that management practices may not be applied universally in all regions if yields are to be optimised in each location. For optimal yield realisation, clonal evaluations/selections need to incorporate the evaluations of the responses to nitrogen fertilizers. It is possible that there are cultivars that respond better in specific environments/locations.

4.4.2 Shoot Nitrogen Content

The pluckable shoot nitrogen content showed no significant variation with fertilizer rate or location (Table 30). Similar results were reported from studies on a single clone in one site Sitienei et al., (2013). The nitrogen content of "two leaves and a bud" was less sensitive to nitrogen fertilization (Othieno, 1988). These findings indicate that increase in nitrogen application from 75 to 300 kg N ha[-1] year[-1] do not result in increase of the partitioning of nitrogen to the pluckable shoots. Increase in nitrogen supply has been reported to improve growth up to a point (Owuor and Othieno, 1996; Owuor and

Wanyoko, 1996) beyond which nitrogen absorbed was not used for growth of shoots but rather accumulated as soluble compounds in the leaves (Mohotti *et al*., 2003). Other observations showed that higher rates of nitrogen increased the photosynthetic rate (Gail *et al.,* 1993), improved shoot fresh weight but reduced the dry matter (Cloughley *et al*., 1983). These findings suggest that the yield increase associated with nitrogen application in tea (Table 29), involves the enhancement of processes that lead to increase in shoot size and weight and shoot growth rates but not increase in nitrogen partitioning into individual shoots at the rates 75-300kg N ha^{-1} year^{-1} in clone TRFK 6/8.

Table 30: Effect of nitrogen rates and location on harvestable shoot nitrogen content (% of dwt), 2012.

N Rate (kg N ha^{-1} year $^{-1)}$	Harvestable shoot nitrogen content				Quantity of nitrogen (Kg N ha^{-1} year^{-1}) harvested with crop per year			
	Timbilil	Changoi	Arroket	Rate mean	Timbilil	Changoi	Arroket	Rate mean
0	3.85	3.24	4.1	3.73	73	112	91	92
75	3.76	3.71	3.95	3.81	70	150	112	111
150	3.88	3.67	4.17	3.91	75	157	139	124
225	3.79	3.84	3.89	3.84	80	154	125	120
300	3.99	3.94	3.99	3.97	79	158	140	126
Site mean	3.85	3.68	4.02		75	146	121	115
CV%	9.72							
	N Rate	Site	RatexSite					
LSD (p≤0.05)	NS	NS	NS					
					4 (5.5)	19	21	14
STDev (CV%*)						(13.2)	(16.9)	(12.1)

As STDev/mean x100

The quantity of nitrogen removed with crop varied with location, however, the variations due to rates of nitrogen at single sites were low (Table 30). Where response to nitrogen was low (Timbilil), quantity of nitrogen removed with crop was lower than that removed at Changoi and Arroket where responses were higher. Thus on replacement basis, where yield responses are low there may be no need to apply to apply in excess of 100kg N/ ha^{-1} year^{-1}. However, even in locations where yields were higher and

responses were better, there may be no justification to apply beyond 150 kg N ha^{-1} year^{-1}, the recommended nitrogen rate (Anon., 2002a; Othieno, 1988).

4.4.3 Nitrogen Use Efficiency (NUE)

The nitrogen use efficiency (NUE) as determined in this study was calculated as per the definition of unit dwt of harvested shoot per unit of N applied (Berendse and Aerts, 1987; Gee and Baader, 1986), that estimates the NUE only where external nitrogen is applied. Thus, the effect of nitrogen application was determined as the yield at a given rate less yield at the control (zero). The correct term would therefore be "Harvestable Applied Nitrogen Use Efficiency". Though tea may realise yields without application of nitrogen fertiliser, the yields may be commercially very low and unsustainable. Table 31 depicts the means of NUE derived from the means of made tea yields.

Table 31: Effect of nitrogen rates and geographical location on NUE (g dwt g^{-1} N), 2012

N Rate(kg N ha^{-1} year$^{-1)}$	Timbilil	Changoi	Arroket	Rate mean
0	-	-	-	
75	-0.98	17.60	12.97	9.86
150	0.53	10.66	11.22	7.47
225	2.17	5.02	7.37	4.85
300	0.47	0.47	7.31	2.75
Site mean	0.55	8.44	9.72	

Mean NUE declined with increasing nitrogen rates. The decline in NUE values followed the pattern of yield increase with increasing nitrogen rates (Table 29). Similar findings were reported for the same clone, TRFK 6/8 in a singe site (Nyabundi, and Boiwa, 2016). NUE decreases with increasing abundance of nitrogen as the plants lose their ability to mine and utilize nitrogen more efficiently (Vituosek, 1982; Birk and Vituosek, 1986; Berendse and Aerts, 1987, Chakwizira *et al.*, 2015) especially under dry conditions (Gauer *et al.* 1992). The extent of change varied with location. Clone TRFK 6/8 showed superior nitrogen use efficiency in Changoi (0.47-17.6 g dwt/g N) and Arroket than Timbilil (7.31-12.97

and -0.98-2.17 g dwt/g N respectively). Though NUE decreases with less moisture (Gauer *et al*. 1992), the superior NUEs observed in Changoi and Arroket could be attributed to the warmer temperatures (Table 28), favouring plant growth in the two sites comapared to Timbilil. The variation of NUE with fertilizer rate varied with location. The findings also indicate that NUE may be environment dependent, resulting in variations in the fertiliser rate at which nitrogen is used most efficiently to produce harvestable tea shoots. Similar findings have been reported for tea yields (Owuor *et al*., 2013; Msomba *et al.,* 2014) in East Africa. The findings demonstrate that for maximising profits from tea growing, recommended nitrogen fertiliser rates should be location dependent. Areas with low NUE should receive lower nitrogen fertiliser rates, while areas with high NUE should receive higher nitrogen fertiliser rates. From this study, there may be no justification in applying more than 100 kg N ha^{-1} year^{-1} in Timbilil and 150 kg N ha^{-1} year^{-1} at Changoi and Arroket, on clone TRFK 6/8. Similar findngs have been made on yield response to fertiliser (Owuor *et al*., 2013; Msomba *et al.,* 2014) in East Africa.

4.4.4 Yield, NUE and Nitrogen Rates Interactions

Correlation analysis of yields, nitrogen rates and NUE showed that the relationships varied with location (Table 32).

Table 32: Effect of location on correlations coefficients (r) between , N rates, NUE and yield, 2012

Location		Rate	NUE
Arroket	Annual yield	.836***	-.790***
	Rate		-.915***
Changoi	Annual yield	-.113	.181
	Rate		-.886***
Timbilil	Annual yield	.246	-.120
	Rate		-.925***

N = 12; ** Correlation is significant at the 0.01 level;
NUE = Nitrogen Use Efficiency; Ann yld = Annual yield; Rate = Nitrogen rate

Yields directly related with nitrogen rates and inversely with NUE at only at Arroket. At Timbilil and Changoi only inverse relations between NUE and rates were significant (p≤0.05). In Tanzania, nitrogen application leading to increase in photosynthetic rate (attributed to increased stomatal conductance and reduced leaf temperatures) and radiation interception was recorded on clone TRFK 6/8 (Gail *et al.,* 1993). However, further increase in fertilizer to 375 kg N Ha-1 yr-1 reduced photosynthetic rate despite decline in stomatal conductance. Higher rates of nitrogen improved shoot fresh weight but reduced the dry matter and increased the proportion of waste fiber, resulting in saleable tea being less responsive to nitrogen fertilizer application (Cloughley *et al.*, 1983). These responses to nitrogen application are not directly related to yield and are also influenced by other factors. This could explain the decline in NUE with increasing nitrogen rates. The inverse relationship of NUE with yields in tea could also be due to degradation of the photosynthetic process because of accumulation of soluble compounds in the leaves at high nitrogen rates. Indeed light saturation of photosynthesis in tea occurred only at the higher fertilizer application rates (Gail *et al.,* 1993). The rate of degradation however is environment dependent. These results demonstrate that application of high rates of nitrogen fertilizer reduce possible profits from tea enterprise as the yield returns from nitrogen application decline. This decline is further enhanced by reduction in tea quality accompanying application of high rates of nitrogen (Cloughley *et al*., 1983; Owuor *et al,* 2010; Owuor *et al*., 2013a; Owuor *et al.,* 1994; Owuor and Othieno, 1996).

4.4.6 Conclusions

Tea yield response to nitrogen varied with the geographical location of production. Though yield increased with nitrogen rates, nitrogen use efficiency declined with applied nitrogen. The responses of nitrogen use efficiency to nitrogen rates also varied with location. Since the shoot nitrogen content showed no significant variation with N rates and location, the yields variation with increasing nitrogen rates are likely to be due to influence of nitrogen on shoot growth factors and not due to soil nutrient

supply factors. Optimal agronomic nitrogen rates will therefore vary with location and therefore fertiliser management practices for tea may not be universally applied across tea growing areas even on the same clone. There is therefore need to develop location specific nitrogen use policies. However, from these results there may be no justification of applying more than 100 kg N ha^{-1} year^{-1} in Timbili, and 150 kg N ha^{-1} year^{-1} in Changoi ang Arroket to clone TRFK 6/8.

4.5. Variations in Nutrient Uptake of Clone TRFK 6/8 at Different Rates of Fertilizer with Geographic Locations

4.5.1 Leaf Nutrient Content

Leaves were sampled for nutrient analysis in the rain season when moisture for uptake was not limiting. Variations in the leaf nutrient levels with location and nitrogen fertiliser rates are presented in Tables 33 and 34 respectively. Of nine nutrients tested, only calcium and iron leaf contents varied significantly ($p \leq 0.05$) with nitrogen rates, both nutrients declining in leaf content with increasing nitrogen rates. Application of fertilizer caused shift in leaf nutrient retention. This shift is not uniform for all nutrients. Therefore, uptake, allocation, residence time and final use from the soil of nutrients in response of fertilizer application cannot be determined by leaf analysis alone. The leaf nutrient content of all nutrients tested, except for manganese, varied significantly ($p \leq 0.05$) with location. Uptake and retention of nutrients from the soil varies with location. The location x nitrogen rate interactions however, was not significant for all the nutrients. Earlier studies found significant variations in leaf nutrient contents with nitrogen rates (Kwach, 2015; Kwach *et al.,* 2011; Kwach *et al.,* 2012; Kwach *et al.,* 2014; Wanyoko, 1982; Owuor *et al.*, 1990; Wanyoko *et al.*, 1990). These variations were however, significant in some sites but not others. This is an indication that that behaviuore of nutrients in the plant varies with the plant's status in response to the environment, which will vary with location and season (Kwach *et al.,* 2011; Kwach *et al.,* 2012; Kwach *et al.,* 2014). Even within the same clone, the tea plant's nutrient

uptake, retention and allocation in response to nitrogen fertilization is not uniform for all nutrients. Further, uptake, retention and allocation of most nutrients will vary with location even within the same clone. Except for the non significant interactions, these findings are nevertheless similar to, though do not mimic the earlier studies (Kwach *et al.,* 2011; Kwach *et al.,* 2012; Kwach *et al.,* 2014; Owuor *et al.,* 1990; Wanyoko *et al.,* 1990) in terms of variations in leaf nutrient levels of with nitrogen feriliser rates and locations. Thus nutrient allocation and reallocation in the plant in response to nitrogen fertilisation regime of tea will vary unpredictably and cannot be used as a guide to optimisation of fertiliser applications.

Table 33: Effects of geographic location and nitrogen rates on mature leaf nutrient content of N,P, K and Ca, 2012.

	N%				P%				K%				Ca%			
	Tmbl	Chgi	Arrkt	Rate mean	Tmbl	Chgi	Arrkt	Rate mean	Tmbl	Chgi	Arrkt	Rate mean	Tmbl	Chgi	Arrkt	Rate mean
0	3.43	3.98	2.97	3.46	0.16	0.30	0.19	0.22	1.38	1.75	1.31	1.48	0.97	0.91	1.20	0.98
75	3.55	4.32	3.10	3.65	0.18	0.30	0.20	0.23	1.52	2.29	1.23	1.68	0.71	0.90	1.05	0.89
150	3.33	4.06	2.87	3.42	0.20	0.29	0.20	0.23	1.63	2.37	1.06	1.69	0.85	0.94	1.23	1.01
225	3.83	3.84	2.98	3.40	0.18	0.30	0.23	0.24	1.50	2.67	1.03	1.73	0.63	0.92	1.15	0.90
300	3.29	4.20	2.82	3.43	0.20	0.43	0.22	0.30	1.52	2.18	1.08	1.59	0.81	0.84	1.11	0.92
Loc Mean	3.39	4.08	2.95		0.18	0.34	0.21		1.51	2.25	1.14		0.78	0.90	1.13	
CV %	9.38				31.01				23.96				8.92			
	Rate (R)	Loc (L)	R x L		Rate (R)	Loc (L)	R x L		Rate (R)	Loc (L)	R x L		Rate (R)	Loc (L)	R x L	
LSD$_{(0.05)}$	NS	0.24	NS		NS	0.06	NS		NS	0.27	NS		0.08	0.06	NS	

Table 34: Effects of geographic location and nitrogen rates on mature leaf nutrient content of Mg, Mn, Zn, Cu, and Fe, 2012.

	Mg (%)				Mn (%)				Zn (ppn)				Cu (ppm)				Fe (ppm)			
	Tmbl	Chgi	Arrkt	Rate mean	Tmbl	Chgi	Arrkt	Rate mean	Tmbl	Chgi	Arrkt	Rate mean	Tmbl	Chgi	Arrkt	Rate mean	Tmbl	Chgi	Arrkt	Rate mean
0	0.15	0.16	0.14	0.15	0.38	0.30	0.36	0.35	10.0	22.0	4.0	12.0	13.3	16.0	9.0	12.8	197	161	199	185
75	0.11	0.17	0.14	0.14	0.30	0.32	0.29	0.30	19.7	30.0	15.7	21.8	7.0	19.0	7.7	11.2	163	158	161	161
150	0.13	0.19	0.15	0.15	0.50	0.31	0.48	0.43	18.0	65.0	6.3	29.8	14.0	16.7	13.7	14.8	181	160	191	177
225	0.08	0.19	0.14	0.13	0.32	0.30	0.31	0.31	19.7	6.3	19.7	15.2	8.7	16.7	9.7	11.7	170	179	185	178
300	0.11	0.16	0.14	0.14	0.33	0.29	0.37	0.33	31.0	4.3	16.7	17.3	13.3	13.7	7.3	11.4	172	134	173	160
Loc Mean	0.11	0.17	0.14		0.37	0.31	0.36		19.7	25.5	12.5		11.3	16.4	9.5		176	158	182	
CV %	12.48				32.6				32.9				32.7				11.2			
	Rate (R)	Loc (L)	R x L		Rate (R)	Loc (L)	R x L		Rate (R)	Loc (L)	R x L		Rate (R)	Loc (L)	R x L		Rate (R)	Loc (L)	R x L	
LSD$_{(0.05)}$	NS	0.017	0.029		NS	NS	NS		NS	13.73	NS		NS	2.95	NS		18	14	NS	

4.5.2 Nutrient Content Interactions

There were no relationship between leaf nutrient contents with nitrogen rate at any location. Correlation analyses, grouped and ungrouped by location, indicate that the variations in leaf nutrient content with location were closely and mostly significantly ($p \leq 0.05$) (Tables 35and 36). Ungrouped, only P, K Mg and Cu were significantly correlated to yields. However, when grouped by location, only K was significantly correlated to yields, in Timbilil while the rest were not significant but had varied magnitudes of correlation with yields at the different locations. These findings demonstrate the interrelation of nutrient uptake and their possible contribution to yields. These interactions may explain the variations in responses in leaf nutrient content to fertiliser application in different locations. However, the results show that at individual locations, individual nutrients contents cannot be predictors of yield and nitrogen requirement.

4.5.3 Conclusions

Nutrient uptake, retention and use as estimated by the leaf nutrient content, varied with nitrogen application rates and also with location. The variation of individual nutrients appeared to be partly as a result of the interaction of the sum of all, or some of the nutrients. These may explain the varied responses to fertiliser application in different locations.

Table 35: The inter-relationships ® between leaf nutrient contents, nitrogen rates and yields

	Timbilil										Changoi										Arroket									
									N										N										N	
	P	K	Ca	Mg	Mn	Zn	Cu	Fe	Rate	Yld	P	K	Ca	Mg	Mn	Zn	Cu	Fe	Rate	Yld	P	K	Ca	Mg	Mn	Zn	Cu	Fe	Rate	Yld
N	-.255	.527	-.595	-.402	-.705	-.175	-.301	-.349	-.612	-.593	.356	-.208	-.489	-.476	.398	-.372	.187	-.688	-.034	.243	-.610	-.326	-.246	.049	-.430	-.325	-.732	-.208	-.705	-.425
P		-.786	.051	-.272	-.321	-.658	-.192	-.255	.866	.708		-.129	-.937*	-.541	-.692	-.676	-.794	-.841	.696	.052		.874	-.115	-.298	.312	.119	.255	-.470	.756	.107
K			-.561	-.377	-.260	.172	-.382	.067	-.859	-.908*			.246	.811	.174	-.429	.251	.430	.586	.775			-.213	-.270	.479	.346	.056	-.481	.463	.052
Ca				.834	.835	.702	.923*	.672	.192	.336				.726	.559	.467	.613	.813	-.504	.133				.950*	.589	.552	.837	.827	-.413	-.620
Mg					.876	.758	.926*	.343	.000	.307					.318	-.142	.364	.680	.209	.658					.550	.554	.645	.807	-.667	-.748
Mn						.778	.791	.559	.043	.239						.247	.943*	.344	-.555	.314						.974**	.701	.532	-.157	-.188
Zn							.826	.746	-.534	-.340							.445	.595	-.840	-.758							.624	.615	-.292	-.123
Cu								.575	-.084	.158								.577	-.580	.167								.715	.083	-.180
Fe									-.295	-.351									-.325	-.040									-.519	-.224
pH									.a	.a									.a	.a									.a	.a
N Rate										.930*										.562										.598

N= 5
*Correlation is significant at 0.05
** Correlation is significant at 0.01
a=cannot be computed because variables are constant

Table 36: Grouped correlation of means of leaf nutrient contents, nitrogen rates and yields, from three locations, Timbili, Changoi and Arroket.

	P	K	Ca	Mg	Mn	Zn	Cu	Fe	N Rate	Yld
N	.712**	.882**	-.517*	.493	-.469	-.458	.712**	-.671**	-.089	.489
P		.657**	-.089	.562*	-.406	-.082	.494	-.728**	.316	.735**
K			-.421	.601*	-.377	-.364	.731**	-.495	.079	.547*
Ca				.411	.316	.849**	-.074	.449	-.100	.322
Mg					-.121	.260	.680**	-.131	-.149	.785**
Mn						.413	.050	.580*	-.074	-.318
Zn							-.061	.440	-.226	.216
Cu								-.176	-.084	.516*
Fe									-.296	-.460
N Rate										.253

N= 15

*Correlation is significant at 0.05

** Correlation is significant at 0.01

4.6. Relationships between Tea Yield Components and Varying Environment Parameters under Different N:P:K (25:5:5) Fertilizer Rates

4.6.1. Yield Components

The recorded yield components; shoot growth rates, shoot dry weights, shoot densities and shoot water potentials are presented in Table 34.

4.6.1.1 Shoot growth rate

The shoot growth rates (sgr) showed significant ($p \leq 0.05$) responses to locations of production (sites) and nitrogen rates (Table 37). Mean sgr increased significantly with increasing nitrogen rate up to 225 kg N ha^{-1} year^{-1}. Shoot leaf lengths had been reported to increase with application of fertilizer over the control (Mokaya, 2016). This is an indication the shoot growth rate may have a maximum threshold for nitrogen at about 225 kg N ha^{-1} year^{-1}. Table rise was faster in fertilizer-applied plots than the control (Odhiambo 1989). These observations are the indication of effects of fertilizer on tea plant growth. Significant ($p \leq 0.05$) site differences in shoot growth rate were in the order Timbilil<Changoi<Arroket. This follows the order of temperature increase with decline in altitude. Effects of temperature on tea shoot groeth have been discussed ealier.

Table 37: Effects of geographical location and nitrogen rates on yield components

	Sgr			Rate mean	Ier			Rate mean	Sdwt			Rate mean	sd			Rate mean	swp			Rate mean
	Tmbl	Chgi	Arrkt		Tmbl	Chgi	Arrkt		Tmbl	Chgi	Arrkt		Tmbl	Chgi	Arrkt		Tmbl	Chgi	Arrkt	
0	0.03	0.03	0.68	0.25	2.02	2.24	0.81	1.69	0.44	0.37	0.14	0.31	107	119	74	100	5.79	6.22	7.21	6.41
75	0.03	0.03	0.99	0.35	1.86	2.45	1.09	1.80	0.49	0.36	0.12	0.32	108	129	80	106	5.68	6.33	7.21	6.41
150	0.03	0.03	1.06	0.37	2.00	2.37	1.20	1.86	0.45	0.36	0.14	0.32	107	132	83	108	6.03	5.83	7.43	6.40
225	0.04	0.28	1.17	0.50	1.90	2.34	1.28	1.84	0.51	0.38	0.13	0.34	105	129	83	106	5.89	6.14	7.23	6.40
300	0.03	0.03	1.17	0.41	1.95	2.46	1.22	1.88	0.47	0.36	0.13	0.32	106	134	85	108	5.76	6.18	7.17	6.37
site mean	**0.03**	**0.08**	**1.01**		**1.95**	**2.37**	**1.12**		**0.47**	**0.37**	**0.13**		**107**	**129**	**81**		**5.83**	**6.14**	**7.25**	
CV%	29.86				13.5				20.12				8.56							
LSD $_{(p\leq0.05)}$	Rate 0.049	Site 0.038	RxS 0.09		Rate 0.11	Site 0.09	RxS 0.2		Rate NS	Site 0.01	RxS NS		Rate 4	Site 3	RxS NS		Rate NS	Site 0.23	RxS NS	

NS= Not Significant Tmbl=Timbilil; Arrkt=Arroket; Chgi=Changoi; Ste=site=location; sgr=shoot growth rate; ier=internode extension rate; sdwt=shoot dry weight; sd= shoot density

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The fertilizer rate x location interactions were also significant (p≤0.05), indicating that yield components response to nitrogen rates varied with location. Indeed, though there were no significant responses to nitrogen rates in Timbilil, significant responses were observed in Changoi and Arroket. These findings indicate fertilizer requirements, even for the same cultivar, may vary from one location to the next. Thus, fertilizer recommendations may be site specific even for a single cultivar planted in different locations.

4.6.1.2 Internode Extension Rate

Internode extension rates (IER) also showed significant (p≤0.05) variations with location and nitrogen rates. Changoi had significantly (p≤0.05) the highest and Arroket the lowest internode extension rates recorded. Mean internode extension rates increased significantly with rising rates of nitrogen and continued increasing even at 300kg N ha^{-1} year^{-1}. This suggests a higher threshold for nitrogen for ier than sgr. The locational differences in IER were significant (p≤0.05), in the order Arroket<Timbili<Changoi. This was different from the order location differences of sgr and suggests that IER may vary between locations in response to some factor other than altitude or temperature. Rate and location interactions were significant (p≤0.05). The response of IER to fertiliser rates varied with location. Indeed, whereas the response to fertiliser not significant in Timbil, responses were significant (p≤0.05) in Changoi and Arroket. Further, in Arroket and Changoi internode extension rates significantly increased with application of nitrogen fertiliser rates. In Timbilil, however, application of nitrogen resulted in a decline in internode extension rates, though this was not significant. The internode extension rate response to fertiliser varied with location. Similar to sgr, this is an indication the fertiliser requirements for a single cultivar of tea may vary with location.

The results show that the shoot growth rates and internode extension rates response to environment vary, contrary to the expectation that these should follow the same pattern especially when

measured in the same clone. Tea shoots from the same population may grow at different rates at differen

stages of growth (Tanton, 1992). The two parameters represent different growth phases of the shoot and

may respond differently to temperature and relative humidity due to the variations in the shoot

metabolism with the growth phase.

4.6.1.3 Shoot Dry Weight and Shoot Density

Shoot dry weights showed only significant ($p \leq 0.05$) response to location but not nitrogen rates

(Table 34). Higher rates of nitrogen increased the photosynthetic rate (Gail *et al.,* 1993), improved shoot

fresh weight but reduced the dry matter (Cloughley *et al*., 1983). In earlier studies, nitrogen rates had no

effect on shoot mass of clone TRFK 6/8 (Odhiambo, 1989). The shoot densities however, showed

significant variations ($p \leq 0.05$) due to nitrogen rates and location. Mean shoot density increased

significantly ($p \leq 0.05$) with application of fertiliser over the control but further increase in fertiliser

application gave no significant response to shoot density. Studies on the same cultivar in a single site had

given similar results but with continued increase in shoot density up to 400 kg N ha^{-1} year^{-1} (Odhiambo,

1989). The highest mean shoot density was recorded in Changoi (129 shoots m^{-2}) and lowest at Timbilil

(81 shoots m^{-2}). Obaga *et al.*, (1989) reported varying clonal response of shoot density with altitude. The

findings demonstrate the variation in responses of yield components to fertiliser application and the

variation of these responses with geographic location of production.

4.6.1.4 Shoot Water Potential

Shoot water potential only significantly varied with site (Table 34). This could be attributed to the

differences in the locational vapour pressure deficits. Shoot water potential of tea shoots has been

demonstrated to be more closely related to vapour pressure deficits than to soil moisture (Tanton, 1982b).

Shoot water potential influences shoot growth by determining the cellular turgidity required for cell

expansion (Odhiambo *et al.,* 1993). These findings suggest a threshold of plant water status for tea shoot

survival and growth, which does not vary with nitrogen rates but varies with location. The findings suggest that tea plants maintain internal water balance despite application of fertilizer, as long as no other factors are limiting.

4.6.3 Yield, yield components and environment interactions

Correlation analysis revealed that significant correlation between yields and yield components and nitrogen rates only occurred in Arroket (Table 38). Yields, shoot growth rate and shoot density showed significantly high correlation nitrogen rates (r=0.930, 0.909, 0.919, respectively $p \leq 0.05$) (Table 35). Though other locations were not significant, the magnitude of the correlations varied with locations. Changoi recorded the highest yields but had the lowest yield response to nitrogen rates (Tables 26 and 30). These findings clearly indicate that the tea crop response to fertilizer is site specific and universal application of fertilizer may only apply as general guideline but production will vary between locations. In Sri Lanka, nitrogen applied at twice the recommended dose, increased bud activity, and most growth parameters were affectedby doubling the recommended dose but not half or zero (Kulasegaram and Kathiravetpillai, 1980). Evaluation of the responses of tea growth parameters' response to nitrogen rates across different environments, particularly in East Africa is not documented. Findings from this stdy indicate that crop requirements will differ from location to location due to variation in environmental factors, the interactions of which will cause variations in crop response between the locations. It is therefore important that the fertilizer application is closely matched with the crop requirements in every location.

Table 38: Effects of location on correlations between nitrogen rates, yield and yield parameters (sgr, sd, sdwt)

	yld	swp	sgr	sd	sdwt
Timbilil N rate	0.598	0.176	0.354	-0.693	0.442
Changoi N rate	0.562	-0.228	0.354	0.822	0.000
Arroket N rate	0.930*	-0.092	0.909*	0.919*	-0.189

N = 5

Though the nitrogen response was highest in Arroket and least in Changoi (Table 38), the yield pattern was reversed with the highest yields being attained at the lowest nitrogen rate in Changoi and at the highest nitrogen rate in Arroket. Regression analysis further indicates that priority of yield factors contribution to yields, including response to nitrogen, will vary with location (Table 35). These ruslts further indicate that tea yield response to fertiliser will vary with location and therefore confirmatory trials need to be conducted in each location to ascertain the optimum fertilizer levels if production is to be optimized. Indeed the findings of the yields and response to nitrogen indicates strongly that nitrogen application rates for crop optimization will vary with location since response to nitrogen application will not always result in highest yields.

4.6.4 Conclusions

Yield and yield components response to nitrogen rates varied with location. This resulted in the highest yields not always being attained at the highest nitrogen levels. The tea crop response to fertilizer is site specific and universal application of fertilizer may only apply as general guideline but will not optimize production. Though a location may have highest yield response to nitrogen application it may not record the highest yields. Tea yield response to fertiliser will vary with location and therefore confirmatory trials need to be conducted in each location to ascertain the optimum fertilizer levels if production is to be optimized.

CHAPTER FIVE

SUMMARY, CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS FOR FUTURE STUDIES.

5.1 Summary

1. The responses of the tea yield and yield components to weather parameters varied with genotypes and environments. Yield components and weather parameters contribution to the total yield also varied with locations.

2. The conversion efficiency, and its components were strongly correlated to yield. However, only altitude was a significant determinant of conversion efficiency. The efficiency of conversion will vary with location and is strongly dependant on temperature.

3. Yield and yield components varied significantly with location and season. Yield components contribution to yield varied with season. Drought and rainfall distribution reduced yields and seasonal yield distribution. Yield components components contribution to yields varied with season.

4. Yield response to nitrogen application rates was significant ($p \leq 0.05$), but the reponses varied with location. Although the changes in nitrogen application rates between 75-300Kg N did not significantly vary the nitrogen content in harvestable shoots, there were considerable variations in the amount of nitrogen removed with crop. The amount of nuitrogen removed with crop however, did not exceed the recommended rate of application (150kg N ha^{-1} year^{-1}). The NUE of clonal tea declined with increasing nitrogen fertiliser rates and was low where yield response to nitrogen fertiliser was low.

5. Of all nine nutrients tested, only calcium and iron leaf contents varied significantly ($p \leq 0.05$) with nitrogen rates, both nutrients declining in leaf content with increasing nitrogen rates. Except for manganese, all nutrients' leaf contents varied significantly with location. This implies that

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fertilisation regime of tea will vary with location if optimisation and sustainability of yields is to be achieved. There were no significant correlations of leaf nutrient contents with nitrogen rate at any location. Variations in leaf nutrient content with location were closely and mostly significantly ($p \leq 0.05$) linked to soil properties, particularly soil pH. There were interactions of nutrient uptake and contribution to yields with soil pH having an impact on the interactions. These variations are likely to lead to varied responses to fertiliser application in different locations.

6. Yield and yield components response to nitrogen application rates varied with location. The highest yields were not always attained at the highest nitrogen levels. Tea crop response to fertilizer is site specific.

5.2 Conclusions

1. Not all yield components can be used as yield indicators for clonal selection in all locations. For optimal production, selected tea clones should therefore be tested before adoption for commercial planting in locations.

2. Altitude is a significant determinant of radiation conversion efficiency. Harvest index radiation use efficiency can thus be used as a yield predictor in clonal tea breeding programmes..

3. Seasonal yield variations were due to seasonal weather factors that limited yields rather than factors favoured higher yields.

4. Weather rather than soils is the major causative factor in the locational variations in response to nitrogen rates. The optimal nitrogen application rate will vary with location.

5. Even within the same clone, the tea plant's nutrient uptake in response to nitrogen fertilization is not uniform for all nutrients. The variation of individual nutrients appeared to be as a result of the interaction of the sum of all or some of the nutrients and their response to soil pH. These variations may explain partially the varied responses to fertiliser application in different locations.

6. The highest yields were not always attained at the highest nitrogen levels. Tea crop response to fertilizer is site specific

5.3 Recommendations

1. To optimize production in each location, selected tea clones from a given location should therefore be tested before adoption for commercial planting in other locations.

2. Harvest index radiation use efficiency has been idntified as an important parameter that can can be used as a yield predictor in clonal tea breeding programmes.

3. Annual crop yields can be optimized by minimizing or ameliorating the seasonal adverse climatic effects on the tea plant such as soil water deficits or low relative humidity.

4. To optimise locational yields and benfits from fertilisation, fertiliser rates need to be evaluated in every location.

5. Leaf nutirent content may not be used as an indicator of tea response to fertilizer.

6. A universal fertilizer rate application may only apply as general guideline for tea production but not for optimization of production in all locations.

5.4 Suggestions for future studies

1. For an accurate G x E yield prediction model, G X E evaluations should be undertaken in more varied tea growing environments for reasonable period, at lest a pruning cycle, to facitiltate more precise regression and correlation analysis.

2. The efficacy of using radiation use efficiency as a clonal yield predictor, particularly in locations of varying altitudes, should be evaluated as probable option to reducing the duration of multi locational field trials.

3. Detailed studies into the seasonal environmental factors interactions and their effect on yield responses are required to understand the causes of seasonal yield variations and how they can be ameliorated.

4. More in-depth soil studies are needed to accompany locational x fertiliser rate response trials to determine or eliminate the soil factor as a contributor to fertiliser response variations.

5. Multi-locational clonal fertiliser rate trials will be necessary for optimisation of locational yields and quality.

6. Further studies are required to the environmental factors (edaphic or non edaphic) responsible for the observed variations in tea leaf nutrients contents in thedifferent growing locations.

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7.1 Appendix 1: Experimental layout, Genotype x Environment trial (One site: the layout is replicated in three sites, plots are randomized within each block)

KANGAITA

REP A					REP B					REP C			
TRFK 7/9	TRFK 303/259	TRFK 303/1199	TRFK 54/40		TRFK 57/15	TRFK 7/9	TRFK 31/8	TRFK 303/1199		TRFK 56/89	TRFK 31/8	TRFK 303/999	BBK 35
TRFK 31/8	BBK 35	TRFK 6/8	TRFK 31/27		TRFK 54/40	TRFK 303/577	TRFK 12/12	TRFK 31/27		TRFK 54/40	AHP S15/10	TRFK 2X1/4	TRFK 303/577
TRFK 12/12	TRFK 303/999	AHP S15/10	TRFK 57/15		TRFK 11/26	AHP S15/10	TRFK 56/89	EPK TN 14-3		TRFK 12/19	EPK TN 14-3	TRFK 6/8	STCK 5/3
TRFK 56/89	TRFK 12/19	TRFK 11/26	STCK 5/3		TRFK 6/8	STCK 5/3	TRFK 303/259	TRFK 2X1/4		TRFK 57/15	TRFK 7/9	TRFK 11/26	TRFK 7/3
TRFK 7/3	TRFK 303/577	EPK TN 14-3	TRFK 2X1/4		TRFK 12/19	TRFK 7/3	TRFK 303/999	BBK 35		TRFK 303/259	TRFK 31/27	TRFK 12/12	TRFK 303/1199

TIMBILIL

REP A					REP B					REP C			
TRFK 7/9	TRFK 303/259	TRFK 303/1199	TRFK 54/40		TRFK 57/15	TRFK 7/9	TRFK 31/8	TRFK 303/1199		TRFK 56/89	TRFK 31/8	TRFK 303/999	BBK 35
TRFK 31/8	BBK 35	TRFK 6/8	TRFK 31/27		TRFK 54/40	TRFK 303/577	TRFK 12/12	TRFK 31/27		TRFK 54/40	AHP S15/10	TRFK 2X1/4	TRFK 303/577
TRFK 12/12	TRFK 303/999	AHP S15/10	TRFK 57/15		TRFK 11/26	AHP S15/10	TRFK 56/89	EPK TN 14-3		TRFK 12/19	EPK TN 14-3	TRFK 6/8	STCK 5/3
TRFK 56/89	TRFK 12/19	TRFK 11/26	STCK 5/3		TRFK 6/8	STCK 5/3	TRFK 303/259	TRFK 2X1/4		TRFK 57/15	TRFK 7/9	TRFK 11/26	TRFK 7/3
TRFK 7/3	TRFK 303/577	EPK TN 14-3	TRFK 2X1/4		TRFK 12/19	TRFK 7/3	TRFK 303/999	BBK 35		TRFK 303/259	TRFK 31/27	TRFK 12/12	TRFK 303/1199

KIPKEBE

REP A		REP B		REP C
TRFK 2X1/4		BBK 35		TRFK 303/1199
EPK TN 14-3		TRFK 303/999		TRFK 12/12
TRFK 303/577		TRFK 7/3		TRFK 31/27
TRFK 7/3		TRFK 12/19		TRFK 303/259
STCK 5/3		TRFK 2X1/4		TRFK 7/3
TRFK 11/26		TRFK 303/259		TRFK 11/26
TRFK 12/19		STCK 5/3		TRFK 7/9
TRFK 56/89		TRFK 6/8		TRFK 57/15
TRFK 57/15		EPK TN 14-3		STCK 5/3
AHP S15/10		TRFK 56/89		TRFK 6/8
TRFK 303/999		AHP S15/10		EPK TN 14-3
TRFK 12/12		TRFK 11/26		TRFK 12/19
TRFK 31/27		TRFK 31/27		TRFK 303/577
TRFK 6/8		TRFK 12/12		TRFK 2X1/4
BBK 35		TRFK 303/577		AHP S15/10
TRFK 31/8		TRFK 54/40		TRFK 54/40
TRFK 54/40		TRFK 303/1199		BBK 35
TRFK 303/1199		TRFK 31/8		TRFK 303/999
TRFK 303/259		TRFK 7/9		TRFK 31/8
TRFK 7/9		TRFK 57/15		TRFK 56/89

7.2 Appendix 2. Experimental layout, fertilisert rate trial showing 7 day plucking frequency plots .used (shaded) out of the whole fertiliser (N) x plucking frequency (PF) trial

TIMBILIL

	1 N 300 PF$_7$	2 N 0 PF$_{21}$	3 N 150 PF$_{21}$	4 N 225 PF$_{14}$	5 N 0 PF$_7$
R E P A	10 N 300 PF$_{21}$	9 N 150 PF$_7$	8 N 300 PF$_{14}$	7 N 225 PF$_{21}$	6 N 75 PF$_{14}$
	11 N 225 PF$_7$	12 N 150 PF$_{14}$	13 N 75 PF$_{21}$	14 N 0 PF$_{14}$	15 N 75 PF$_7$
	20 N 225 PF$_{21}$	19 N 225 PF$_{14}$	18 N 150 PF$_{21}$	17 N 75 PF$_{14}$	16 N 0 PF$_{21}$
R E P B	21 N 225 PF$_7$	22 N 300 PF$_{14}$	23 N 150 PF$_{14}$	24 N 300 PF$_7$	25 N 300 PF$_{21}$
	30 N 75 PF$_{21}$	29 N 0 PF$_{14}$	28 N 0 PF$_7$	27 N 75 PF$_7$	26 N 150 PF$_7$
	31 N 225 PF$_{14}$	32 N 75 PF$_{14}$	33 N 225 PF$_{21}$	34 N 150 PF$_{21}$	35 N 225 PF$_7$
R E P C	40 N 75 PF$_7$	39 N 300 PF$_7$	38 N 300 PF$_{14}$	37 N 150 PF$_{14}$	36 N 0 PF$_{21}$
	41 N 300 PF$_{21}$	42 N 150 PF$_7$	43 N 0 PF$_7$	44 N 75 PF$_{21}$	45 N 0 PF$_{14}$

CHANGOI

	1	2	3	4	5
R **E** **P** **A**	1 N 225 PF$_7$	2 N 150 PF$_{14}$	3 N 300 PF$_{14}$	4 N 300 PF$_7$	5 N 75 PF$_{21}$
	10 N 0 PF$_7$	9 N 300 PF$_{21}$	8 N 75 PF$_7$	7 N 0 PF$_{14}$	6 N 75 PF$_{14}$
	11 N 225 PF$_{21}$	12 N 0 PF$_{21}$	13 N 150 PF$_7$	14 N 150 PF$_{21}$	15 N 225 PF$_{14}$
R **E** **P** **B**	20 N 300 PF$_{21}$	19 N 300 PF$_{14}$	18 N 0 PF$_{14}$	17 N 150 PF$_7$	16 N 75 PF$_{14}$
	21 N 225 PF$_7$	22 N 150 PF$_{14}$	23 N 225 PF$_{21}$	24 N 225 PF$_{14}$	25 N 0 PF$_7$
	30 N 150 PF$_{21}$	29 N 75 PF$_{21}$	28 N 75 PF$_7$	27 N 0 PF$_{21}$	26 N 300 PF$_7$
R **E** **P** **C**	31 N 75 PF$_{14}$	32 N 0 PF$_{21}$	33 N 300 PF$_{21}$	34 N 75 PF$_7$	35 N 300 PF$_7$
	40 N 150 PF$_{21}$	39 N 225 PF$_{21}$	38 N 150 PF$_{14}$	37 N 225 PF$_7$	36 N 0 PF$_{14}$
	41 N 150 PF$_7$	42 N 300 PF$_{14}$	43 N 225 PF$_{14}$	44 N 0 PF$_7$	45 N 75 PF$_{21}$

SOTIK

1 N 300 PF$_7$	2 N 0 PF$_{21}$	3 N 150 PF$_{21}$	4 N 225 PF$_{14}$	5 N 0 PF$_7$
10 N 300 PF$_{21}$	9 N 150 PF$_7$	8 N 300 PF$_{14}$	7 N 225 PF$_{21}$	6 N 75 PF$_{14}$
11 N 225 PF$_7$	12 N 150 PF$_{14}$	13 N 75 PF$_{21}$	14 N 0 PF$_{14}$	15 N 75 PF$_7$
20 N 225 PF$_{21}$	19 N 225 PF$_{14}$	18 N 150 PF$_{21}$	17 N 75 PF$_{14}$	16 N 0 PF$_{21}$
21 N 225 PF$_7$	22 N 300 PF$_{14}$	23 N 150 PF$_{14}$	24 N 300 PF$_7$	25 N 300 PF$_{21}$
30 N 75 PF$_{21}$	29 N 0 PF$_{14}$	28 N 0 PF$_7$	27 N 75 PF$_7$	26 N 150 PF$_7$
31 N 225 PF$_{14}$	32 N 75 PF$_{14}$	33 N 225 PF$_{21}$	34 N 150 PF$_{21}$	35 N 225 PF$_7$
40 N 75 PF$_7$	39 N 300 PF$_7$	38 N 300 PF$_{14}$	37 N 150 PF$_{14}$	36 N 0 PF$_{21}$
41 N 300 PF$_{21}$	42 N 150 PF$_7$	43 N 0 PF$_7$	44 N 75 PF$_{21}$	45 N 0 PF$_{14}$

REP A (rows 1–15), REP B (rows 16–30), REP C (rows 31–45)

N = Nitrogen Rate (75, 150, 225, 300); PF = Plucking Frequency (7, 14 and 21 days intervals)