RESPONSE OF DIFFERENT TEA (*Camellia sinensis* [L.] O. Kuntze) CLONES TO ENVIRONMENTAL FACTORS AT TWO SITES IN KENYA

LANG'AT, Joseph Kimutai

(MPhil, PGDMC, B.Sc., Dip.Agron., Dip. CH., Dip.Ed.)

Reg. No. AGR/D.PHIL/04/05

A Thesis Submitted in Partial Fulfillment for the Requirements of the Award of the Degree of Doctor of Philosophy (Ph.D)

in

Crop Ecophysiology

Department of Seed, Crop and Horticultural Sciences

University of Eldoret, Kenya

2014

DECLARATION

Declaration by the Candidate

I declare that this research is my original work and has not been presented in this or any other University for any degree. No part of this thesis may be reproduced without the prior written permission of the author and/ or University of Eldoret.

LANG'AT, Joseph Kimutai (Reg. AGR/DPHIL/04/05)
Dept of Seed, Crop and Horticultural Sciences, University of Eldoret
Signature .... Date ....

Declaration by the Supervisors

This thesis has been submitted for examination with our approval as the University supervisors:

1. Prof. Wilson Kipkoech Ng'etich (Ph.D)
   Department of Soil Science, University of Eldoret
   Signature .... Date ....

2. Prof. Caleb Obiero Othieno (Ph.D)
   Department of Soil Science, University of Eldoret
   Signature .... Date ....

3 Prof. Patrick Wachira Mathenge (Ph.D)
   Department of Crop Science, Karatina University
   Signature .... Date ....

DEDICATION

To my late father Joshua Mungwana Kiprono Arap Bomet (1919-1985), who did not live to see me graduate, my mum Mrs. Anjelina Taprantich C. Bomet, my wife Salome Langát, and children: Petronella Cherono Langát, Winyfred Chepkemoi Langát and DC Kiprotich Mutai Langát for their unwavering support and prayers.

ABSTRACT

Tea (*Camellia sinensis*) is a rural-based enterprise and is the leading cash crop in Kenya, making significant contribution to the economy. It is currently the single largest export commodity, accounting for about 26% of the country's total export earnings. In 2012, tea brought in US$ 1.24 billion in foreign exchange earnings. However, tea production is affected by changes in weather, e.g. in 2006, tea yields declined by 5.46% as a result of adverse weather conditions. Studies on effects of weather on tea yields have been conducted in few sites in Kenya. The objective of this study was to determine the effects of environmental factors on yield performance of selected tea genotypes at different agro-ecological sites in Kenya. A split-plot layout for sites was set out in an existing experiment, established in 1998 in RCBD and conducted at two sites differing in altitude and climatic conditions in Kenya: Kangaita (0^{O}30'S and 37^{O}16'E, 2100 m.a.s.l.) in Kirinyaga and Kipkebe (0^{O}17'S and 35^{O}3'E, 1740 m.a.s.l.) in Borabu. Timbilil (0^{O}22'S, 35^{O}21'E, 2200 m.a.s.l.) in Kericho was used as a reference site. The study investigated the genotype versus environment (radiation, temperature, rainfall and location) (G×E) interactions of four tea clones of scientific and commercial importance to the country (AHP SC 31/37, EPK TN14-3, TRFK 301/5 and TRFK 31/8). Initial soil characterization conducted in 2009 showed that texture at Kangaita is sandy loam with a pH of 4.1, while both Kipkebe and Timbilil had clay texture with a pH of 4.6 and 4.0 respectively. Kipkebe soil had higher contents of K, Ca, Mg and Mn while Kipkebe was higher only in P. Kipkebe experienced higher ambient temperatures with mean of $20.0^{O}C$ compared to Kangaita's $15.5^{O}C$. The study recorded a $2^{O}C$ rise at Kipkebe between 2000 ($17.6^{O}C$) and 2010 ($19.6^{O}C$). There was a corresponding rise in ISR by a mean of 0.9 MJm^{-2} per annum (20.3MJm^{-2} in 2007, 21.5MJm^{-2} in 2008 and 21.7MJm^{-2} in 2009) at Timbilil. Low radiation intensities at Timbilil in 2007 corresponded with low made tea yields at Kangaita (2.1 t $ha^{-1}y^{-1}$) and Kipkebe (2.6 t $ha^{-1}y^{-1}$) compared to 2008 (4.4 t $ha^{-1}y^{-1}$ and 3.2 t $ha^{-1}y^{-1}$) and 2009 (3.1 t $ha^{-1}y^{-1}$ and 3.0 t $ha^{-1}y^{-1}$) respectively. Season 1 (mid-December - March) PAR gave 1,571 mol $m^{-2}s^{-1}$ at Kangaita and 1,510 mol $m^{-2}s^{-1}$ for Kipkebe, while 1,304 mol $m^{-2}s^{-1}$ and 1,226 mol $m^{-2}s^{-1}$ was recorded in season 2 (April to August) at Kangaita and Kipkebe respectively. In the third season, PAR was 1,358 mol $m^{-2}s^{-1}$ at Kangaita and 1,360 mol $m^{-2}s^{-1}$ at Kipkebe. The study computed PAR to total solar radiation ratio in tea at Kericho to be 0.45. ANOVA showed significant difference in temperature across locations, yield across the three years (F pr. $\leq$ 0.01) and rainfall between seasons 1 and 2 (F pr. $\leq$ 0.05). No statistical difference existed in PAR between G×E. Pearson correlation analysis showed a significant strength of association between temperature and location, and rainfall and location (F ratio$\leq$0.01). The study concluded that PAR to total solar radiation in tea over Kericho is 0.45 and that there exists a strong positive correlation between PAR and rainfall and mean made tea yield.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

ACRONYMS AND ABBREVIATIONS

AGB: Above-ground biomass.

Amplitude: The maximum displacement from the mean in a harmonic variation.

Damping depth (d): This is a constant characterizing the decrease in amplitude with an increase in distance from the soil surface. It is defined as $(2D_h/\omega)^{1/2}$, where D_h is the *thermal diffusivity* and ω is the *frequency of temperature fluctuation*. For annual fluctuation, $\omega = 2\pi/365\ d^{-1}$.

EY: Economic Yield.

***f*:** Fraction of solar energy intercepted by canopy.

gl/bush: *Green leaf per bush*, as used in kg gl/bush.

***i*:** Harvest index.

ISR: *Incident Solar Radiation*, units MJm^{-2}.

m.a.s.l.: *metres (height) above sea level*.

MJm^{-2}: *Megajoules per square metre (ISR)*. Unit used to measure solar radiation intensity.

mm: *Millimetres (rainfall)*.

$molm^{-2}s^{-1}$: *Moles per square metre per second*. Units of measuring PAR.

mt: Made tea

mV: *Millivolts*. Equivalent to 1000 of a volt, it is the SI unit of electromotive force, the difference of potential that would drive one ampere of current against one ohm resistance.

nm: *Nanometres* (1 nm = 10^{-9}m).

OPV: Open pollinated variety.

PAR: *Photosynthetically active radiation*, visible light spectrum responsible for driving photosynthesis, and lies at a wavelength between 400nm and 700nm.

PPFD: *Photosynthetic photon flux density*, another word for PAR.

Rep(s): *Replication(s)*. Refers to the number of repeated plots of treatments/ clones/ trial under study, i.e. different blocks.

$\boldsymbol{R_S}$: Broadband direct irradiance.

e: Radiation (conversion) use efficiency.

SLM: *Specific leaf mass*.

s: Solar energy received by plant/ crop/ canopy.

Thermal diffusivity (of soil): Thermal diffusivity is a composite parameter that indicates how fast temperature change occurs in soil subjected to a thermal gradient. Thermal properties of soil are dependent on material composition, fabric or packing arrangement, water content and temperature. Thermal conductivity is determined using a single probe method (needle probe thermal conductivity method), while heat capacity and thermal diffusivity are determined using a dual probe method (specific heat dual probe method).

Time lag: As used in soil temperature measurement is the number of days from an arbitrary starting date to the occurrence of the minimum temperature in a year.

TRIEA: Tea Research Institute of East Africa (TRIEA).

TRFK: Tea Research Foundation of Kenya, a government body mandated to carry out research on tea in Kenya.

W: As used in irradiance, stands for *Watts*.

Wm^{-2}: *Watts per square metre* (irradiation). This is a unit of measuring light energy.

ACKNOWLEDGEMENT

First and foremost, I sincerely thank my able supervisors - Prof. Wilson K. Ng'etich, Prof. Caleb O. Othieno and Prof. Patrick W. Mathenge for sparing a lot of their time to guide me through the project identification, data collection, drafting and thesis writing stages. I also thank the School of Agriculture and Biotechnology (SAB), University of Eldoret for quality teaching and academic guidance, and more so for the success of the entire study.

This study could not have been possible without the great guidance and assistance from the Tea Research Foundation of Kenya (TRFK) staff. More specifically, the following deserve special mention for the central role played in realization of the project's success: Dr. Wilson K. Ronno, Research Director (2004 - April 2009), who granted my request in 2007 to carry out research on tea with the support of his staff; Prof. Wilson K. Ng'etich (Head of Crop Environment Department upto 2007) who played a lead role in identifying the research area, providing relevant published journals and identifying the tools and sites to use in the research problem.

Upon setting up the project at Kipkebe, Kangaita and Timbilil sites, the TRFK field officers offered great assistance while collecting data on radiation, yield, rainfall and temperature. S. Lang'at (Kipkebe 2007), C. Nyakundi (Kipkebe (2008-2009), R. Koske (TRFK Headquarters), S. Njuguna (Kangaita, 2007-2008), P. Ayiemba (Kangaita), S. Mutembei (Kangaita), M. Chelangat and R. Ng'eno (library) are some of the field officers who supported me during this process. As I followed-up on the project at the TRFK Head Office, the following senior officers came in handy: Mr. Wilson Chirchir (Finance & Administration Manager upto 2010), Dr. John Wanyoko (HOD Chemistry), Dr. John Bore (Deputy Director), Dr. D. M. Kamau (Kangaita, currently based at TRFK HQs), Mr. K. Nyabundi (Kangaita, now at TRFK Headquarters) and Dr. S. Kamunya (HOD Botany). My gratitude will not be complete without acknowledging my employer's contribution to this project. Despite the strict book-publishing submission deadlines and other demanding office duties expected of me, the Jomo Kenyatta Foundation management granted me permission to attend coursework and visit research sites to collect data. My wife, children, my mother and other family members for sacrices made, facilitation, patience and encouragement. Ultimately, I thank the Almighty God for His Guidance, and specifically for giving me good health, knowledge, strength and resources to carry out this study successfully. I am deeply grateful.

CHAPTER ONE

INTRODUCTION

1.1 Economic Importance of Tea

Tea beverage is manufactured from the tender leaves and buds of the evergreen shrub *Camellia sinensis* (L.) O. Kuntze (Muthumania *et al*., 2013). It is a rural-based agricultural enterprise which is the leading cash crop in Kenya, making significant contribution to the economy (Bandyopadhyay, 2011). As a labour intensive industry, it employs over four million Kenyans (about 10% of total population) living in the rural settings directly and indirectly by empowering them economically all-year round (Tea Board of Kenya, 2012; Onduru *et al.*, 2012; Tea Research Foundation of Kenya, 2011) and is currently the single largest export commodity, accounting for about 26% of the country's total export earnings (Kilel *et al*., 2013). Kenya is the third largest producer of tea (displacing Sri Lanka), after India and China and largest exporter of black tea in the world, supplying 22% of the world's black tea (Kilel *et al*., 2013) with smallholder production accounting for about 66% of total tea production (378 million kilograms in 2011) (Onduru *et al.*, 2012). Black tea represents the majority of tea traded internationally and takes about 80% of global tea market (Tanui *et al*., 2012). In 2012, tea earned the country US$ 1.24 billion in foreign exchange from 429.6 million kg exported (Tea Board of Kenya, 2013) and contributes about 2.4% of Gross Domestic Product (GDP) (Kilel *et al*., 2013; Food and Agricultural Organisation, 2012 and Onduru *et al*., 2012). Tea contributes directly to the objectives of the Economic Recovery Strategy (ERS) as a rural-based enterprise. It also impacts positively on gender empowerment with 50% of all labour being women (Tea Research Foundation of Kenya, 2011). Additionally, it continues to contribute to the overall growth of agriculture in line with the Agricultural Sector Development Strategy (ASDS): 2010-2020 (Government of Kenya, 2010; Government of Kenya, 2008). The crop also contributes significantly to the development of rural infrastructure (Food and Agricultural Organisation, 2012) and curbs rural-urban migration (Tea Research Foundation of Kenya, 2011). More importantly, it contributes significantly to environmental conservation through enhanced water infiltration, reduced surface erosion, and mitigation of global warming through carbon sequestration (Tea Research Foundation of Kenya, 2010b).

1.2 Origin and Distribution of Tea

1.2.1. Centres of origin of tea

Tea is an evergreen, perennial understorey shrub cultivated for its actively growing young shoots that are used in the manufacture of tea beverage. It is a highly out-crossing and self-incompatible crop (Kamunya *et al.*, 2012) and follows the C_3 pathway of photosynthetic system in carbon dioxide assimilation (Satyanarayana, 1994). Tea is the most important crop species in the genus *Camellia*, and over 200 species have been reported (Kamunya *et al.*, 2012). Tea crop is thought to have originated from the fan-shaped area extending from the region bordering Assam (state at the extreme north-eastern part of India), North Myanmar (formerly Burma - a country in South-East Asia on the Bay of Bengal and Andaman Sea), Southwestern part of China (since pre-historic times) and Tibet (Kamunya *et al.*, 2012; Barua, 1989). These are areas of monsoon climate with warm, wet summers and cool, dry (less wet) winters. From the main centres of cultivation in South East Asia, tea has been introduced into many areas of the world with diverse climatic conditions (Carr and Stephens, 1992; Kamau, 2008).

1.2.2. History of tea growing in Africa

The first tea plant was grown in the Cape of Good Hope in South Africa in 1687 (Kamunya *et al.*, 2012). It was not until the second half of the 19th century that actual planting on the African continent in the surrounding areas of Durban (Kamunya *et al.*, 2012). It was then planted near Blantyre, Malawi, in 1878 with good results. This elicited a commercial tea growing venture that commenced in 1891 at Malanje, Malawi. Successful tea growing in Malawi resulted in its spread to Mozambique, Zimbabwe and Tanzania during the 1920s (Kamunya *et al.*, 2012). There are no reports, however, regarding the source of planting materials in these countries (Anon, 1962).

Tea was first introduced into Kenya in 1903 by the Caine brothers using open pollinated variety (OPV) seeds from Assam. In 1905, a plantation was established at Limuru (Kamunya *et al*., 2012; *http://www.tearesearch.or.ke*, 2010). The seedlings raised here were then distributed to other regions of the country, notably the highlands west of the Rift Valley province and Mt. Kenya region (Figs. 3.1 and 3.2). Being highly self-incompatible and predominantly out-crossing, tea tends to produce highly heterogeneous progenies. The early introductions were therefore highly variable forming the initial populations of mixed genotypes. Uniformity and stability in yield and quality of the mixed genotypes could not be maintained, hence the search for more uniform high yielding tea cultivars commenced in earnest (*http://www.tearesearch.or.ke*, 2010).

Commercial estate farming started in 1924. The early industry was dominated by European colonial settlers who were the only ones with access to germplasm. Moreover, the colonial government did not allow African peasants to grow cash crops until 1937 when commercial maize cultivation was liberalized, followed by cotton (M'Imwere, 1997). It was not until the 1950s when smallholder cultivation started. In 1960, the Special Crops Development Authority (SCDA) was established to promote the cultivation of tea within the smallholder agricultural sub-sector. This latter evolved to become the Kenya Tea Development Authority (KTDA), whose major task was to facilitate the expansion of tea cultivation into native lands (Wachira, 2002). The first set of clones was released in 1964 (*http://www.tearesearch.or.ke*, 2010).

The industry is structured into two major sub-sectors: the large estate and small holder subsectors. The latter subsector, with average holdings ranging from less than one hectare to twenty hectares, accounts for about 66% of the total area under the crop and 60% of the total production (Tea Research Foundation - Strategic Plan, 2011). Due to the perennial nature of tea plant, leaves are harvested almost throughout the year (Muthumania *et al.*, 2013). Tea ranks second after water as the most consumed liquid worldwide and plays central role in human health (Cheruiyot, 2008), and is popularly consumed either as a green (non-fermented), white, yellow or Oolong (semi-fermented), black or dark (full-fermented) (Kamunya *et al*., 2012).

1.2.3. Climatic factors affecting tea production

The tea plant grows in a variety of climates/ soils and has wide ecological amplitude in various parts of the world (Waheed *et al*., 2013). It is therefore difficult to specify the ideal climate tea requires for good growth especially with regards to most of the meteorological parameters (Bhagat *et al*., 2010). At present, tea is grown in latitudes ranging from the equator to 33^{O}S (Natal, South Africa) and 49^{O}N (Georgia, USA); between sea level (Bangladesh) to 2600 m.a.s.l. (Mt. Kenya region). The climates in these altitudes and latitudes range from mediterranean to hot, humid tropics (Ng'etich, 1995; Carr and Stephens, 1992). It is mainly grown in prime agricultural and forest land and can be in production for upto 100 years if well managed (Tea Growers Handbook, 2002; Kamau, 2008).

(a) Rainfall

Tea production is mainly dependent on the amount of rainfall received and its distribution (Waheed *et al*., 2013). Tea plant is affected by both excess and shortage of water as its growth, development and yield depend on the soil moisture status (Bhagat *et al*., 2010). For tea crop to become commercially viable, an annual rainfall of 2500-3000 mm is considered optimal, with a minimum of 1200 mm (Waheed *et al*., 2013; Tea Growers Handbook, 2002 and Bhagat *et al*., 2010). Commercial tea growing in Kenya covers areas with altitudes ranging from 1600 to 2600 metres above sea level with average annual rainfall between 1300 mm and 2200 mm (Food and Agricultural Organisation, 2012; Tea Growers Handbook, 2002). In 2006, there was a 5.46% decline in tea yield in Kenya (310,578 tons made tea) compared to the previous year (328,498 tons made tea) due to soil water deficit and hail incidences (Tea Research Foundation of Kenya, 2006).

(b) Soil and air temperature

Soil temperature in many instances is of greater significance to plant life than air temperature (Tea Growers Handbook, 2002), as it affects growth of root system components, initiation and branching, orientation and direction of growth, and root turnover (Bhagat *et al*., 2010). The optimum soil temperature within feeder root depth of the soil is 20-25^{O}C (Tea Growers Handbook, 2002). Minimum and maximum atmospheric temperature is $13^{O}C$ and $30^{O}C$ respectively (Waheed *et al*., 2013; Food and Agricultural Organisation, 2012; Tea Growers Handbook, 2002 and Bhagat *et al*., 2010).

(c) Solar radiation

Light, water and nutrition are the major environmental factors affecting photosynthesis of tea (Bhagat *et al*., 2010). Radiation is important because it raises the average temperature for the day (Bhagat *et al*., 2010). Total radiation (direct & diffuse), measured in Wm^{-2}, is composed of wavelengths while PAR (400-700 nm) is a section of total radiation (Jones, 1992).

(d) Edaphic factors

These areas are characterised by heavily leached acidic soils with pH ranging from 4.0 to 5.5 (Food and Agricultural Organisation, 2012), mainly of volcanic origin, that normally contains low available nitrogen, phosphorus low base nutrients and high aluminium and manganese contents (Tea Growers Handbook, 2002).

1.2.4. Canopy characteristics in light interception

Plant canopy, whose main purpose is to absorb solar radiation to power photosynthesis (Huemmrich, 2013), is the spatial arrangement of the above-ground organs of plants in a plant community (Campbell and Norman, 1989). The shape of the crown and the arrangement of its foliage are the two most basic parameters affecting the light capture efficiency of plants (Valladares and Pearcy, 2000). The arrangement and quantity of the leaves influence how well light penetrates the canopy, affecting the distribution of light to the leaves. For maximum tea clonal output to be realized, an environmental factor like radiation is the key contributory factor (Huemmrich, 2013).

1.3 Genetic Improvement of Tea in Kenya

Early settlers introduced pioneer seedling germplasm in Kenya obtained from seed extracted from a limited number of countries since tea was not all that widespread. Just as in other African countries where tea was introduced, pioneer tea plantations comprised seedling tea types mainly from the descendants of the Manipuri hybrid seed, which later formed the base populations from which jat selections (i.e. improved seed populations) were made. The seed used to establish these plantations largely comprised of random natural OPVs between the Assam and China varieties (Tea Research Foundation of Kenya, 2005). The seedling germplasm was heterogeneous due to natural outcrossing (M'Imwere, 1997). Seedling tea however lacked uniformity in yield and optimal quality attributes as it was raised from unimproved mixed seeds. The seedling types are commonly referred to as '*jats*' depending on the origin or seed orchard. This heterogeneity resulted in a great variation in yield, quality and suitability for fermentation. The focus thereafter shifted to yield as the main selection criteria (Green, 1971). This led to the early planters in Kenya to visually select *jats* akin to assamica (Assam) varieties within the seedling populations on the basis of vigour, plucking point density and large shoot size, and use them as seed bearers. This marked the beginning of unplanned, though deliberate step towards development of improved seed populations. Early breeders therefore, were able to select seed parents, which, to them, possessed outstanding attributes. Selected '*jats*' later became the seed bearers (progenitors) used to raise future seedling populations by open pollination. This breeding approach resulted in slow progress in yield and black tea quality improvement even though the later generations of seedling populations were much better than the ancestral pioneer stocks. In addition, initial selection was biased towards yield with little attention being accorded other attributes such as black tea quality and resistance/tolerance to biotic and abiotic stress factors (Kamunya, 2012).

Later, discovery of single-whole leaf cuttings as the fastest method of establishing uniform and high yielding and quality cultivars led to rapid expansion of tea cultivation in small holder subsector (Kamunya, 2012). Research in vegetative propagation started in 1951 with the development of clonal teas and suitable methods of vegetative propagation, i.e. cuttings obtained from a mother bush in the field and carefully tended in special nursery beds until they are 12 - 28 months old. The mother bushes were selected according to well-defined criteria, notably homogeneity, vigour of the bush, density and regular distribution of the shoots on the plucking table, weight of the shoots, suitability for fermentation and manufacture, suitability for propagation by cuttings, tolerance to drought and pests (Kamunya *et al.*, 2012; Bandyopadhyay, 2011).

The initial selections were based on similarity to the Assam varieties, vigour, density of plucking points and shoot size. Clonal tea was introduced in which vegetative propagation from one parent material was done to form many genetically identical plants. The clones selected for high yields, were compared mainly to seedling tea, and later (after 1964) clone TRFK 6/8 for quality (*http://www.tearesearch.or.ke*, 2010). So far, more than 500 tea cultivars have been bred and released to the public in China, India, Sri Lanka, Kenya, Japan, Bangladesh Indonesia, and some other countries (Kamunya *et al*., 2012). Approximately half of the world tea acreage consists of clonal tea gardens. In East Africa, maximum yields of released cultivars vary significantly from 3 t ha^{-1} for the unselected seedling types (Wachira, 2001) to 11 t ha^{-1} for clone AHP S15/10 (Oyamo, 1992), while those in Central Africa show a much smaller range between the seedlings (4.2 t ha^{-1}) and clone cultivars - SFS 204 (5.8 t ha^{-1}) (Ellis, 1978). The cultivars released in India (Bezbaruah, 1988) and Sri-Lanka (Shanmugarajah, 1999) showed a maximum yield of about 3 tha^{-1}.

Although Kenya was ranked third in the 2011 tea production after China and India, the country has the highest productivity (2,500 kg mt/ha/y) compared to other major tea growing regions worldwide, i.e. India (1,650 kg mt/ha/y), Sri Lanka (1,600 kg mt/ha/y) and Indonesia (900 kg mt/ha/y) (Tea Board of Kenya, 2012). This is attributable to deployment of appropriate Research and Development technologies in the production value chain. Of these technologies, use of improved vegetatively propagated tea cultivars is the most important, without which application of optimal agronomic inputs like fertilizer and harvesting practices would be futile (Kamunya, 2012).

1.4 The Global Tea Production

Tea is produced in over 20 countries with major producers being India, China, Kenya, Sri Lanka, Vietnam, Turkey, Indonesia, Iran, Georgia, Japan, Bangladesh, Argentina, Malawi, Uganda and Tanzania (Bandyopadhyay, 2011; International Tea Committee, 2009). The 2009 statistics of the International Tea Committee showed that 2008 global production stood at 3.8 million metric tons, up from 2.9 million metric tons in

1999 (Table 1.1). The world plantation coverage has risen to 140 million hectares in 2008, up from 108 million hectares in 1993 (International Tea Committee, 2009 and Cheruiyot, 2008).

In the 2010, global tea production reached 4.16 billion kg for the first time ever. This increase was largely due to consistent expansion of cultivated land and replacement of low yielding bushes with high yielding varieties in China (contributed 1.47 billion kg), combined with significant crop recoveries in Kenya (399 million kg) and Sri Lanka (331 million kg). India produced 966 million kg over the same period (International Tea Committee, 2011).

Black tea continued to be the most predominantly produced tea in the world. Out of the total tea output of 4.16 billion kg recorded in 2010, about 60% (2.51 million kg) was black tea, 31% (1.28 billion kg) green tea and 9% (366 million kg) other teas (International Tea Committee, 2011).

World production of tea has been rising in the last 10 years (Table 1.1 in the next page). The continental data was obtained from major producing countries.

Table 1.1: World production of tea in thousand metric tons (mt) and percentage share of world production, 1999-2008

Continent		World Production of Tea - '000 Metric Tons (mt) and % Share per Continent									
		1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**
Asia	**mt**	2,444	2,436	2,500	2,532	2,647	2,739	2,864	2,982	3,077	3,187
	%	82.8	83.2	81.8	82.0	82.1	81.9	82.7	83.3	82.1	83.8
Africa	**mt**	401	400	467	462	477	506	488	483	559	518
	%	13.6	13.6	15.1	14.9	14.9	15.2	14.1	13.5	14.9	13.6
CIS	**mt**	18	9	9	9	9	8	7	8	9	9
	%	0.6	0.3	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2
South America	**mt**	78	76	76	76	77	74	90	98	97	92
	%	2.7	2.6	2.5	2.5	2.4	2.3	2.6	2.8	2.6	2.2
Oceania & Others	**mt**	8	8	7	8	8	8	8	8	8	8
	%	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.2
Grand Total	mt	2,949	2,929	3,059	3,086	3,217	3,335	3,458	3,580	3,751	3,804
	%	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

(Source: The International Tea Committee, Annual Bulletin of Statistics 2009).

Key:

(a) **CIS** (Commonwealth of Independent States) made up tea producing countries: *Azerbhaijan*, *Georgia* and *Russia Federation*. CIS is a confederation of independent states that were formerly constituent republics of the Soviet Union, established in 1991. Member states are Armenia, Belarus, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan.

(b) **Oceania**: *Australia* and *Papua New Guinea*.

From Table 1.1, developing countries in Africa and Latin America have experienced fluctuation in tea production owing to the economic recession experienced globally in mid 2000's. This crunch resulted in downward trend in market share resulting in unfavourable trading terms by tea buyers in Europe, Middle East and America. Other factors that may have contributed to downward trend are uprooting and abandoning of the crop by smallholder farmers for other crops and land uses. Argentina is a major producer of tea in Latin America, contributing an average of 2.3% of world market share, while the remaining 0.2% is taken by others in that continent (International Tea Committee, 2009).

China continued to be the world's leading tea producer in 2010 accounting for 34% of the global tea supply. Other key producers were India (24%), Kenya (10%) and Sri Lanka (8%) (Fig. 1.1) (International Tea Committee, 2011).

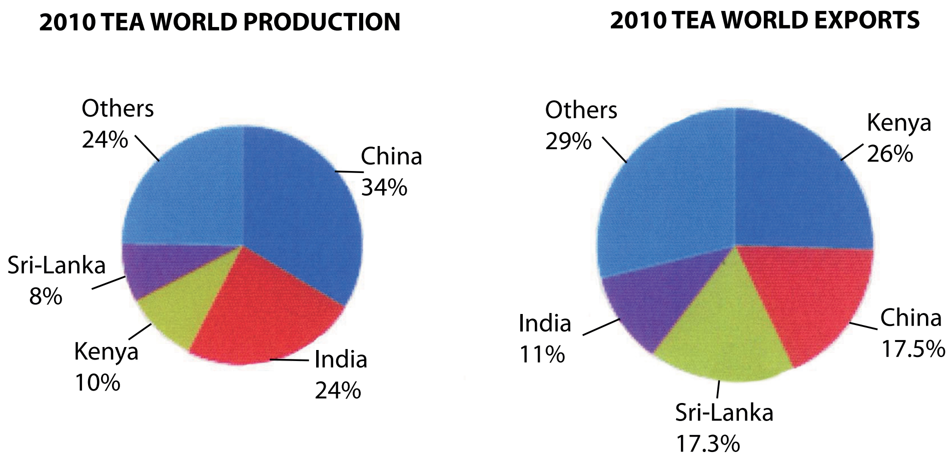


Fig. 1.1: World tea production and exports in the year 2010 (Source: International Tea Committee, 2011).

1.5 Tea Production in Kenya

Kenyan tea sector is divided into two main sectors: the large scale/ estate sector made up of multinational and local companies and the smallholder sector. The two sectors produced a total of 377.9 million kg in 2011. Out of this figure, the smallholder sub-sector contributed 58% (218.5 million kg), while the plantation sub-sector yielded 42% (159.4 million kg) (Tea Board of Kenya, 2012).

In 2011, most tea growing regions experienced depressed and poorly distributed rainfall during the second quarter besides relatively hot and dry weather conditions in the first quarter. However, compared to the last five years, production for 2011 was higher than the output recorded in 2007 to 2009, as given in Fig. 1.2 (Tea Board of Kenya, 2012).

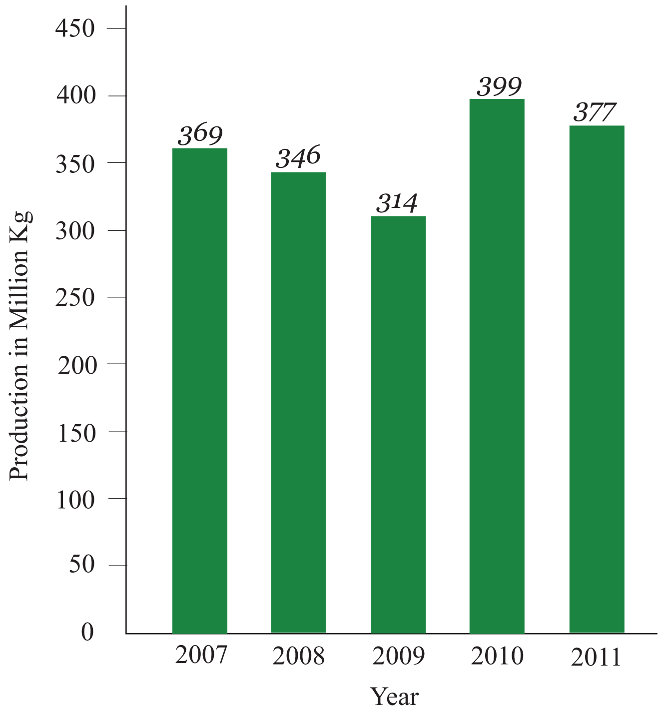


Fig. 1.2: Kenya tea production trend, 2007-2011 (Source: Tea Board of Kenya, 2012).

The Kenyan area under tea crop progressively shot up by over 39,000 ha between 1999 and 2008 (International Tea Committee, 2009). This explains why Kenya's tea production rose by a margin close to 100,000 metric tons over the same period, from 248,709 metric tons in 1999 to 345,817 metric tons in 2008. It is from this huge increase in tea planted area (hence production) that Kenya moved from rank 4 in production in 1999 (after India, China and Sri Lanka) to third place, having overtaken Sri Lanka in 2004 and 2007. In 2011, it was the third largest tea producer globally (Tea Board of Kenya, 2012).

In Kenya, tea is produced in the East and Western parts of the Rift, along the equator, as shown in Fig. 1.3. Specifically, the tea growing areas in Kenya at present are in the following Counties: Bomet, Embu, Kakamega, Kericho, Kiambu, Kirinyaga, Kisii, Meru, Murang'a, Nakuru, Nandi, Nithi, Nyamira, Nyeri, Trans Nzoia and Vihiga (Food and Agricultural Organisation, 2012 and CIAT, 2011).

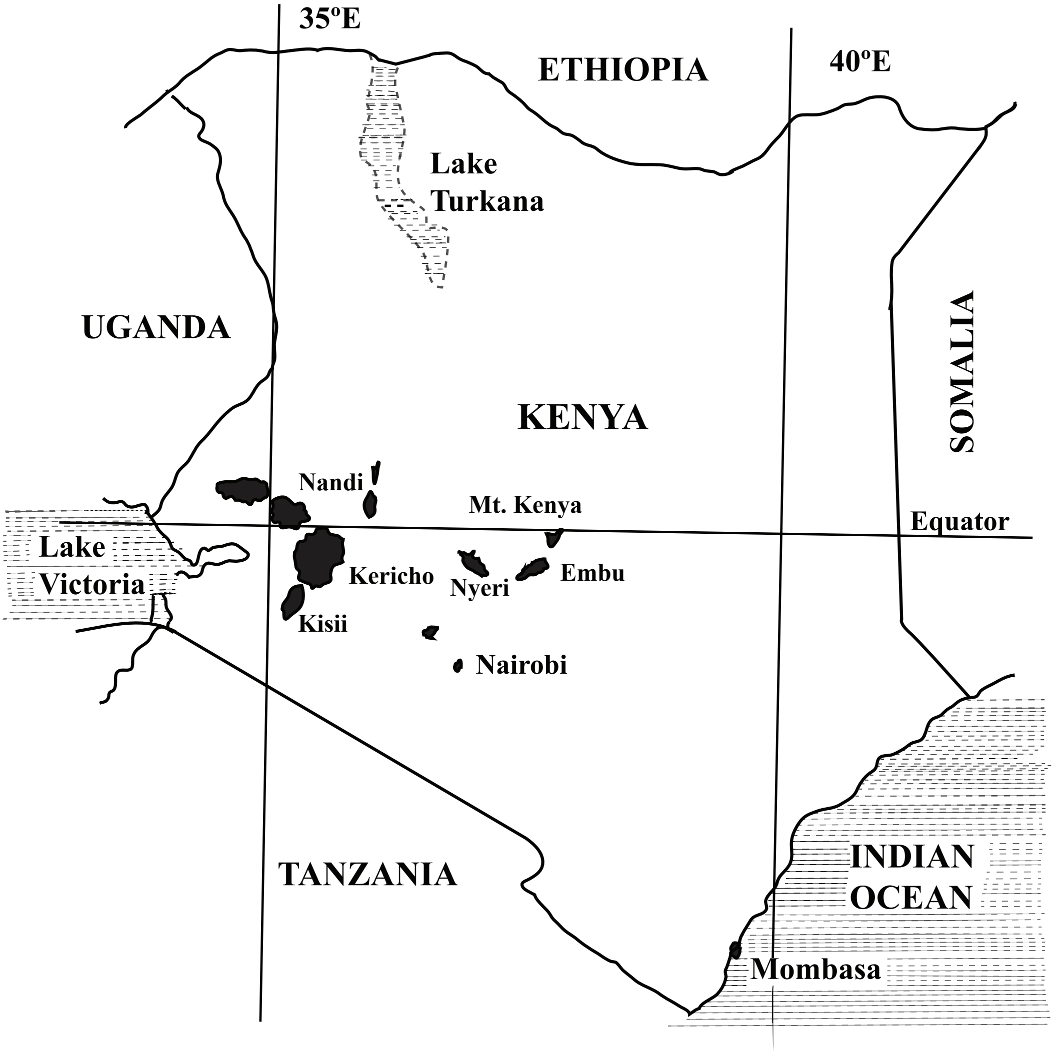


Fig.1.3: Map of tea growing areas (painted black) in Kenya.

1.6 Tea Export in Kenya

Tea is the most popular (Bandyopadhyay, 2011) and affordable beverage globally (Onduru *et al*., 2012). It is second to water worldwide as the most consumed liquid, and is rapidly assuming a significant role in human health (Cheruiyot, 2008). It is on this basis that in the year 2010, Kenya remained the leading exporter of tea accounting for 26% of world exports (Fig. 1.1). Other key exporters were China (17.5%), Sri Lanka (17.3%) and India (11%) (International Tea Committee, 2011).

Kenya is Africa's leading black tea exporter (International Tea Committee, 2009). In 2011, Kenya tea export volume reached 421 million kg, which was slightly lower compared to 441 million mgs recorded in the year 2010. This tea was exported to 54 market destinations worldwide in 2011 compared to 48 destinations in 2010. Amongst Kenya's tea export markets, Pakistan was the leading export destination having imported 19.2% compared to Egypt's 19.0%. The reduced volume of tea to Egypt was largely attributed to political unrest within the country at the beginning of the year 2011. Political unrest also affected Kenya tea exports to Yemen, which recorded a drop of 9%. Other key export markets were UK (16.2%), Afghanistan (10.5%) and Sudan (6.2%). These five markets accounted for 71% of Kenya tea export volume while the other 49 markets accounted for 29% (Tea Board of Kenya, 2012).

Amid all these gains, the Ethical Tea Partnership report (2011) that predicts more than 10% temperature increase, averaging an additional 2.3^{O}C by 2050 may impact negatively on the impressive economic performance of tea and erode the positive gains made if studies reporting the effects of weather on tea yields in Africa is not diversified. Arising from this eminent temperature change, studies to evaluate G×E of tea clones was initiated.

1.7 Statement of the Problem

Limited information is available on work done on genotypes at different sites as the majority of research reporting the effects of weather on tea yields in Kenya has been carried at single sites only (Ng'etich *et al.*, 2001, Burgess, 1992; Carr and Stephens, 1992). The few that were done at different sites by Ng'etich (1995), Cheruiyot (2008) and Bore (2008) may need further follow-up to beef up on the G×E studies. Furthermore, information on the impact the total radiation has on the yield of tea (*Camellia sinensis*) genotypes is limited.

Soil water deficit of 217 mm in Kericho and Sotik areas coupled with a number of hail incidences in the west of the Rift Valley in 2006 resulted in a 5.46% decline in tea yields compared to the previous year (Tea Research Foundation of Kenya, 2006).

Investigations on the relationship between PAR and total solar radiation in other crops have been investigated in low altitude areas by Gonzalez and Calbo (2002); McCree (1972); Howell *et al.* (1983); Meek *et al.* (1984) and Moon (1940). None has, however, researched on this ratio on tea in the canopy-covered highland regions of Kenya.

Soil temperature, after soil water, is of greater ecological significance to plant life than air temperature, and there is evidence that soil temperature influences the growth of tea (Carr and Stephens, 1992), with major implications on yield (White *et al.*, 2009). Soil temperature estimation is, therefore, critical to the understanding of land surface-atmosphere interactions (Lakshmi *et al.*, 2003), as it affects most of the bio-physical processes occurring underground (Gorthi, 2011). This important area has not been given the research priority it deserves (Lal, 1979). Models on soil temperature estimation using air temperature have been carried out on bare grounds, in low altitude areas and in the sub-tropical regions only by Zheng *et al*. (1993); Hillel, (1982); Smith *et al.* (1998); Wu and Nofziger (1999), among others, but none has been done on canopy-covered highland regions of Kenya.

1.8 Justification of the Study

Tea is the leading cash crop in Kenya, and has a major impact on the economy. It is the single largest export commodity, accounting for about 20% of the total export earnings for the country. Export earnings rose from Sh. 112.2 billion in 2012 to Sh114.4 billion in 2013 (Tea Board of Kenya, 2014). The industry transformed lives of over four million Kenyans (about 10% of total population) living in the rural areas by empowering them economically. The crop contributes significantly to the development of rural infrastructure and curbs rural-urban migration (Tea Board of Kenya, 2012; Tea News, 2012; Tea Research Foundation of Kenya, 2011). It contributes directly to environmental conservation through enhanced water infiltration, reduced surface erosion, and mitigation of global warming through carbon sequestration (Ministry of Agriculture, 2007).

Owing to reported temperature changes which may impact negatively on performance of tea, these positive gains may be lost if studies reporting the effects of weather on tea yields in Kenya is not diversified. It is on the basis of significant role that tea contributes to Kenya's economy that the G×E evaluation of tea clones of the same age but planted at different agro-ecological sites was undertaken.

1.9 Objectives

The broad objective of this study was to determine the effects of critical environmental factors on clonal tea production at two sites in Kenya.

Specific objectives were to:

(i) Determine the total solar radiation, PAR and interception by different tea clones at two sites;

(ii) Determine the effects of rainfall, soil temperature, air temperature on clonal yield at each site.

1.10 Hypotheses

The following hypotheses were tested in this study:

H_1: Variations in environmental conditions (total solar radiation, PAR, rainfall, air and soil temperature) contribute to significant differences in yield among different tea clones in Kenya.

H_o: Variations in environmental conditions (total solar radiation, PAR, rainfall, air and soil temperature) do not contribute to significant differences in yield among different tea clones in Kenya.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Tea, *Camellia sinensis* (L.) belongs to the plant family Theaceae. There are three races of tea plant in the world that constitute the cultivated genetic pool: China, Assam and Cambod (Bandyopadhyay, 2011). Cultivated tea varieties are natural hybrids of the original tea species, *C. sinensis* (L.) O. Kuntze, *C. assamica* (Masters) and *C. assamica* sub-species *lasiocalyx* (Planchon ex Watt) (Mondal *et al.*, 2004). The tea plant in its wild state can grow upto 15 metres tall and has a taproot to oblique root system (Bonheure, 1990).

2.2 Types of Tea

It is generally considered that the existing populations of tea plants are largely derived from two original taxa, based on their origin and growth habits. These 2 categories are China and Assam teas. The third category is a hybrid between China and Assam varieties, and is called Cambod. Tea is highly a heterozygous, outcrossing crop and is strongly self-incompatible, with most of its morphological, physiological and biochemical descriptors showing continuous variation and high plasticity (Bandyopadhyay, 2011). The subsequent sexual generations from hybridization is, therefore, highly heterogyneous. Despite their heterogeneity, leaf pose angles and leaf macro-physiological features, including leaf colour, are used in identifying varieties and/or hybrids. Leaf, floral morphology and growth habits can be used to distinguish types (Mondal *et al.*, 2004).

2.2.1. China tea - *Camellia sinensis* var. *sinensis* [Linus]

The variety sinensis, also called china tea is a slow-growing, dwarf plant, with shrub-like appearance. It is thought to have been a shrub which originally grew in the open. It has small, erect and narrow, serrated, dark-green leaves. It has erectophile leaf pose with leaf angle less than 50^{O} (Willson and Clifford, 1992). It is thought to have originated from southern China. It is suitable for growing in marginal areas of the sub-tropics and is more drought tolerant, hence can survive short frost periods (Banerjee, 1992) (Fig. 2.1).

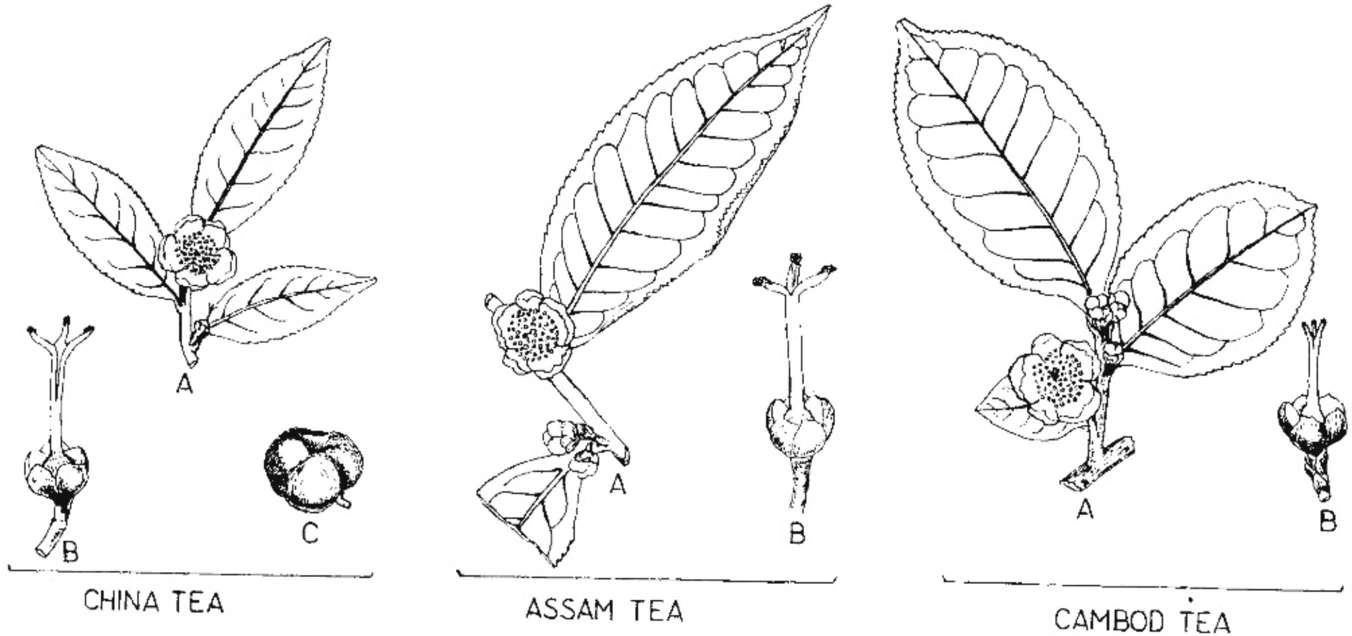


Fig. 2.1: Outline of China, Assam and Cambod tea varieties. A = Natural size of a flowering shoot; B = Pistil (x4); C = Natural size of a fruit (Source: Wilson and Clifford, 1992).

2.2.2. Assam tea - *Camellia sinensis* var. *assamica* [Masters] Kitamura

This is a fast growing, tall plant with features of a full tree. It is indigenous to north-eastern part of India called Assam and is thought to have evolved as under-storey tree in a forest environment. It is typified by large, horizontally held, broad, mostly non-serrated, light green leaves. It has a erectophile leaf angle more than 70^{O}. It is a tropical variety sensitive to dry and cold weather conditions (Banerjee, 1992). It is the predominant variety in Kenya due to its high yield (Willson and Clifford, 1992) (Fig. 2.1).

2.2.3. Cambod tea - *Camellia sinensis* var. *assamica* spp. *lasiocalyx* [Planchon ex Watt]

The Cambod tea type, also known as *Shan* tea, is a hybrid between China and Assam teas from Cambodia. It has semi-erect leaves. It is not commonly grown in Africa but mainly cultivated in Indonesia, Democratic Republic of Congo (DRC) and Reunion (Seurei *et al.*, 1997). Fig. 2.1 shows the main features of Cambod tea variety.

2.2.4. Clonal tea - *Camellia sinensis* var. *assamica* and var. *sinensis*

Clones are genetically identical plants and give uniform yield and quality (Bandyopadhyay, 2011). Kenya's tea germplasm is predominantly of the *C. sinensis* var. *assamica* type, and is highly diverse though many of the clones are genealogically related (Wachira *et al*., 2001). Genetic variability in tea is desirable because it provides a buffer against co-evolving factors of natural hazards like diseases, pests and changing environment (Bandyopadhyay, 2011). Mostly, clonals are bred to thrive in adverse tea growing locations, tolerate pest infestation or diseases and accounts for about 60% of all tea in Kenya (Kamunya *et al.*, 2012). In 2001, the first tea clones of var. *sinensis* tea genetic resources from Japan and China were introduced (Tea Research Foundation of Kenya, 2002). These have since been cloned and transplanted into field trials where they have established well (Kamunya *et al*. 2012). In 2003, TRFK imported clonal cuttings of 10 accessions of tea from Tanzania, namely TRIT 201/10, TRIT 201/16, TRIT 201/43, TRIT 201/44, TRIT 201/47, TRIT 201/50, TRIT 201/55, TRIT 201/73, TRIT 201/75, and TRIT 201/82 (Tea Research Foundation of Kenya, 2006). Introductions of seed from China in 2004 was cloned and used to develop improved green tea cultivars (Kamunya *et al.*, 2012). TRFK has developed over 1,000 improved clones, out of which 50 clones have been selected for consistent superiority in yield (some yielding 5 - 8 tons mt/ha/yr) and cup quality characters. These clones have been released for commercial exploitation by both smallholder and large estate growers (Tea News, 2012). The 4 genotypes (treatments) tested in this study are clones bred locally.

2.3 C_3, C_4 and CAM Photosynthesis

Three photosynthetic pathways exist among terrestrial plants: C_3, C_4 and crassulacean acid metabolism (CAM) photosynthesis (Ehleringer and Cerling, 2002). C_3 species, evergreen woody plants and perennial herbaceous plants (e.g. tea, rice, wheat, spinach, tomato, apple, peach and eucalyptus) represent approximately 85% of all higher plant species, while C_4 species, occuring primarily in monocotyledonous plants (e.g. maize, sugarcane and sorghum), account for about 5%. CAM species (e.g. pineapple, agave and cacti) make up the remaining 10% (Yamori *et al*., 2013 and Ehleringer and Cerling, 2002). In C_3 plants, the first product of photosynthesis is a 3-carbon molecule, while in C_4, initial photosynthetic product is a 4-carbon molecule (Hall, 2001). The enzyme responsible for the initial fixation of CO_2 in C_4 plants (PEP carboxylase) can exhibit much greater ability to fix CO_2 at ambient levels of CO_2 than the enzyme responsible for the initial fixation of CO_2 in C_3 plants (RuBP carboxylase or rubisco) (Hall, 2001). CAM occurs in many epiphytes and succulents from arid regions. The differentiation of two cell types, mesophyll cells (MC) and bundle sheath cells (BSC), is required for efficient C_4 photosynthesis. Thus, the leaves of C_4 plants have more complicated structural and functional features than those of C_3 plants (Hatch, 1999 and Ueno, 2001).

2.4 Tea Production Factors

The yield of harvestable shoots of tea shrub is affected mainly by the environmental factors (Muthumania *et al*., 2013). Adequate, well distributed rainfall, optimum soil and air temperature, sunshine hours and change of seasons greatly influences the performance of the tea crop (Bhagat *et al*., 2010).

2.4.1. Solar irradiance and PAR

Solar radiation is the primary driver of plant photosynthesis (White *et al*., 2009). Solar irradiance, R_{si}, includes both direct beam and diffuse shortwave radiation reaching the earth's surface; and is defined as the radiant energy reaching a horizontal plane at the earth's surface (Evett *et al.*, 1994).

Photosynthetically active radiation (PAR) is a small portion of the solar electromagnetic spectrum visible light spectrum, wavelength ranging from 0.36 to 0.7 μ, which actively participates and drives the process of photosynthesis (Kumar *et al*., 2008). PAR, usually defined as the waveband of blue and red region between 0.4 μ and 0.7 μ by majority of investigators (Jones, 1992), may be expressed on the basis of energy (Wm^{-2}) or as a stream of particles called quanta or photons (mol m^{-2} s^{-1}) (McCree, 1981). The concepts of units for the quantification of light is given in Table 2.1.

Table 2.1: Concepts of units of light

Media	**Energy system (Wm^{-2})**	**Photon system (mol m^{-2} s^{-1})**
Flat light sensor	Irradiance PAR, 400-700 nm, energy units	Photon irradiance PAR quantum units

Source: Taiz Lincoln and Zeiger Eduardo, 5th Edition 2010.

Direct solar radiation plays a critical role in dry matter production of a crop (Hall, 2001). Dry matter partitioning is the apportioning of the assimilates to the various plant organs and is influenced by all the main environmental factors and by genotype (Ng'etich, 1995). Partitioning of assimilates in different parts of plants (harvestable young leaves, branches, stem and roots) between treatments and sites were determined through measurement of radiation use efficiency (RUE) for dry matter output (g MJ^{-1}) (Kool *et al.*, 1996; Rong *et al.*, 1996). RUE is a crop specific parameter, and the efficiency of conversion of absorbed light into carbon varies with time, light intensity, temperature and water availability (Schapendonk *et al.*, 1998).

Tea requires at least 5 sunshine hours per day (Squire, 1977). Tea yield drops drastically under cloudy conditions and with heavy and continuous rainfall, just like it does when weather is hot, dry and sunny (Bhagat *et al.*, 2010). For solar radiations above 350 Wm^{-1}, Squire (1977) observed that single top leaves are photosynthetically light saturated while whole canopies require 700-800 Wm^{-1}, a value equivalent to full sunlight in the cooler seasons of many high altitude tea areas. The rate of photosynthesis depends on the rate of absorption of photons and not the rate of absorption of energy (Jones, 1992). Net solar energy is also required for increased leaf, air and water temperature; transpiration and increased respiration. Its net or gross is determined mainly by environmental factors, chiefly irradiance (Wm^{-2}), the availability of CO_2 and temperature (Jones, 1992).

Research has shown that clones differ in their response to air temperature through base temperature for shoot extension ($\boldsymbol{T_{be}}$). This factor can be exploited for cultivation of tea clones in suitable environments. Similarly, dry matter production and partition (hence yield) is dependent on both air and soil temperature. Plants growing in warm environments produce higher amounts of dry matter compared to those in cooler areas (Ng'etich, 2002).

2.4.2. Soil water and soil temperature

Soil moisture and soil temperature properties influence soil-plant relationships and serve as a determinant of the chemical, mechanical, and biological processes that occur in the soil (Cochran, 2010).

(a) Soil moisture content and its measurement

Soil moisture is defined as the amount of water level present in the top layers (10 cm) of the soil that interacts with the atmosphere through evaporation and transpiration (Kaleita *et al.*, 2003), whereas root zone soil moisture is the water that is available to plants, which is generally considered to be in the upper 200 cm of soil (*http://www.ghcc.msfc.nasa.gov*, 2011). Soil moisture is classified into three states: saturated (wet), moist, and dry (Soil Survey Staff, 1999). Saturated occurs when water is not held by the soil and flows freely through soil pores, usually associated with a water table. Moist occurs when water is held by the soil at tensions greater than 0 to less than 1500 kPa, where water moves down to a saturated substratum and can cause leaching of clay, carbonates, *etcetera*; and dry occurs when water is held at tensions greater than or equal to 1500 kPa. In a dry state, water in soil is not available to keep most mesophytic plants alive (Cochran, 2010).

The importance of soil water to crops include: (1) nutrient dissolution in the soil and solute absorption by plant roots; (2) effects on soil temperature, aeration and microbial activity; and (3) physiological processes in plant cells (maintaining cell turgidity and transport of solutes and photosynthates) (Mahilum, 2004).

The standard method of soil water content measurement involves taking a physical sample of the soil, weighing it before any water is lost. It is then dried for 48 hours in an oven at 105^{O}C to drive off all moisture and attain a constant particle weight. Thereafter, weight is taken again to determine mass of water in the soil (Walker *et al.*, 2004; Gardner, 1986). The mass of water lost on drying is a direct measure of the soil water content. This measure is normalized either by dividing by the oven-dry mass of the soil sample, or by converting the mass of water to a volume (by dividing the mass of water by the density of water) and dividing this volume of water by the volume of the sample. This method is standard and reliable but there are some problems to look out for if high accuracy is required (International Atomic Energy Agency, 2008). The other standard method of measuring soil moisture content is the thermogravimetric method, which requires oven drying of a known volume of soil at 105^{O}C and determining the weight loss. This method is time consuming and destructive to the sampled soil, meaning that it cannot be used for repetitive measurements at the same location. However, it is indispensable as a standard method for calibration and evaluation purposes (Walker *et al.*, 2004).

(b) Soil factors and measurements

There is a higher correlation between soil and air temperatures than with humidity, precipitation, wind speed and solar radiation (Salamene *et al.*, 2010). However the correlation between soil and air temperature reduced with increased soil depth. This behaviour is expected, since the air is in direct contact with the soil surface (Salamene *et al*., 2010). In a study carried out at a site having summer mean air temperature of 14.1^{O}C, Smith *et al*. (1998) reported annual mean air temperatures of (2.0-2.5)^{O}C below soil temperatures at 50 cm, and and a range of 1.0-2.0 ^{O}C below soil temperatures at 150 cm.

Successful prediction of soil temperature with the help of air temperature minimizes time, cost, and equipment maintenance necessary for on-site monitoring of the same and will help researchers to use data from other sources (Ahmad and Rasul, 2008). Soil temperature fluctuates annually and daily, mainly affected by variations in air temperature and solar radiation. The annual variation of daily average soil temperature at different depths can be estimated using a sinusoidal function presented as *Eq. 2.2* (Hillel, 1982; Marshall and Holmes, 1988; Wu and Nofziger, 1999).

(c) Soil temperature measurement models

Soil temperature greatly affects most of the bio-physical processes occurring underground as it plays an important role during the life cycle of the plants right from germination, root extension, emergence to the reproductive stage (Ahmad and Rasul*,* 2008). A significant relationship exists between averaged daily air temperature and observed daily soil temperature at 10 cm depth (Zheng *et al.,* 1993).

While carrying out a study on thermal homogeneity of soil at Kericho in which tea was grown under different mulch treatments on bare and thin soil covers, Stigter *et al.* (1984) showed that temperatures at any depth within differently coloured homogeneous soils with identical or low evaporation are related to each other via the ratio given in *Eq. 2.1*.

$$R = \frac{1-\rho_1}{1-\rho_2} = \frac{\theta_1(z,\,t) - \theta_{1z}}{\theta_1(z,\,t) - \theta_{2z}} \qquad \textit{Eq. 2.1}$$

Where R is the ratio (soil temperature), t = time, ρ (rho) being the reflection coefficient for solar radiation of the respective soils, $\theta(z,t)$ (theta) the temperature pattern at depth

z and θ_z the average temperature at that depth. The applicability of this equation was to facilitate interpretation and forecasting of soil temperature patterns. For the underlying theory to be valid, the soil should be thermally homogenous with respect to thermal properties, and θ should approximately be constant with depth or be a linear function of depth (Stigter *et al.* 1984).

In a separate study, Hillel (1982) developed sinusoidal function, which used the annual variation of daily average soil temperature at different depths to estimate soil temperature. He described the annual variation of daily average soil temperature at different depths with the following sinusoidal function:

$$T(z,t) = T_a + A_o e^{-z/d} \sin\left[\frac{2\pi\,(t - t_o)}{365} - \frac{z}{d} - \frac{\pi}{2}\right] \qquad \textit{Eq. 2.2}$$

Where $T(z,t)$ = soil temperature at time t (d) and depth z (m);

T_a = the average soil temperature (^oC);

A_o = the annual amplitude of the surface soil temperature (^oC);

d = the damping depth (m) of annual fluctuation and t_o is the time lag (days) from an arbitrary starting date (taken as January 1) to the occurrence of the minimum temperature in a year. The damping depth is defined by the formula:

$$d = \sqrt{\frac{2D_T}{\omega}}$$

where D_T = thermal diffusivity; and $\omega = 2\pi/365\ d^{-1}$.

Assumptions employed in the derivation of the temperature model were:

1. A sinusoidal temperature variation at the soil surface z = 0. That is

$$T(o,t) = T_a + A_o \sin\left[\frac{2\pi\,(t - t_o)}{365}\right] \qquad \textit{Eq. 2.3}$$

where T_o is the average soil temperature, A_o is the amplitude of the annual temperature function, t_o a time lag from an arbitrary starting date (e.g. Jan. 1) to the occurrence of the minimum temperature in a year.

2. At infinite depth, the soil temperature is constant and is equal to the average soil temperature.
3. The thermal diffusivity is constant throughout the soil profile and throughout the year.

During daytime, surface soil is warmer (longer amplitude) than the sub-horizon due to its more direct exposure to solar radiation. At a depth of 50 cm and below, soil temperature tends to be constant and is much lower (shorter amplitude) than that of the surface horizon (Mahilum, 2004). Fig. 2.2 demonstrates the relationship between the amplitude and the temperature.

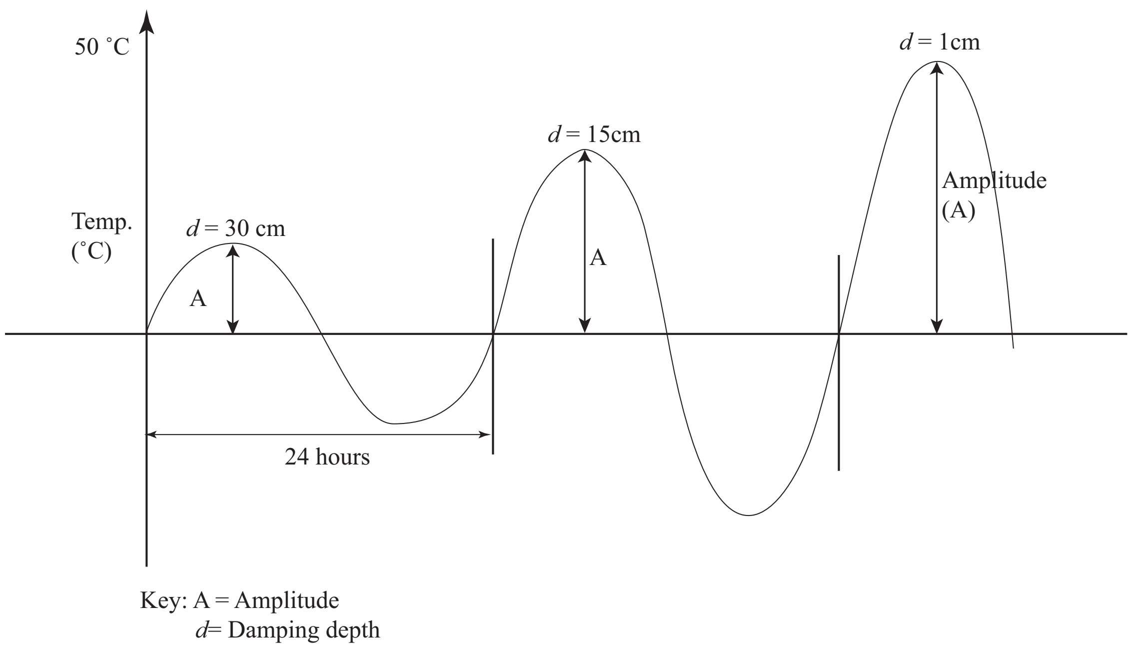


Fig. 2.2: Temperature highest at soil surface, damping increasing with depth.

Upon repeated measurements of air and soil temperatures using sinusoidal function, Wu and Nofziger (1999) affirmed that air temperatures can be used to estimate soil temperatures. The model consistently under-estimates soil temperatures by about 2^{O}C on bare soils. The correction for soils that are not bare will likely be less since those soil temperatures are somewhat less due to shading from the plants (Hillel, 1982).

2.5 Partitioning of DM, Yield, Altitude, Harvest Index and Temperature

Yields of crops are determined mainly by the strength of the sources and sinks (source-limited or sink-limited) (Muthumania *et al*., 2013). All leaves on a plant undergo a transition from a sink (a net carbon importer) to a source (a net carbon exporter) during their development. The early growth of a leaf is supported by carbohydrate imported from other sources in the plant. These sources are usually other mature leaves or photosynthetic organs on the plant, or in the case of a seedling, the cotyledons. As the lamina expands and the leaf matures, levels of photosynthesis increase until the leaf can support itself. When the amount of carbon accumulated by photosynthesis is greater than the requirement of respiration and growth, a positive carbon balance is achieved by that leaf. The leaf then becomes an exporter of carbon (Roberts *et al*., 1999). Studies on tea in Kenya and elsewhere suggest temperature is more likely to affect the yield by influencing the size of the sink for assimilate than photosynthesis or stored carbohydrate (Squire *et al*., 1993). The main components of the tea shoot sink are the mean shoot mass (related to length of shoot) and the number of shoots plucked (Tanton, 1979).

The yield of harvestable shoots is affected mainly by the environmental factors (Muthumania *et al*., 2013). In the past, attempts were made to correlate photosynthesis and associated factors (radiation interception, canopy light interception, leaf area index and base temperatures) with crop yield, using unharvested tea bushes as controls (Squire, 1977). Unlike many source-limited vegetative crops, tea growth is sink-limited (Tanton, 1979). Thus, yield is determined by the growth characteristics of the shoots in terms of the rate of extension, mass and number per unit area and factors that influence them (Matthews and Stephens, 1998).

Tea yields of 1-4 t ha^{-1} y^{-1} of dry shoot tips, which is similar to that produced by latex rubber, are much less than that of other vegetative crops like grasslands or forests growing in similar conditions, e.g. cassava growing at 1500 - 2000 m.a.s.l. yields 10-20 t ha^{-1} y^{-1}. As a C_3 plant, tea is less productive compared with crops that go through the C_4 carbon assimilation pathway (Satyanarayana, 1994). This low production phenomena is partly because plucking restricts tea biomass production, but mainly because the harvest index (***i***) of tea is small (Magambo and Cannell, 1981). Earlier investigators reported ***i*** of tea to vary from 7.5 to 12.5, but Ng'etich (1995) found ***i*** for clone AHP S15/10 to be 37 %. The high ***i*** for clone S15/10 was mainly associated to equally high yield of 11 t ha^{-1} y^{-1} and 95 % light interception reported by Oyamo (1992) and Ng'etich (1995).

The yield potential of any crop is determined by the climate and its day-to-day variation i.e. weather (Carr and Stephens, 1992). Climate refers to the statistics of weather, i.e. a measure of the average pattern of variation in temperature, precipitation, cloudiness, humidity, atmospheric pressure, atmospheric particle count, wind and other meteorological variables in a given region for a period of over 30 years. Weather is the fluctuating state of the atmosphere in a given region at a specific point in time (World Meteorological Organization, 2013). Climate determines where a crop is grown and the yield potential. When the nutrients are not limiting, the important weather variables are: solar radiation, temperature, saturation deficit of the air and soil water availability. The three principal growth processes affected in all crops are: (a) expansion of the leaves (crop canopy), shoots and roots; (b) production and storage of dry matter, mainly carbohydrates, and (c) partitioning of the dry matter between the various plant organs (leaves, stems, shoots, flowers, fruits, roots) (Carr and Stephens, 1992).

Several environmental factors influence the growth and yield of tea, with those associated with altitude expressing greatest importance not only in Kenya, but also in many parts of the world (Squire *et al.*, 1993). In Kericho, for instance, it has been found that the yield of made tea from seedling varieties habitually decreased by 200 to 300 kg ha^{-1} for each 100 m rise in altitude. There is a strong evidence that some clones are more sensitive to altitude than others, probably due to systematic change in temperature (Obaga *et al.*, 1989; Squire *et al.*, 1993).

2.5.1. Temperature and solar radiation

When other factors such as dry air and soil nutrients are not limiting, the rate at which tea flushes is largely controlled by temperature. Tea will grow under a wide range of temperatures provided that frost does not occur. Different researchers report different ranges for optimum temperatures, i.e. while Tanton (1982a) gives the optimum range of 18-20^{O}C, Carr and Stephens (1992) have a wider range of 18-30^{O}C. There is a ***base*** (minimum) temperature for shoot ***extension*** ($\boldsymbol{T_{be}}$), i.e. unfolding of leaves (12-13^{O}C for most tea cultivars), below which the rates of growth (shoot expansion) are very slow, and the ***optimum*** temperature ($\boldsymbol{T_{oe}}$), [18-30^{O}C as given by Carr and Stephens (1992)], above which growth rates decline reaching zero at ***maximum*** temperature ($\boldsymbol{T_{me}}$).

Further work done by Stephens and Carr (1993) in Ngwazi Tea Research Unit, southern Tanzania afirms that $\boldsymbol{T_{be}}$ is not only different between clones, but may vary between seasons and with different nutritional status. These authors concluded that the wide range of mean temperatures (from 15^{O}C to 20^{O}C) meant that the duration of shoot replacement cycle (the time taken for an axillary bud to be released from apical dominance to develop three leaves and a terminal bud), in fully irrigated tea receiving 450 kg N ha^{-1}, varied from 63 days in the warm wet season to 95 days in the cool dry season. As for unirrigated and unfertilized plots, it took 75 and 180 days. It is however noted that some cultivars like sinensis varieties can tolerate lower temperatures as exhibited by the CUPPA-tea crop growth model developed by Matthews and Stephens (1998). In this model, base temperature for shoot development used was 8^{O}C and 10^{O}C for shoot extension with an optimum temperature of 24^{O}C. In a trial done in Mufindi, Tanzania, Squire *et al*. (1993) determined $\boldsymbol{T_{be}}$ for clones S15/10 and TN 14-3 to be 7.5^{O}C, while Ng'etich (1995) reported $\boldsymbol{T_{be}}$ for TN 14-3 of 6.1^{O}C and that the $\boldsymbol{T_{be}}$ was 1.3 - 2.9^{O}C higher than that of development, giving rise to differences in shoot lengths between sites. Between $\boldsymbol{T_{be}}$ and $\boldsymbol{T_{oe}}$, rates of development increase linearly with temperature. If the temperatures exceed the $\boldsymbol{T_{oe}}$, rates of growth declines linearly (Carr and Stephens, 1992).

Once the $\boldsymbol{T_{be}}$ has been identified, the time (***t***) required for shoots to reach pluckable size can be related to the prevailing temperature (***T***) by the equation:

$$t = \frac{A}{(T - T_{be})}; \qquad \text{where A = thermal time (degree days).} \qquad \textit{[Eq. 2.4]}$$

Thermal time is the integral of time and temperature above the T_{be} required for a process to be completed. Provided no other environmental factor restricts shoot growth, the thermal time required by shoots to reach pluckable size should be similar, irrespective of differences in temperature, altitude or the growth rate of shoots (Obaga *et al.*, 1988).

2.5.2. Solar radiation and conversion efficiency

Biomass is produced by the process of photosynthesis, and is lost by the process of respiration, which provides the energy necessary for growth and maintenance. Respiratory loss of photoassimilates accounts for 65% of the gross DM produced in tea, where loss is highest in the wood (31%), followed by the roots (20%) and the leaves (9%) (Satyanarayana, 1994).

The conversion efficiency (***e***) is the proportion of solar radiation intercepted (received) by the leaves (***Si***), which is converted to dry matter (Willson and Clifford, 1992; Squire, 1985).

$$\mathrm{DM} = \boldsymbol{S_i} \times \boldsymbol{f} \times \boldsymbol{e} \qquad \textit{[Eq. 2.5]}$$

Variable ***f*** is the fraction of light intercepted. The value of ***e*** may vary between the low and high yielding clones, nutritional and water status of the crop. Other factors that may affect ***e*** are shade trees or shelter belts as they reduce radiation energy reaching the surface of the tea canopy (Willson and Clifford, 1992). A canopy of tea is light saturated at about 700-800 Wm^{-2}, which is 75% of full sunlight, resulting in the ***e*** of this radiation to be in the range of 0.6 to 1.2 gMJ^{-1} of PAR. This translates to about 50% of total solar radiation, depending on location, temperature and the type of clone (Carr and Stephens, 1992). There have been limited direct estimates of ***e*** for tea, but data from Othieno (1976), Magambo and Cannell (1981) suggested about 0.6 gMJ^{-1} (PAR) for pluckable tea. In comparison, the maximum ***e*** measured for tropical plantation crops such as oil palm, cocoa, coconut and rubber ranges from 1.2 to 1.6 gMJ^{-1} (Squire, 1985).

2.5.3. Factors influencing tea yields

Ng'etich (1995) reported that yields from commercial estates in Kenya had risen over the past 50 years from about 1,000 kg ha^{-1} in 1950's to over 3,500 kg ha^{-1} in 1990's. He attributed this rise to a combination of factors including planting new clones and increased fertiliser inputs. Oyamo (1992) attributed yield increases to technological changes and better agronomic management, where yields of upto 11,000 kg ha^{-1} were reported for S15/10 in a commercial field at 1900 m altitude. Increased tea yields have also been reported to be contributed by certain factors between sites and over time. Increase in yield has been attributed to: the amount of solar radiation received at each site; the amount of solar radiation intercepted by the crop canopy; the efficiency of conversion of intercepted radiation to dry matter, and partitioning of dry matter to the useful product (Carr and Stephens, 1992).

The Tea Research Foundation of Kenya uses a factor of 0.225 to convert *green leaf mass* to *dry matter* (Tea Research Foundation of Kenya, 2002).

2.5.4. Factors that limit yield of tea

Factors such as temperature, sunlight, day-length and genotypic characteristics affect the potential yield (Corley, 1983). The factors that have been documented to limit yield include: removal of young shoots (Tanton, 1979), air temperature (Ng'etich *et al*., 2001; Tanton, 1982a; Carr and Stephens, 1992), soil temperature confounded with dry air (Tanton, 1982a; Othieno *et al.*, 1992; Odhiambo *et al.*, 1993; Chen and Fong, 1994; Nixon *et al.*, 2001), hail (Ng’etich *et al.*, 2001; Othieno *et al.*, 1992), day-length (Tanton, 1982b), soil temperature (Ng'etich *et al*., 2001) and solar radiation (Squire, 1977). Falling temperatures and soil physical and chemical conditions greatly limits tea yield (Ng'etich *et al*., 2001).

According to Squire (1985) and Carr and Stephens (1992), the yield of a crop can be analysed in terms of the product of: (a) solar energy received by a crop, $\boldsymbol{s}$, (b) the fraction of this energy intercepted by the canopy, $\boldsymbol{f}$, (c) conversion efficiency of the intercepted radiation to dry matter, $\boldsymbol{e}$, and (d) the fraction of the total dry matter partitioned to the useful product, known as the harvest index, ***i***. It is factor '***i***' that makes *Eq. 2.6* (potential yield) different from *Eq. 2.5* (dry matter).

$$\text{Potential yield} = [\boldsymbol{s} \times \boldsymbol{f} \times \boldsymbol{e} \times \boldsymbol{i}] \qquad [Eq.\ 2.6]$$

Throughout the Kenyan tea areas, ***s*** is unlikely to vary significantly to the extent of affecting yield. This is because despite differences in latitudes, the experiments performed in Kericho (Kenya) and Mufindi (Tanzania) on ***s*** gave similar annual totals (Carr and Stephens, 1992). Canopy will be large and uniform but ***f*** being a fraction and, depending on the leaf pose angle and canopy depth, will vary between clones. Most of the variation between clones and fields will be in ***e*** and ***i***.

Othieno (1976) and Magambo and Cannell (1981) suggested ***e*** value of 0.6g/MJ for pluckable tea that estimates the quantities to be converted to DM.

2.5.5. Dry matter partitioning

Biomass is defined as mass of live or dead organic matter. Biomass plays two major roles in the climate system: (i) photosynthesis withdraws CO_2 from the atmosphere and stores it in plants as biomass, part of which is transferred to the soil when it decomposes or is stored in protected soil carbon pools; (ii) biomass burnt by fire emits CO_2 and other trace gases and aerosols to the atmosphere (Food and Agricultural Organisation, 2006).

Chloroplasts are the fundamental units for photosynthesis. Typically, there are about 10 million chloroplasts in each cm^2 of leaf. Chloroplasts nearest the leaf surface receive the greatest irradiance and therefore absorb more light per unit chlorophyll than chloroplasts in the centre of a leaf (Evans, 1999). The composition of chloroplasts is flexible, being particularly responsive to the light environment, which alters the relative abundance of many of the protein complexes (Anderson, 1986). Dry matter partitioning is the apportioning of the photoassimilates to the various plant organs and is influenced by all the main environmental and cultural factors and by genotype.

The rate of dry matter production depends on the incident solar energy, canopy area available to intercept radiation, the availability of water and nutrients and the conversion efficiency (Wachira and Ng'etich, 1999).

2.5.6. Factors that affect partitioning of assimilates

Seasonal fluctuations in tea yield are determined by factors that affect the partitioning of assimilates between the young shoots which make up the yield and the rest of the bush (Squire, 1985). Yield of processed tea is determined by (a) the number of shoots per unit area, (b) their rate of growth, and (c) their average dry weight at harvest (Carr and Stephens, 1992). Partitioning takes place according to the demand from various sinks, which depend on the rate of utilisation of assimilates for growth from stored starch that has been accumulated during the period when there was excess for respiration purposes. Tea plant responses to the environment are normally expressed by changes in total dry matter production and harvestable yield (Ng'etich, 1997). The ability of a tea bush to produce optimally therefore, depends on its capacity to photosynthesize and partition assimilates to harvestable shoots. This ability is enhanced by good canopy management (removal of overgrown shoots), application of growth regulators and addition of photosynthetically efficient maintenance leaf (letting up). About 40% of photosynthates are mobilized to growing shoots, and 20% to dormant *banjhi* (dormant bud at the apex of a dormant shoot) shoots. Any cultivar or practice that mobilizes more photosynthates to harvestable shoots would improve the productivity, making full use of the favourable environment (Marimuthu *et al.*, 1994).

2.5.7. Relationship between harvest index (*i*), radiation use efficiency (*e*) and dry matter (DM)

Clonal differences in dry matter production, partitioning and harvest index (***i***) may be used to select for high yield potential. Factor ***i***, defined as the fraction of the total dry matter partitioned to harvestable shoots, is low in tea and ranges from 7% to 37% (Ng'etich, 1995). Burgess (1992) reported similar results from young tea plants in Tanzania. In 1994, Burgess recorded ***i*** of upto 24% for irrigated clone 6/8 in Mufindi, Tanzania.

Radiation use efficiency (***e***, g/MJ) describes the transformation efficiency from energy into dry matter (DM) of crop canopy. While Donald and Hamblin (1976) defined harvest index (***i***) as the ratio of (grain) yield to total above-ground biomass (AGB), Bhardwaj and Bhagsari (1989) defined it broadly as the ratio between economic yield (EY) and the total biomass, i.e. biological yield (BY). ***i*** influences EY more than any other yield determining plant trait. These authors argued that yield improvements could be achieved if a high ***i*** was selected for in a competitive environment.

Yield improvement in tea would come from an increase in either ***e*** or ***i*** (Squire, 1985). Factor ***e*** varies little with temperature. It therefore means that yield variations between sites are mainly due to ***i*** and ground cover (Ng'etich *et al.*, 2001a). It has been found that various environmental and agronomic factors can have significant effects on the ***e*** and ***i*** (Li *et al.*, 2011). The relationship between plant DM and radiation intercepted has been termed the ***e*** (Monteith, 1977). A number of crop growth simulation models have been developed using the ***e*** concept to forecast crop growth and yield in different environments (Brisson *et al.*, 2003). Therefore, data collection of the ***e*** and ***i*** can be used as a valuable tool in interpreting crop response to different environmental and climatic changes, and is also increasingly important in the assessment of crop growth and production (Sinclair and Muchow, 1999).

The low yield of tea compared with other C_3 vegetative crops cannot be wholly attributed to its low biomass productivity when plucked, because plucking decreases total leaf production by only 20%. The important factor limiting tea yield is its small ***i*** (Magambo, 1981). In the study carried by Magambo in 1981, only 11% of the above ground dry matter increment was removed as yield, compared to 30-70% in grasslands, forests and root crops.

The results obtained by past researchers seem to suggest that the ***i*** is bound to rise as enhanced agronomic and modern technological approaches are applied, resulting in higher yields. Magambo (1983) reported that ***i*** of harvested tea decreases with age which they attributed to the increase in the proportion of total dry matter accounted for by the wood in the frame of the bush. Yield differences is attributed mainly to ***i*** and ground cover. But since mature tea covers 95-99% of the ground, yield differences can then be said to be as a result of ***i*** (Ng'etich *et al*., 2001). Other authors have made investigations of ***i*** on other plants as given in Table 2.2 below.

*Table 2.2: Harvest Indices (**i**) of selected tea clones and other plants*

No.	Plant	Clone	*i*	Yield/yr	Published by	Remarks
1.	Palm oil	-	42%		Cannell, 1985; Magambo and Cannell, 1981	Forest trees (40-85%) have higher ***i*** compared to that of tea (7-37%).
2.	Tea (*C. sinensis*)	EPK TN 14-3	11%	2.1 t ha^{-1}	Ng'etich, 1995	Resulting from trials carried out by Ng'etich at Timbilil and Changoi between 1992 and 1994.
		S15/10	37%	6.9 t ha^{-1}	Ng'etich, 1995 (***i***); Kigalu *et al*., 2008 (yield).	The study reported high yield (Oyamo, 1992; Kigalu *et al.*, 2008) in Kenya and southern Tanzania respectively, and ***i*** (Ng'etich, 1995) at Kaproret Estate, Kericho, Kenya.
				11 t ha^{-1}	Oyamo, 1992	
		6/8	24%	6 t ha^{-1}	Burgess, 1992	Publication following research carried out in Mufindi, Southern Tanzania.

During the 1992 to 1994 trials carried out at Timbilil and Changoi areas of Kericho, a uniform rise in ***i*** from date of planting (0 days) to when the clone was over 3 years (1,200 days) was recorded. Ng'etich (1995) recorded ***i*** at 4% during first harvest (300 days after planting) and showed an upward trend upto a maximum ***i*** of 11% at 1,100 days after planting.

Generally, high yielding clones tend to have greater above ground biomass, hence high dry matter production and harvest index than low yielding clones. This has been demonstrated by clone S15/10, which is a very high yielding clone that has realized a record yield of 11,000 kg mt $ha^{-1}year^{-1}$ and a high ***i*** of 37% (Tea Growers Handbook, 2002, pp. 35).

The high yield of clone S15/10 reported by Ng'etich *et al*. (2001) was possible because this clone had ***i*** of 37% constituting yield, while the remaining 63% was dry matter. While this may seem high for tea, the reports from Tanzania of 24% (Burgess, 1992) for clone 6/8 yielding 6 t ha^{-1} suggests this may not be unreasonable. Clone TN 14-3, perceived to be low yielding by earlier authors, yielded 2.1 t ha^{-1} in 1995, and 2.9 t ha^{-1} in this study. Its (TN 14-3) ***i*** was determined as 11% by Ng'etich in 1995.

2.6 Distinct Seasons of the Year in Tea Growing Areas

The growing conditions of tea in various seasons are described by Stephens *et al.* (1992) and Ng'etich *et al.* (1995) as: (1) the main dry-warm season running from mid-December to the end of March; (2) a cool-wet season from April to August; and (3) a warm-wet or warm dry season from September to mid-December. It is well established that the growth of tea is affected by these differences in weather patterns (Kamau, 2008).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental Sites Description

Three sites were identified for the study, of which one was a reference site: Kipkebe tea estate in Nyamira, Kangaita in Kirinyaga and Timbilil (reference) in Kericho Counties.

3.1.1. Kipkebe Tea Estate – Nyamira County

Kipkebe Tea Estate is situated in Borabu district, Nyamira County. It is located at an elevation of 1740 m above sea level, at a latitude of 0^{O} 17’ S and longitude 35^{O} 3’ E (Fig. 3.1).

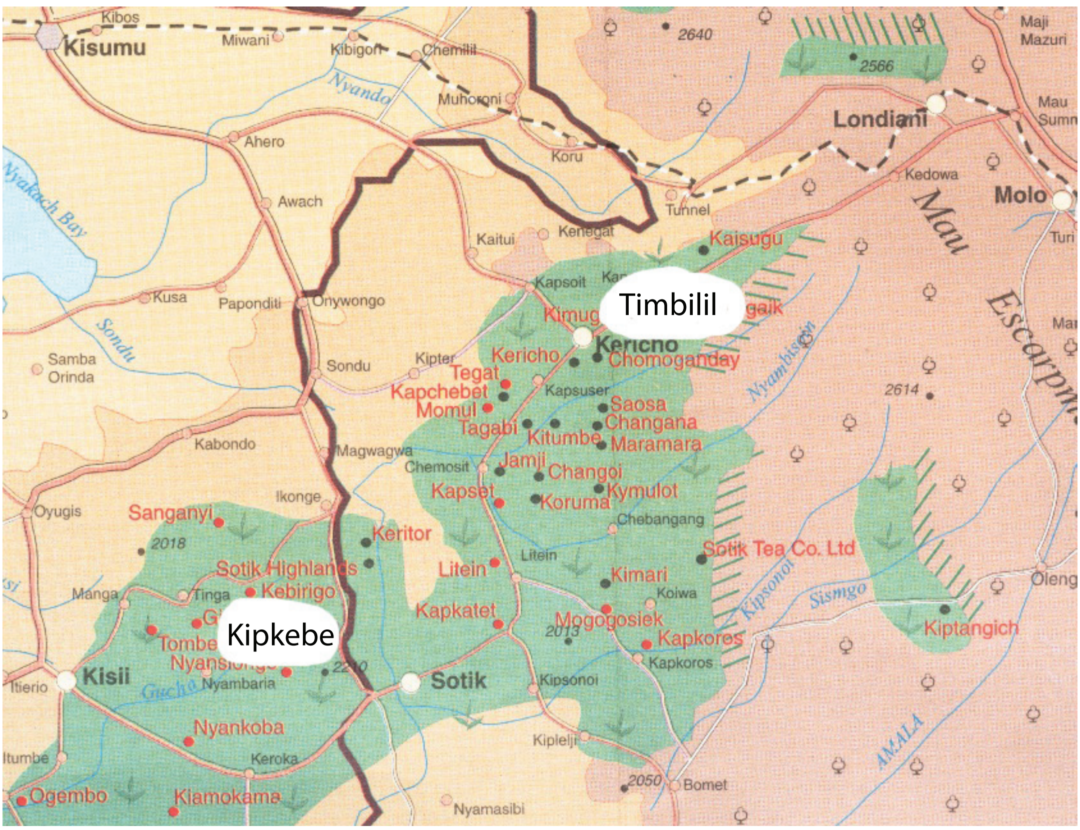


Fig. 3.1: Map of the tea growing region west of the Rift Valley, showing the location of Timbilil and Kipkebe sites (Source: Tea Map of Kenya - publication of the Tourist Maps (K) Ltd., 2003).

3.1.2. Timbilil TRFK HQs Farm – Kericho County

Experiments used as reference were conducted at the TRFK's Timbilil tea farm, Kericho County ($0^{O}22$'S, $35^{O}21$'E, elevation of 2200 m.a.s.l.). It experiences annual rainfall between 1500 mm and 2500 mm, has deep red volcanic soils (nitosols) and its topography is undulating, gentle slopes (Tea Research Foundation of Kenya, 2009b).

3.1.3. Kangaita Tea Research sub-station – Kirinyaga

Kangaita is a Tea Research Foundation sub-station located in Kirinyaga district, and has an elevation of 2100 m above sea level. It is situated in a latitude of 0^{O} 30' S and longitude of 37^{O} 16' E. Fig. 3.2 shows the map of part of the tea growing region east of the Rift Valley, where Kangaita experimental site is located.

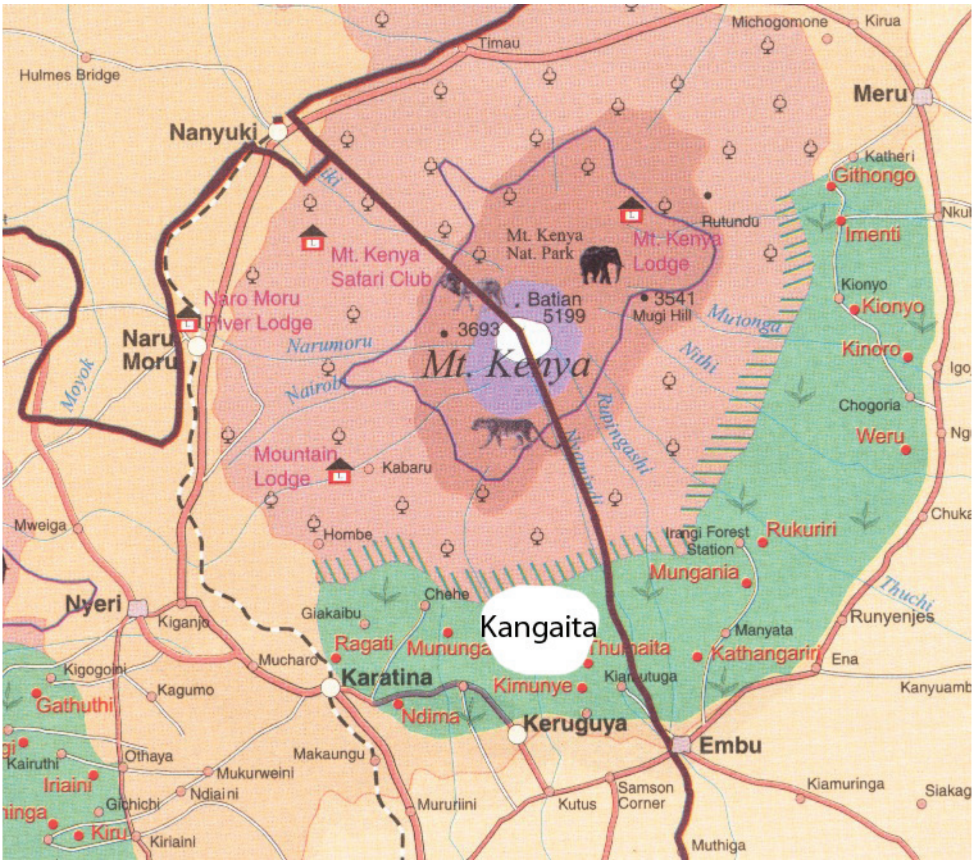


Fig. 3.2: Map of the tea growing region east of the Rift Valley, showing the location of Kangaita site.

(Source: Tea Map of Kenya - a publication by the Tourist Maps (K) Ltd., 2003).

Fundamental locational and ecological factors from the study sites are given in Table 3.1. Rainfall and temperature (soil and air) means were measured between 2002 and 2005 (4 years).

Table 3.1: Location and altitude data of experimental sites

No.	Trial site	County	Altitude (m)	South	East	*Rainfall and temperature mean, 2002 - 2005*		
						Mean rainfall (mm)	**Mean air Temp. (^{O}C)**	**Mean soil Temp. (^{O}C)**
1.	Timbilil	Kericho	2,200	0^{O}22'	35^{O}21'	1,994	16.6	18.7
2.	Kangaita	Kirinyaga	2,100	0^{O} 30’	37^{O} 16’	1,953	15.3	18.6
3.	Kipkebe	Borabu	1,740	0^{O} 17’	35^{O} 3’	1,638	19.8	Unavailable

3.2 Treatments (Genotypes)

Four tea clones of commercial interest in Kenya were used in this study, i.e. EPK TN 14-3, TRFK 301/5, AHP SC 31/37 and TRFK 31/8 (Table 3.2). Clone TRFK 31/8 was used as a standard (control) as it is grown by the majority of smallholder farmers in the region. These genotypes had been randomly assigned to the plots. The experiment had been set up in RCBD for the purpose of G×E studies when it was planted in June 1998.

This experiment covered all months of the year right from October 2007 to November 2009, and captured the 3 tea seasons as suggested by Ng'etich (1995) and Stephens *et al.* (1992).

3.2.1. Clone EPK TN 14-3

This clone is a China variety and has a small to medium, light green, semi-erect leaves, with characteristics between the China and Assam tea varieties. It has been used for planting in areas with high pH (Wanyoko, 1988). It has an average to high yielding clone developed in Nandi for high soil pH, hence tolerant to high soil pH and coldness (Kamunya *et al.*, 2012). This clone is less susceptible to scale insects though also moderately preferred by the red crevice mite (Tea Research Foundation of Kenya, 2005). Irrespective of where the leaves are produced, cold factory fermentation conditions at temperature range between 15^{O}C and 25^{O}C (not 35^{O}C as is used for other clones) is ideal to achieve high quality black tea output, as is detected through sensory evaluations (Owuor *et al.*, 1999). It is however unpopular with the pluckers since it is difficult to harvest shoots with more than two leaves and a bud, as the stems become fibrous and hard. It has a fast growth rate and a low base temperature. The base temperature for shoot extension (T_{be}) for this clone is 8.8°C (Ng'etich, 1995; Tea Research Foundation of Kenya, 2002).

3.2.2. Clone TRFK 301/5

This is a Cambod variety type whose seed was sourced from Reunion and officially released for commercialization in Kenya in 2001 (Kamunya and Msomba, 2011). The highest yield recorded at Timbilil, Kericho is 5,909 kg of made tea ha^{-1} $year^{-1}$ (Kamunya *et al.*, 2012). It is of medium black tea quality, has dense canopy, easily sun-scorched in nursery, good cup quality, resistant to pests and tolerant to root knot nematode, is of average stability/adaptability and good for silvery tips (Kamunya and Msomba, 2011; Tea Research Foundation of Kenya, 2005).

3.2.3. Clone AHP SC31/37

This Assam tea variety has been found to be relatively tolerant to red crevice mite and very susceptible to water stress. Its immature leaf colour is yellow green (Kamunya *et al.*, 2012; Tea Research Foundation of Kenya, 2005). It is a commercial, high yielding variety and is used to compare with others during plant improvement studies (Tea Research Foundation of Kenya, 2010a).

3.2.4. Clone TRFK 31/8

This is an Assam variety whose seed was sourced from Ambangulu in Tanzania. TRFK 31/8 is one of the oldest clones, having been officially released for commercialization in Kenya in 1964. The highest yield recorded at Timbilil is 5049 kg ha^{-1} y^{-1}. It is of medium quality index, moderate in resistance to pests and diseases, susceptible to high pH and is of average adaptability/stability. This clone has a total catechin content of 21.5% (compared with 20.7% of TRFK 303/577, 27.1 % of TRFK 6/8 and TRFK 301/5's 22.5%. Catechins are health improvement compounds (Tea Research Foundation of Kenya, 2005).

3.3 Experimental Design and Layout

A split plot layout for sites was set out in an existing experiment that was established in 1998 in Randomized Complete Block Design (RCBD), each with three replications (blocks) - A, B and C. This experiment had two factors: **sites (environment)** (whole or main-plot factor) and **genotypes (G)** (split-plot factor). The spacing adopted was 1.2m×0.6m, with 30 bushes per plot with Keinama purple (K-purple) acting as guard rows. The main treatments were 4 tea genotypes (clones). The genotype versus the environment (G × E) interactions were studied, where the following individual comparisons were made:

(i) the sites (3)
(ii) clones (4) within sites
(iii) clones across sites (G×E)
(iv) Time (Years).

The experimental layout showing the genotypes (treatments) at both Kangaita and Kipkebe study sites were similar, and is given in Table 3.2.

Table 3.2: Kipkebe and Kangaita experimental layout showing randomization

Blocks	Block A	Block B	Block C
Treatments	TRFK 301/5	AHP SC 31/37	TRFK 31/8
	TRFK 31/8	TRFK 31/8	AHP SC 31/37
	AHP SC 31/37	TRFK 301/5	TRFK 301/5
	EPK TN 14-3	EPK TN 14-3	EPK TN 14-3

3.4 Statistical Model

Statistical analysis was done using the split plot design following the model:

$Xjklm = \mu + xj + \beta k + \varepsilon jk + \tau ij + \lambda il + \varepsilon jklm.$

Where:

$Xjklm$ = Plot observation

μ = Mean of observation

xj = Main treatment effect (Genotypes)

βk = Block/ replication effect (A, B, C)

εjk = Error (1)

τij = Sub-treatment effect (Environmental factors - E, including direct radiation, PAR, rainfall, seasons, soil and air temperature, yield)

λil = Interaction main treatment (G) and the sub-treatment (E)

$\varepsilon jklm$ = Error (2).

3.5 Soil Characterization

3.5.1. Soil sampling and preparation

Soil samples for laboratory analysis (physical and chemical) from Kangaita and Kipkebe were taken in October 2009, while that from Timbilil was sampled in August 2009.

Generally, the feeder roots of tea plants are concentrated in the 0-20 cm-depth (Wanyoko, 1999). But since some mobile plant nutrients and water are extracted by the roots from lower layers of soil, this study sampled soil between 0 cm and 60 cm depth.

Soil samples were taken from the experimental sites in 5 depths (0.10 m, 0.15 m, 0.20 m, 0.30 m and 0.60 m) (Cooper, 1979; Eeles, 1979). Four sampling holes were made in each plot and the soil at the same level bulked. In the lab, the samples were air-dried, ground using pestle and mortar to pass through a 2-mm standard sieve in readiness for extract preparation (McLean, 1982; Tan, 1996).

3.5.2. Physical properties

Hydrometer method was used to analyze air-dried, sieved (2-mm) samples for particle size ranges and soil texture. The ratios of sand, silt and clay particles to determine water retention capacities were carried out (Jacob and Clark, 2002).

3.5.3. Chemical properties

The field moist soil samples were analysed for pH using a combination of electrode pH-metre in a soil to water (v/v) ratio of 1:1, measured in saturated mud while saturated soil moisture content was determined from saturated mud and weighing method (McLean, 1982; Tan, 1996). The amount of P (ppm) that existed in extracts of soil was determined by spectrophotometer (Olsen and Sommers, 1982) while the extract was analysed for K (ppm) using a flame photometre (Spencer, 1950; Tea Growers Handbook, 2002). Atomic Absorption Spectrophotometre (AAS) method was used to analyse for Mg (ppm), Mn (ppm) and exchangeable Ca (meq/100 g) (Spencer, 1950; Tea Growers Handbook, 2002), while total organic carbon (C) (ppm) was determined by use of the Walkley–Black oxidation method (Walkley and Black, 1934; Tan, 1996).

3.6 Incident Solar Radiation (ISR)

In this study, tube solarimeter (Plate 3.1) whose output in tube solarimeter is in *millivolts* was used to measure both direct and diffuse radiation. Direct radiation measurements were recorded at least 3 times weekly between 1100 and 1400 hours by use of broadband tube solarimeter apparatus for the 4 treatments per location. These measurements were done for a period of 3 years.

3.6.1. ISR (Wm^{-2}) at Timbilil Agromet Station

Radiation measurement apparatus had not been installed in tea research sub-stations outside Timbilil. But since the 3 trial sites (Timbilil, Kangaita and Kipkebe) lie close to the equator (Table 3.1), an ISR experiment was set up at Timbilil to provide a suitable platform to measure radiation data that represents the scenario that could have been witnessed in the other two research sites. The radiation measurements (MJm^{-2}) were recorded daily at Timbilil Agromet at 0900 hours, while corresponding ceptometer (PAR) and tube solarimeter direct solar irradiation (***E_{dir}*** in ***Wm^{-2}***) were recorded between 1100 and 1400 hours.

Plate 3.1: Use of tube solarimeter and voltmeter equipment to measure solar radiation reaching top of tea canopy (Source: Author, 2009).

3.6.2. ISR (Wm^{-2}) at Kangaita and Kipkebe trial sites

Direct solar radiation ($\boldsymbol{E_{dir}}$) measurements formed core part of this study. This research was conducted between October 2007 and November 2009 at Kangaita and Kipkebe trial sites. Part of the study was done in 2012 at Timbilil for the purpose of cross-referencing the earlier (2007-2009) findings. The main purpose of conducting $\boldsymbol{E_{dir}}$ measurements was to establish its relationship with yield, the 3 seasonal tea crop peak patterns and precipitation.

(a) Methodology: Direct solar irradiance (E_{dir}) measurement

Readings were recorded between 1100 and 1400 hours by use broadband tube solarimeter (for recording-mV) and a multitester/ multimeter (voltmeter) (reading) at least thrice weekly. Over 3 tea bushes per clone in a block/ replication (each site had 3 replications) were randomly picked for the purpose of taking both the top and bottom tea canopy radiation measurements. These irradiation means (*mV*) were converted to total radiation (Wm^{-2}) using *Eq. 3.1*.

(b) Tube solarimeter placement and readings taken on top and below tea canopy

Tube solarimeter was placed on top of a tea bush where it gained exposure to the full spectrum of electromagnetic radiation of the sun. As the solar radiation impacted the earth's surface, the sensors within the device measured a full $180^{O}C$ radius around the instrument, finding the density and changes in this radiation. The tube, connected to the voltmeter, was mounted horizontally on top of the crop (Plate 3.1) and readings taken after a period of about 20-35 seconds, by which time, tube solarimeter readings (*millivolts*) would have stabilized. After recording top of canopy readings, the tube solarimeter was placed at the base of the same tea bush to measure solar radiation reaching maintenance layer.

(c) Broadband tube solarimeter tube calibration

Different tube solarimeters were used to measure light measurements in three different locations in Kenya (Table 3.1). These tubes were calibrated separately using the KIPP and Zonen tube solarimeter (Plate 3.2 below) to obtain a specific conversion factor for each one of them. The ratio obtained was multiplied by the value reflected on the multitester to give the correct measurements in *millivolts (mV)*. Computed conversion factor for Kangaita was determined as 1:1, while for Kipkebe, 1:0.706. Timbilil was 1:0.986.

Plate 3.2: The KIPP and Zonen solarimeter equipment (Source: Author, 2009).

Broadband tube solarimeter readings (*mV*) were converted to total direct radiation (solar) units (*Watts per square metre - Wm*$^{-2}$) as given in *Eq. 3.1*. The broadband irradiance results are given as $\boldsymbol{R_s}$. Hence, direct solar irradiance, $\boldsymbol{E_{dir}}$:

$$\boldsymbol{E_{dir}} = \left[\frac{(r \times cf)\ \text{mV} \times 1{,}000}{11.7\ \text{mV}}\right] \text{Wm}^{-2} \qquad [Eq.\ 3.1]$$

Where r = Broadband direct radiation measurement (in *mV*) by use of solarimetre tube apparatus.
cf = Conversion factor ratio determined using KIPP calibration apparatus. Ratios as follows: Kangaita (1.00); Timbilil (0.986) Kipkebe (0.706).
1000 = Figure to convert Kwm^{-2} energy units to Wm^{-2}.
11.7 = KIPP calibration factor
mV = Millivolts.

The fraction of solar energy intercepted by the canopy (***Si***), direct and PAR are given by the equation:

$$\boldsymbol{Si} = \left(\frac{\boldsymbol{Ti} - \boldsymbol{Bi}}{\boldsymbol{Ti}}\right) \qquad Eq.\ 3.2$$

Where ***Ti*** (Wm^{-2}) is irradiance captured on top of canopy while ***Bi*** (Wm^{-2}) is that energy reaching beneath the tea bush, i.e. maintenance layer. Leaves on this layer play an equally important role as those located at the top in that food reserves are stored here and used to maintain the crop.

3.7 The Timbilil PAR Measurements

The performance of tea clones has been shown to vary in relation to the agro-ecological zone and climate that it is exposed to. A clone that displays superior qualities in one region may not necessarily depict the same when grown in a different environment. It is on the basis of this understanding that this research studied 4 clones in two locations in the period starting October 2007, ending November 2009. PAR and temperature were isolated for investigation in this study.

This study used data taken between March and April 2012, at Timbilil. PAR and total radiation measurements were taken thrice daily, i.e. 1000 hours, 1200 hours and 1400 hours, by use of ceptometer (Plate 3.3 below) and tube solarimeter (total radiation). Readings were taken with these two radiation measurement apparatus concurrently on top (Plate 3.1) and beneath the canopy with a view of obtaining ceptometer versus tube solarimeter ratios, hence determine PAR. The KIPP and Zonen (Plate 3.2) was used to calibrate tube solarimeter where a conversion factor (*cf*) of 0.706 was obtained. E_{dir} (Wm^{-2}) was then determined using *Eq. 3.1*.

Plate 3.3: The ceptometer apparatus at the TRFK used to measure PAR in mol m^{-2} s^{-1} (Source: Author, 2012).

Concurrent photosynthetic photon flux density (PPFD) readings (*mol* m^{-2} s^{-1}, i.e. PAR quantum units) were recorded for the purpose of obtaining the site-specific 'ε' (epsilon) value. Plate 3.1 depicts tubes mounted horizontally on top of tea canopy for the purpose of recording radiation capture by the plant. The quantity of PAR intensity is given the symbol $\boldsymbol{Q_p}$.

Gonzalez and Calbo (2002) define photosynthetic photon flux density (PPFD) or $\boldsymbol{Q_p}$, as a measure of photosynthetically active radiation (PAR) that can be related to solar broadband irradiance $\boldsymbol{R_s}$ using:

$$\boldsymbol{Q_p} = \mathcal{E} R_s \qquad \textit{(Eq. 3.3)}$$

which can be applied either to global, direct or diffuse radiation. The ratio 'ε' (epsilon) can be considered as a product of two ratios: (i) the fraction of the broadband energy that lies in the PAR wave-band (400-700 nm), whose published values global irradiance are around 0.45, and (ii) the photon or quantum efficiency of this band (Gonzalez and Calbo, 2002). McCree (1972) gave the the value of 4.57 µE/J when both direct and diffuse radiation are present, and 4.24 µE/J when the radiation is purely diffused. Gonzalez and Calbo (2002) therefore estimates values for ε to be near 2 µE/J. These figures are arrived at by use of measured light energy units, usually in millivolts or Wm^{-2}.

Taiz and Zeiger (2011) and Skye Instruments Ltd (2012) defines moles as the number of photons (1 mol of light = 6.023×10^{23} photons, Avogadro's number). Skye Instruments Ltd (2012) further gives the conversion between Wm^{-2} and $mol/m^2/sec$ as:

$$\frac{119.708}{\text{Wavelength (nm)}} = \frac{x\ (W/m^2)}{y\ (mol/m^2/s)} \qquad \textit{Eq. 3.4}$$

Thus, for an appropriate value over the waveband 400-700 nm (PAR) under natural light conditions:

$$\frac{119.708}{\text{Wavelength (nm)}} = \frac{1}{4.6} \qquad \textit{Eq 3.5}$$

It therefore means that daylight readings of Y Wm^{-2} can be converted to $mol/m^2/sec$ by multiplying by 4.6.

3.8 Air Temperature, Soil Temperature and Rainfall

In this experiment, air temperature and rainfall measurements were recorded in all months of the year starting January 2007 through to December 2009 at Kangaita, Kipkebe and Timbilil using meteorological apparatus found in each of the sites. Rainfall amounts was determined at 0900 hours daily using standard rain gauge as recommended by the Kenya Meteorological Department, while dry-bulb thermometers were used to measure daily maximum and minimum temperatures.

3.8.1. Air temperature

Dry-bulb thermometer was housed in a Stevenson screen (Plate 3.4) to shield it and other meteorological instruments against precipitation and direct solar radiation from outside sources, while allowing free air circulation around them. The thermometer was mounted on a moveable wooden stand within a stand of about 1.5 m height over a neat short grass surface in each site. To reflect as much direct radiation as possible, the whole structure is painted white, with sloping roof covered with aluminium. The sites where the stands were set are large, open areas with free air circulation and no buildings, trees or other obstructions in the vicinity as recommended by Mwebesa (1970). The dry-bulb thermometers were used to measure daily maximum and minimum temperatures at Kangaita, Timbilil and Kipkebe research sites.

Plate 3.4: The (thermometer) Stevenson screen, Symons-pattern earth (soil) thermometer and grass-minimum thermometer (Source: Author, 2009).

3.8.2. Soil temperature

Symons-pattern earth thermometer (Plate 3.4), designed to measure temperatures at depths of 30 cm or more, was used to measure soil temperature at Timbilil. This instrument was suspended inside a stout metal tube closed at the bottom by a cone of solid metal and sunk in the soil. Soil temperature readings were taken between 0800 hr and 1900 hr daily. This was done by raising the thermometer to the eye-level to prevent parallax error and taken as quickly as possible to the nearest 0.1^{O}C. The bulb of the thermometer is embedded in a micro-crystalline paraffin wax to prevent it from being affected by changes in temperature when drawn to the surface to take a reading (Plate 3.5). This allows slow change of temperature during reading, hence eradicate significant errors. A metal cap is provided to prevent water collecting in the tube (Plates 3.4 and 3.5) (Mwebesa, 1970).

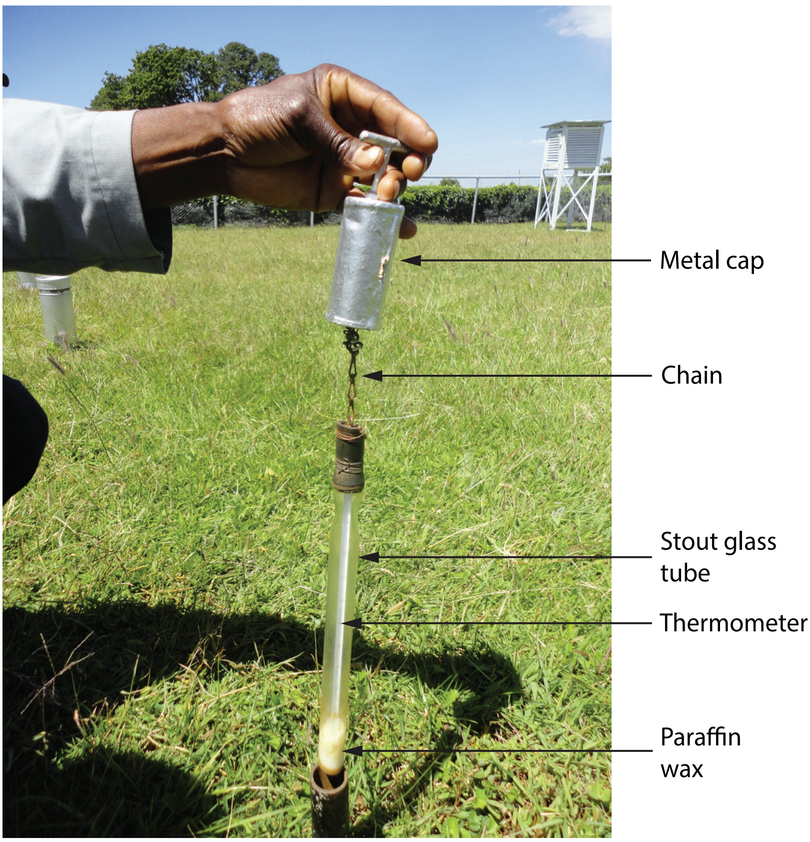


Plate 3.5: The 30-cm long Symons-pattern earth thermometer used to take soil temperature at Timbilil (Source: Author, 2009).

3.8.3. Rainfall measurements

Rain gauge recommended by Kenya Meteorology Department was used to measure the amount of rainfall at 0900 hours daily. Water that collected in the glass bottle graduated in millimeters was poured into a measuring cylinder. When 0.05 mm or less was measured, the rainfall was recorded as trace. While taking readings, the measuring cylinder was held horizontal to the eye level to guard against parallax error.

3.9 Yield Measurements

3.9.1. Harvest methodology

Harvesting was done by selecting tender apical shoots growing above the pre-determined plucking table, notably two leaves and a bud at the top of tea canopy. The manually picked green leaves were collected in a back-pack type of basket. To maintain a low table height for ease of subsequent harvesting activities, breaking bark on tea bushes was done. The harvest of green leaf was done in a 14-day interval or twice a month in the two trial sites.

3.9.2. Conversion factor: Green leaf to made tea

(a) The general rule

To make 1 kg made tea, one requires approximately 4.5 kg of green leaf to use, or the out-turn of green leaf is about 22.5% (Tea Growers Handbook, 2002 pp. 228).

(b) Shoot dry mass:fresh mass ratio

The TRFK has traditionally used a constant factor of **0.225** to convert green leaf mass to made tea (mt) normally considered to have a moisture content of less than 3% (Anon, 1998; Ng'etich *et al*., 2001; Tea Growers Handbook, 2002). The TRFK published ratio was, therefore, adopted and used in this study.

Each experimental plot measured 120 cm × 60 cm (4 ft × 2 ft) and had 20 tea bushes, translating to 13,448 plants per hectare. This information was used to obtain a conversion factor of 151.29 kg mt ha^{-1}, this figure being equivalent to 1 kg of harvested green leaf, as follows (*Eq. 3.6*):

$$\left(\frac{0.225 \text{ mt} \times 13{,}448 \text{ plants ha}^{-1}}{20 \text{ plants/ trial plot}}\right) = 151.29 \text{ mt ha}^{-1} \qquad \textit{Eq. 3.6}$$

Where: 0.225 = Shoot dry mass : fresh mass ratio, a TRFK constant conversion factor obtained based on quantities of green leaf used to make made tea (mt) (Ng'etich, 1995)

13,448 = number of tea bushes (plants) per hectare;

20 = Number of plants under study per 120 cm × 60 cm experimental plot.

The conversion factor given in *Eq. 3.6* (151.29) is multiplied by weight (kg or tons) of green leaf to give weight of made tea per hectare (kg mt ha^{-1} or t mt ha^{-1}).

3.10 Soil Temperature Estimation Using Air Temperature

At the TRFK Timbilil (control/ reference) trial site, soil temperature at *d*=0.3 m and grass minimum temperature measurements have been carried out since the inception of the research institution. A similar trial was set up Kangaita for the purpose of comparing differences between air and soil temperature outputs. The outcome of this trial, whose measurements span 11 years (2000-2010), was used to come with a model that is proposed to be used to estimate soil temperature at 30 cm-depth in the tea growing areas having similar climatic conditions with Timbilil and Kangaita. This concept intends to improve on the Wu and Nofziger (1999) and Smith *et al*. (1998) trials. It is on the basis of publications from these researchers and the Timbilil and Kangaita soil and air temperature measurements that this study modified Hillel's model to be used to estimate soil temperature at 30-cm depth using atmospheric temperature in the tea growing zones of Kenya. The 11-year meteorological outcome was applied in *Eq. 3.7* as part of the formula used to come up with a modified soil temperature estimation model.

$$T_{est\text{-}canopy} = (dT_{mb} - dT_{mm}) \qquad \text{Eq. 3.7}$$

where $T_{est\text{-}canopy}$ = Hillel's modified estimated soil temperature at 30 cm in canopy-covered areas (e.g. tea).

dT_{mb} = Mean measured soil temperature on a daily basis at a depth of 30 cm in areas covered by canopy, e.g. tea bushes.

dT_{mm} = Mean recorded or estimated mean daily air temperature in tea growing zone.

The outcome of this study, as presented in *Eq. 3.7*, was used to estimate soil temperature at a depth of 30 cm at Kangaita and Kipkebe, using known air temperatures, over the same period of time. Statistical comparison of soil temperature results of the two sites were done for the purpose of if it can be applied elsewhere.

3.11 Schedules of Measurements

Summary of all the measurements undertaken in this study are listed in Table 3.3 below.

Table 3.3: Summary of schedules of measurements

No.	Parameter	Measurement schedule	Site
1.	Air and soil temperature (^{O}C)	Daily at 0900 hrs, 2000-2010	Kangaita, Kipkebe, Timbilil
2.	Rainfall (mm)	Daily at 0900 hrs, 2007-2009	Kangaita, Kipkebe, Timbilil
3.	Total radiation (Wm^{-2})	3 times/week, 1100-1400hrs, 2007-2009; 2012	Kangaita (2007-09), Kipkebe (2007-09), Timbilil (2012)
4.	PAR	March, April 2012; 10.00 hr, 12.00 hr, 14.00 hr	Timbilil (Reference site)
5.	Soil physical and chemical properties	October 2009	Kangaita, Kipkebe, Timbilil
6.	Yield ($t\ ha^{-1}y^{-1}$)	14-day interval, 2007-2009	Kangaita, Kipkebe

3.12 Statistical Analysis

G×E analysis was done using split plot design statistical model as explained in Chapter 3 (section 3.4). Two-way ANOVA ($p \leq 0.05$) for split plot design (GenStat, 2012; Stern *et al*., 2001) was used to determine significance of direct radiation, PAR and yield between and within seasons and genotypes and temperature (air and soil at d=30 cm) and rainfall across locations and years. Correlation ANOVA (Pearson) was used to compare the relative strength of parameters and determine significance/ interrelationship between PAR, seasons, temperature and rainfall (SPSS, 2011; Pallant, 2011).

CHAPTER FOUR

RESULTS

Data utilized in this study was measured daily (temperature and rainfall), weekly (radiation and yield), monthly (collating yield, rainfall and temperature measurements) while soil sampling was done once. Although the largest bulk of radiation measurements was carried between out 2007 and 2009, additional supporting data was measured at Timbilil in 2011 and 2012.

Some outcomes of the analysis are based on the growing period of tea as described in section 2.5 (Chapter 2). When these seasons are used, the results reflect months of the year and the three growing conditions of tea (Ng'etich, 1995; Stephens *et al.*, 1992).

4.1 Soil Characterization

4.1.1. Physical characterization of Kangaita, Kipkebe and Timbilil soils

Sampled soils from the three sites were subjected to lab physical characterization, and the outcome given in Table 4.1 below.

Table 4.1: Physical properties (particle distribution and textural classes) in the three trial sites (0-60 cm)

Site	Depth (cm)	Moisture content (%)	% Sand	% Clay	% Silt	Texture	Report
Kangaita	*0-30*	34.76	62.24	18.98	15.98	Sandy loam	• Gritty, slightly plastic and has high rate of hydraulic conduction of water.
	30-60	35.66	64.93	21.51	8.09	Loamy sand	
	Mean	**35**	**64**	**20**	**12**	**Sandy clay loams**	• Poor water holding capacity.
Kipkebe	*0-30*	35.34	26.80	43.04	30.13	Clay	• **Clay** soils ≥40%. Best at 47%.
	30-60	39.16	23.99	48.18	27.82	Clay	• Good water holding capacity, porosity and permeability despite high clay content.
	Mean	**37**	**25**	**46**	**29**	**Clay**	
Timbilil (control)	*0-30*	39.86	31.64	57.72	10.64	Clay	• **Clay** in the entire soil profile.
	30-60	40.62	15.90	72.86	11.24	Clay	• Good water holding capacity, porosity and permeability.
	Mean	**40**	**24**	**65**	**11**	**Clay**	

4.1.2. Chemical characterization of Kangaita, Kipkebe and Timbilil soils

Soils sampled from the three sites were subjected to lab chemical analysis, and the summary of the outcome is given in Table 4.2. Appendices 8.6 (Kangaita), 8.7 (Kipkebe) and 8.8 (Timbilil) carry detailed chemical characterization results.

Table 4.2: Chemical properties (mineral content) of soils sampled in October 2009 (0-60 cm)

Site	Depth (cm)	pH (1:2.5)	P ppm	K ppm	Ca ppm	Mg ppm	Mn ppm
Kangaita	0-10	4.10	82	276	130•	43•	46
	20-30	4.15	15	215	22•	13•	41
	40-60	4.12	12**	162	16•	10•	28•
	Mean	4.12	36	218	56•	22•	38•
Kipkebe	0-10	4.53	7**	622	1,117	231	84
	10-20	4.55	6**	480	1,166	259	49
	20-30	4.58	6**	401	1,075	236	38•
	40-60	4.62	9**	358	1,255	263	28•
	Mean	4.6	7**	465	1,153	247	50
Timbilil (control)	0-10	4.05	9**	290	725	107	64
	10-20	3.85	8**	248	245	58	58
	20-30	3.93	9**	239	236	52	38•
	40-60	4.04	10**	240	182	49	30•
	Mean	3.97	9**	254	347	67	48
Reference values		pH ≥6.5 unsuitable for tea growing, ≤3.5 too low (W&C, 1992 pp. 143)	*14 ppm* available P in Kenyan tea soils is adequate (W&C, 1992 pp. 139)	*811 ppm* available P in Kenyan tea soils is adequate (W&C, pp. 139)	*180 ppm* available P in Kenyan tea soils is adequate (W&C, 1992, pp139)	*303 ppm* available P in Kenyan tea soils is adequate (W&C, 1992 pp139)	*50 ppm* available P in Kenyan tea soils is adequate.

Key: (1) ** Nutrient highly deficient. (2) • Low base content. (3) W&C, 1992 = Willson and Clifford, 1992. (4) Conversion of units *ppm* to *meq/ 100 g soil*, it is divided by K (390), Ca (200), Mg (121) (Marx *et al.*, 1999).

4.2 Incident Solar Radiation (ISR) at Timbilil Agromet Station

The annual totals and monthly mean summary of radiation measurements (MJm^{-2}) taken at the Timbilil Agromet Station between January 2007 and December 2009 are presented in Table 4.3, but detailed data is given on Appendix 8.9.

Table 4.3: Mean monthly radiation (MJm^{-2}) and daily sunshine hours, 2007-2009 at Timbilil

Year	2007	2008	2009	Mean	SED
Mean daily sunshine hours (No.)	6.2	7.0	7.1	6.8	±0.493
Monthly radiation means (MJm^{-2})	20.3	21.5	21.7	21.2	±0.757

4.3 ISR (Wm^{-2}) at Kangaita and Kipkebe

Having taken broadband radiation raw data (***mV)*** in the field, the readings were then converted to total radiation (Wm^{-2}) (*Eq. 3.1*).

4.3.1. Kangaita radiation (E_{dir} Wm^{-2}) and the computed *Si* ratio

Radiation measurements were done at Kangaita's experimental plots. Table 4.4 shows computed fraction of intercepted E_{dir} (Wm^{-2}) by the canopy of the clones (***Si***) between 2007 and 2009. Reference on determination of ***Si*** (or ∑***RSi***) is made to *Eq. 3.2* (Chapter 3, pg. 43).

*Table 4.4: Fraction of E_{dir} (Wm^{-2}) intercepted by tea canopy of the clones cummulatively **(∑RSi)** at Kangaita, 2007-2009*

Clone and year	∑*RSi* (unitless) on the tea clones					No. of rain days
	301/5	31/37	31/8	TN 14-3	Annual mean	
2007	0.83	0.82	0.81	0.82	**0.82**	**163**
2008	0.83	0.82	0.83	0.82	**0.82↔**	**152↓**
2009	0.79*	0.79*	0.78*	0.79*	**0.79*↓**	**134↓**
Mean	***0.82***	***0.81***	***0.81***	***0.81***	**0.81**	
SED	***±0.023***	***±0.017***	***±0.025***	***±0.017***		

*Key: 1. * Less radiation intercepted by tea clones at Kangaita in 2009 due to leaf fall occasioned by drought.*
2. ↔ = Figure remained constant (unchanged)
3. ↓ = Figure decreased.

Cummulative radiation interception ratio (∑***RSi***) by all clones in 2007 and 2008 at Kangaita lay in the range of 78-83%, allowing only 17-22% irradiance to the maintenance layer (Table 4.4). In 2009, however, radiation capture by canopy showed a reversed cycle/ deviation, with all the clones recording a uniform ∑RSi of 79% from mean of 82% intercepted in 2008. Less radiation interception by tea clones at Kangaita in 2009 was due to leaf fall occasioned by drought.

4.3.2. Kipkebe radiation (E_{dir} Wm^{-2}) and the computed *Si* ratio

Just like it was done in the Kangaita trial, E_{dir} measurements were carried out at TRFK's Kipkebe experimental plots concurrently with Kangaita. Table 4.5 depicts the ratio of incoming and captured irradiance (∑***RSi***).

Table 4.5: Fraction of E_{dir} (Wm^{-2}) cummulatively intercepted by tea canopy of the clones **(∑*RSi*)** *at Kipkebe, 2007-2009*

Year	∑***RSi*** on the tea clones				
	301/5	**31/37**	**31/8**	**TN 14-3**	**Annual mean**
2007	0.61	0.58	0.57	0.64	**0.60**
2008	0.78	0.78	0.78	0.79	**0.78↑**
2009	0.79	0.82	0.83	0.87	**0.83↑**
Mean	***0.73***	***0.73***	***0.73***	***0.77***	**0.74**
SED	***±0.101***	***±0.129***	***±0.138***	***±0.117***	

Key: ↑ = Interception increased

With E_{dir} standard deviation of 150.8 for Kangaita and 97.4 for Kipkebe for the 3 year period, the graph shown as Fig. 4.1 (next page) was generated with standard error bars.

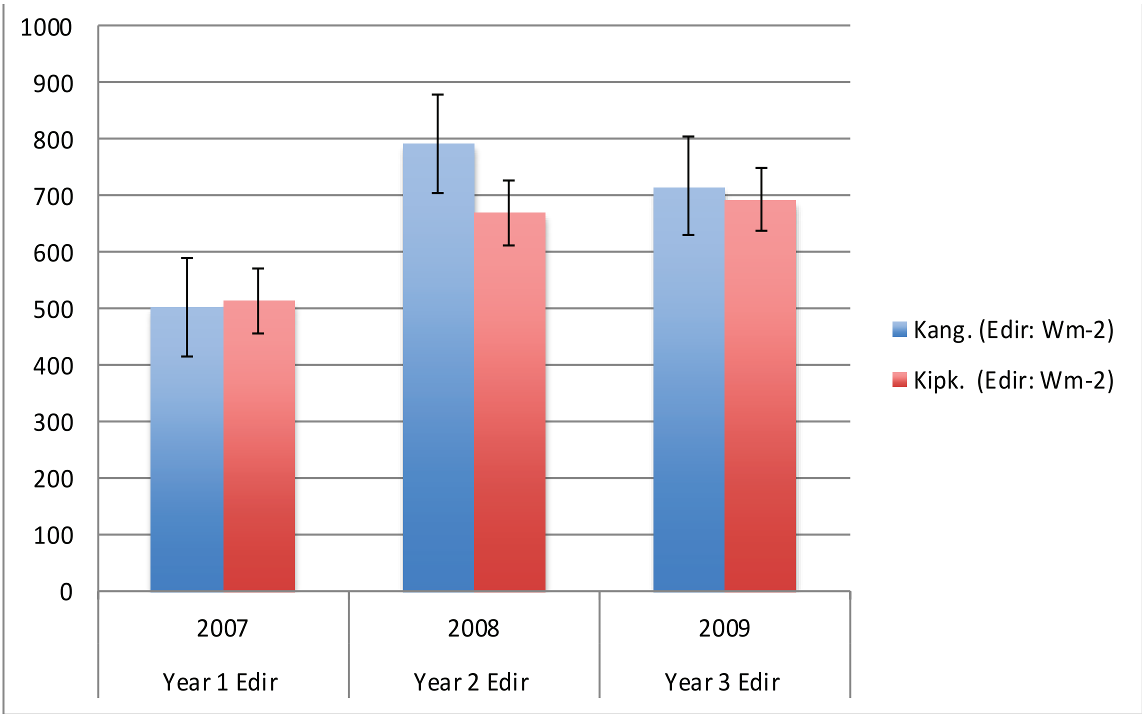


Fig. 4.1: Comparison of Edir (Wm^{-2}) at Kangaita and Kipkebe experimental sites in three years of experiment (2007-09) by columns with standard error bars.

4.3.3. E_{dir} (Wm^{-2}) across locations

Direct radiation results shown (E_{dir}) (Wm^{-2}) taken at the top and base of tea canopy is carried in Table 4.6.

Table 4.6: Summary of Kangaita and Kipkebe daily mean E_{dir} (Wm^{-2}) measurements, 2007-2009

Parametre	Site	Position	Treatment (tea clones)				
			301/5	31/37	31/8	TN 14-3	Annual Mean
Direct radiation (Wm^{-1})	Kipkebe	Mean for Top	623	624	625	627	625
		Mean for Base	168	160	161	138	157
	Kangaita	Mean for Top	677	656	692	656	670
		Mean for Base	125	124	134	126	127

4.3.4. E_{dir} and *Si* across seasons and clones

Table 4.7 contains measured direct radiation (E_{dir}) and computed intercepted solar radiation (*Si*) for Kipkebe and Kangaita in all the three seasons of the year.

*Table 4.7: Direct (**E_{dir}**) and intercepted irradiance (**Si**) grouped into 3 distinct seasons in tea growing areas of Kenya for top and basal parts of tea bushes, computed between 2007 and 2009*

Season	Location	E_{dir} Rep means (Wm^{-2}) Top	Base	*Si* (individual sites)	*Si* mean for sites
1	Kangaita	857	138	0.84	0.82
	Kipkebe	730	145	0.80	
2	Kangaita	630	148	0.77	0.81
	Kipkebe	592	84	0.86	
3	Kangaita	656	134	0.80	0.78
	Kipkebe	657	157	0.76	

Fig. 4.2 illustrates the light interception ratio (*Si*) seasonal conformity theory.

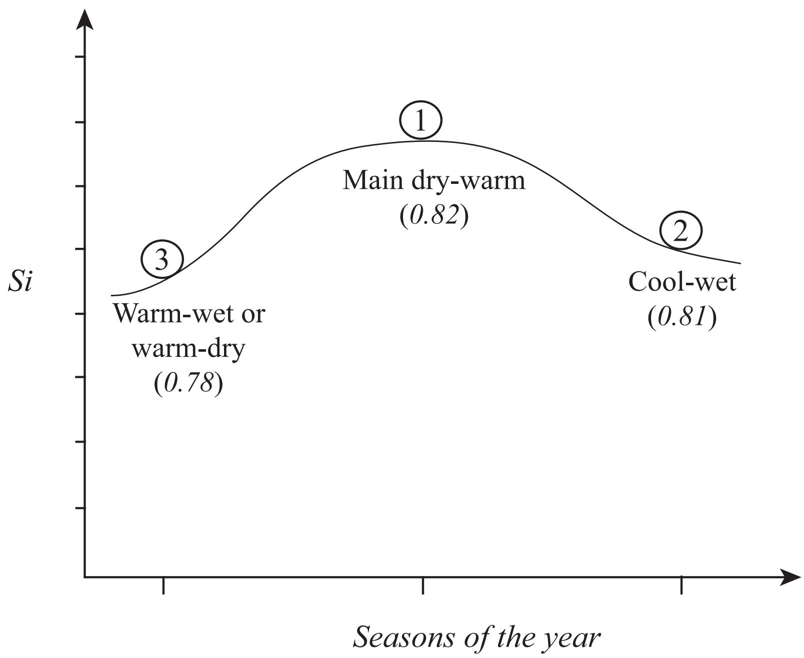


Fig. 4.2: Conformity of light interception measurements to seasonal patterns, Kangaita and Kipkebe sites combined, data given in Table 4.7.

It can be deduced from Fig. 4.3 below that the Kangaita $\sum RSi$ ratios are significantly higher than Kipkebe's because Kangaita had better established canopy structure comparatively.

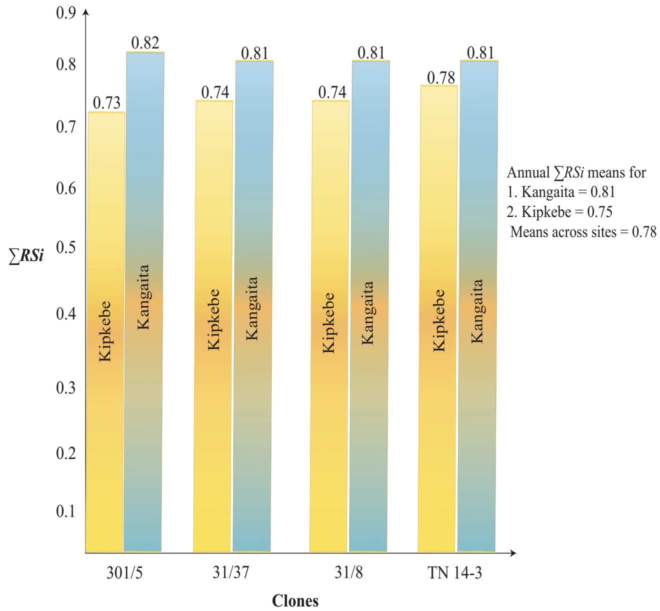
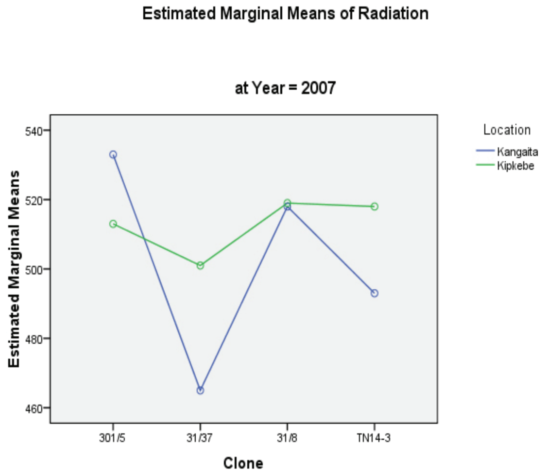


Fig. 4.3: Bar chart for the $\sum$***RSi*** *ratios across sites calculated from the 2007-2009 measurements.*

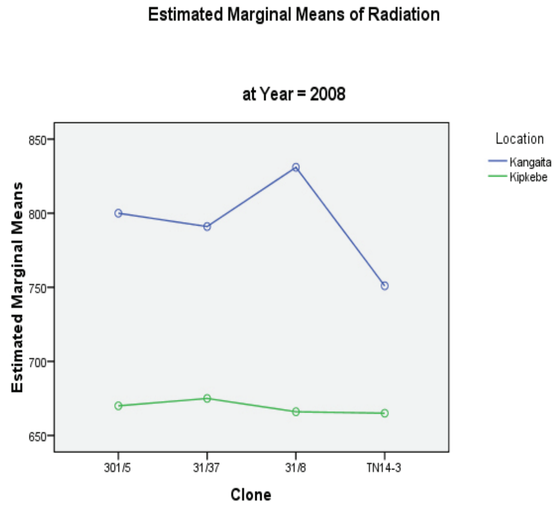
4.3.5. Statistical analysis

(a) Univariate ANOVA - Estimated marginal means of radiation

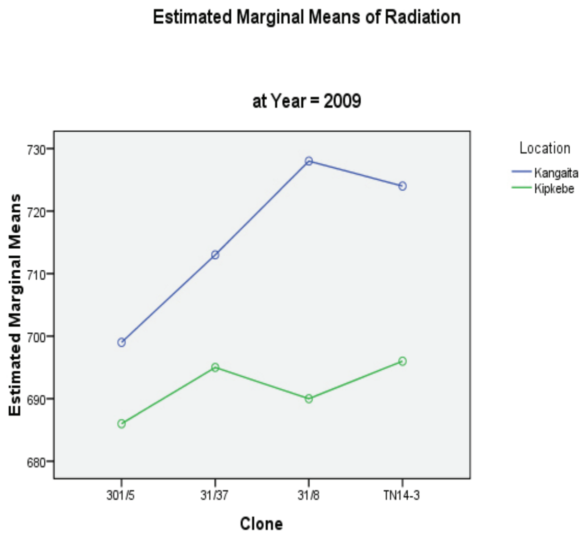
The three-year clonal radiation results on top of canopy (Appendix 8.11) were subjected to univariate ANOVA. A positive correlation between clones existed in the estimated marginal means measured between 2007 and 2009 (Fig. 4.4). The top canopy of clone 301/5 at Kangaita harvested the highest quantities of irradiance in 2007, while clone 31/8 recorded the highest in both 2008 and 2009. The outcome depicts clone 31/8 as a widely adapted variety.



(i)



(ii)



(iii)

Fig. 4.4: Clonal univariate ANOVA to estimate radiation marginal means across Kangaita and Kipkebe in (a) 2007; (b) 2008; and (c) 2009.

(b) ANOVA

Radiation across the replications, seasons and sites were subjected to ANOVA (GenStat, 2012) to determine significance at ≤ 0.05. The outcome of the analysis is given in Table 4.8.

Table 4.8: ANOVA of clonal radiation capture within and across replications, seasons and locations (Variate: Radiation)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	2	61900	30950	0.34	
Rep.Season stratum	6	592876	98813	1.09	
Rep.Season.Site stratum	9	158345	17594	0.19	
Genotype	3	10533	3511	0.04	0.990
Residual	267	24165523	90508		
Total	287	24989178			

No significant differences (F ratio ≤ 0.05) in radiation captured by the 4 clones (genotypes) was found to exist within and across the sites and seasons.

4.4 Ratio Between PAR and Total Radiation

4.4.1. Timbilil measurements

(a) '*ε*' Results

This study was done at Timbilil to determine relationship between PAR and total solar radiation. The PAR measurements was converted from ceptometer $\boldsymbol{R_S}$ readings in *mol* $m^{-2}\,s^{-1}$ (PAR) to direct radiation - Wm^{-2} for the purpose of determining the $\boldsymbol{Q_P{:}R_S}$ ratio from the relationship $\boldsymbol{Q_p} = \varepsilon R_s$, hence '***ε***' (epsilon value) by use of *Eq. 3.3*. The broadband tube solarimeter was calibrated against the standard using the KIPP and Zonen.

Table 4.9 presents the 'ε' Timbilil value, a computed ratio between Q_P and R_S, taken between March and April 2012.

Table 4.9: Mean daily radiation results (Wm^{-2} for E_{dir} & mol $m^{-2} s^{-1}$ for PAR) for top tea canopy, and determination of the value 'ε' in an experiment carried out at Timbilil, March-April 2012

Time (hr)	PAR (Ceptometer) quantum units ($mol\ m^{-2} s^{-1}$)	PAR converted to E_{dir} (Wm^{-2}) *[Eq. 3.5]*: Q_P	Conversion from tube solarimeter *(mV)* to direct solar irradiance (Wm^{-2}) *cf=0.706)*: R_S	Ratio of Q_P:R_S (ε values) at top of canopy
1000	1,268	276	609	0.4532
1200	1,435	312	725	0.4303
1400	1,095	238	497	0.4789
Mean	**1,266**	**275**	**610**	**0.4541**; SED ±0.0243

The mean ratio of PAR to total solar radiation (ε) at Timbilil was 0.45.

(b) ∑*RSi* results

The proportion of cummulative solar radiation values intercepted by the canopy (∑***RSi***) of the measurements derived using *Eq. 3.2* are presented in Table 4.10.

Table 4.10: ∑RSi at different times of the day at Timbilil (2012)

Time of measurement	∑*RSi*
1000 Hr	0.48
1200 Hr	0.42
1400 Hr	0.42

The proportion of irradiance intercepted by leaves on top canopy of tea plants (∑*RSi*) was higher at 1000 hr (48%) compared to hours later in the day (42%).

4.4.2. Conversion of R_S Kangaita and Kipkebe measurements to *PAR*

Since *Eq. 3.3* states:

$$Q_P = \varepsilon R_S;$$

PAR measurement apparatus was unavailable at Kipkebe and Kangaita. Therefore, having calculated the value of ε from Timbilil trial to be **0.45**, this figure was used to convert direct radiation data (R_S *in* Wm^{-2}) taken at Kipkebe and Kangaita to *PAR* (in $mol\ m^{-2}\ s^{-1}$), since these two sites (Kangaita and Kipkebe) lie near the equator as is the case with this study's reference point - Timbilil (Table 3.1), The data is given in Table 4.11.

Table 4.11: The 2007-2009 Kangaita and Kipkebe $\mathbf{R_S}$ *and* $\mathbf{Q_P}$ *values, with* ε **= 0.45** (SE ±0.0243)

Clone	Canopy	Kangaita			Kipkebe		
		R_S (Wm^{-2})	R_S × 4.6, i.e. conversion of R_S (Wm^{-2}) to *PAR* ($mol\ m^{-2}\ s^{-1}$)	Q_P ($Q_P=\varepsilon R_S$) (PAR in $mol\ m^{-2}\ s^{-1}$)	R_S (Wm^{-2})	R_S × 4.6, i.e. conversion of R_S (Wm^{-2}) to *PAR* ($mol\ m^{-2}\ s^{-1}$)	Q_P ($Q_P=\varepsilon R_S$) (PAR in $mol\ m^{-2}\ s^{-1}$)
301/5	Top	677	3114	***1401***	623	2866	***1290***
	Base	125	575	***259***	168	773	***348***
31/37	Top	656	3018	***1358***	624	2870	***1292***
	Base	124	570	***257***	160	736	***331***
31/8	Top	692	3183	***1432***	625	2875	***1294***
	Base	134	616	***277***	161	741	***333***
TN 14-3	Top	656	3018	***1358***	627	2884	***1298***
	Base	126	580	***261***	261	635	***286***

4.4.3. Conformity of PAR to three distinct seasons of the year in tea growing areas

As stated in section 2.5 of this thesis, published work points out that there exist three seasonal patterns in tea growing regions in Kenya. This study aimed at establishing the relationship between PAR outputs and the seasonal patterns in the highland regions of Kenya.

Eq. 3.3 was used to convert broadband direct radiation measurements taken at Kangaita and Kipkebe to PAR units (mol m^{-2} s^{-1}) as carried in Appendix 8.14 and Table 4.12.

Table 4.12: PAR (mol m^{-2} s^{-1}) and ***∑RSi*** *measurements grouped into 3 distinct seasons in tea growing areas of Kenya for top and basal parts of tea bushes, computed between 2007 and 2009. This study uses* **ε = 0.45** *for top canopy as calculated in Table 4.9.*

Season	Location	Q_p (PAR) location means (*mol m^{-2} s^{-1}*), with ε = 0.45	***∑RSi per location*** *(Eq. 3.2 based on PAR)*	***∑RSi per season*** *(Eq. 3.2 based on PAR)*
1	Kangaita	1,571	0.90	0.90
	Kipkebe	1,510	0.89	
2	Kangaita	1,304	0.88	0.90
	Kipkebe	1,226	0.92	
3	Kangaita	1,358	0.89	0.88
	Kipkebe	1,360	0.87	

4.4.4. Statistical analysis of Genotype (PAR) versus Environment (G×E) and seasons

Data was subjected to test G×E statistical relationship (ANOVA) (GenStat, 2012) and PAR and the 3 seasons. Results of this test are given in Table 4.13.

Table 4.13: ANOVA for G×E (Variate: PAR)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Environment (E) stratum	1	812853	812853	3.70	
E×Rep	4	877934	219484	0.39	
E×Rep×Season	12	6679598	556633	0.28	
Genotype (G)	3	93090	31030	0.02	0.997
G×E	3	35716	11905	0.01	0.999
Residual	120	239415650	1995130		
Total	143	247914841			

No significant difference was found to exist between PAR interceptions among genoptypes (G×E) in the two separate (within and across) environments. Likewise, no significant difference existed between PAR capture by the genotypes across seasons. This meant that the genotypes were equally suitable be grown in the sites where the experiments were conducted.

4.5 Air Temperature and Rainfall Measurements

The main climatic variables influencing yield of tea are temperature, the saturation deficit of the air and, through influence on plant and soil water deficits, rainfall and evapotranspiration (Stephens *et al.*, 1992). Saturation deficits (SD) above 2.3 kPa in Malawi (Tanton, 1982b) and soil water deficits exceeding 40mm in Tanzania (Stephens and Carr, 1993) have been reported to reduce yields. In Kenya, yield reductions of 200 kg ha^{-1} annually have been observed in commercial fields for every 100m rise in altitude, mainly due to associated temperature differences. Other climatic variables such as water stress and low soil temperatures have also been reported to reduce tea yields (Othieno *et al.*, 1992).

4.5.1. Temperature results

Arising from the recorded monthly temperature data for the period January 2007 to December 2009 averaged based on daily measurements and captured in Appendices 8.17 (Kangaita), 8.18 (Kipkebe) and 8.19 (Timbilil), mean minimum, mean maximum and overall mean daily temperatures spread over a period of 3 years is presented in graph depicted in Fig. 4.5. The daily averages of three-year measurements were tabulated (Table 4.14) and illustrated in Fig. 4.6. The three seasons of the year identified by Stephens *et al.* (1992) and Ng'etich *et al.* (1995) were marked and labelled in these illustrations (Figs. 4.5 and 4.6) to determine if Kangaita, Kipkebe and Timbilil follow the 3-seasonal pattern.

Table 4.14: Mean monthly rainfall and daily mean air temperature measurements for Kangaita, Kipkebe and Timbilil, January 2007 to December 2009

Month	Monthly means of 3-year rainfall measurements (*mm*)			Daily means of 3-year temperature measurements (^{O}C)		
	Kangaita	Kipkebe	Timbilil	Kangaita	Kipkebe	Timbilil
Jan.	72	105	91	15.9	20.4	17.0
Feb.	80	60	92	16.0	20.6	16.5
Mar.	112	103	157	16.8	20.8	17.1
Mean Season 1	***88***	***89***	***113***	***16.2***	***20.6***	***16.9***
Apr.	316	166	235	16.1	20.1	16.6
May	345	129	219	16.0	19.9	16.2
June	100	120	176	14.7	19.5	15.8
July	69	133	191	13.5	19.3	15.3
Aug.	137	163	223	13.2	19.0	15.8
Mean Season 2	***193***	***142***	***209***	***14.7***	***19.6***	***15.9***
Sept.	60	171	261	15.4	19.7	16.0
Oct.	353	95	251	16.0	20.5	16.2
Nov.	125	103	109	15.6	19.7	16.4
Dec.	89	111	99	15.6	19.9	16.6
Mean Season 3	***157***	***120***	***180***	***15.7***	***20.0***	***16.3***
Total	**1858**	**1459**	**2104**	**184.8**	**239.4**	**195.5**
Mean	**155**	**122**	**175**	**15.4**	**20.0**	**16.3**

4.5.2. Pearson correlation analysis of temperature across the 3 locations

Importance: Pearson square analysis was to determine correlation significance between temperature across the 3 locations (Kangaita, Kipkebe and Timbilil) at $p \leq 0.01$. This outcome determines use of temperature for further analysis. The outcome is given in Table 4.15.

Table 4.15: Temperature correlation in the 3 sites

Parameter interactions	Kangaita	Kipkebe	Timbilil
Kangaita	1	0.887**	0.829**
Kipkebe	0.887**	1	0.797**
Timbilil	0.829**	0.797**	1

** : *Correlation is significant at the 0.01 level (2-tailed).*

Temperature correlation between sites was significant at the 0.01 level (Pearson 2-tailed) between Kangaita and Kipkebe (p=0.887), Kangaita and Timbilil (p=0.829) and Timbilil and Kipkebe (p=0.797). Temperature difference between Timbilil and Kipkebe was closer compared to Kipkebe and Kangaita.

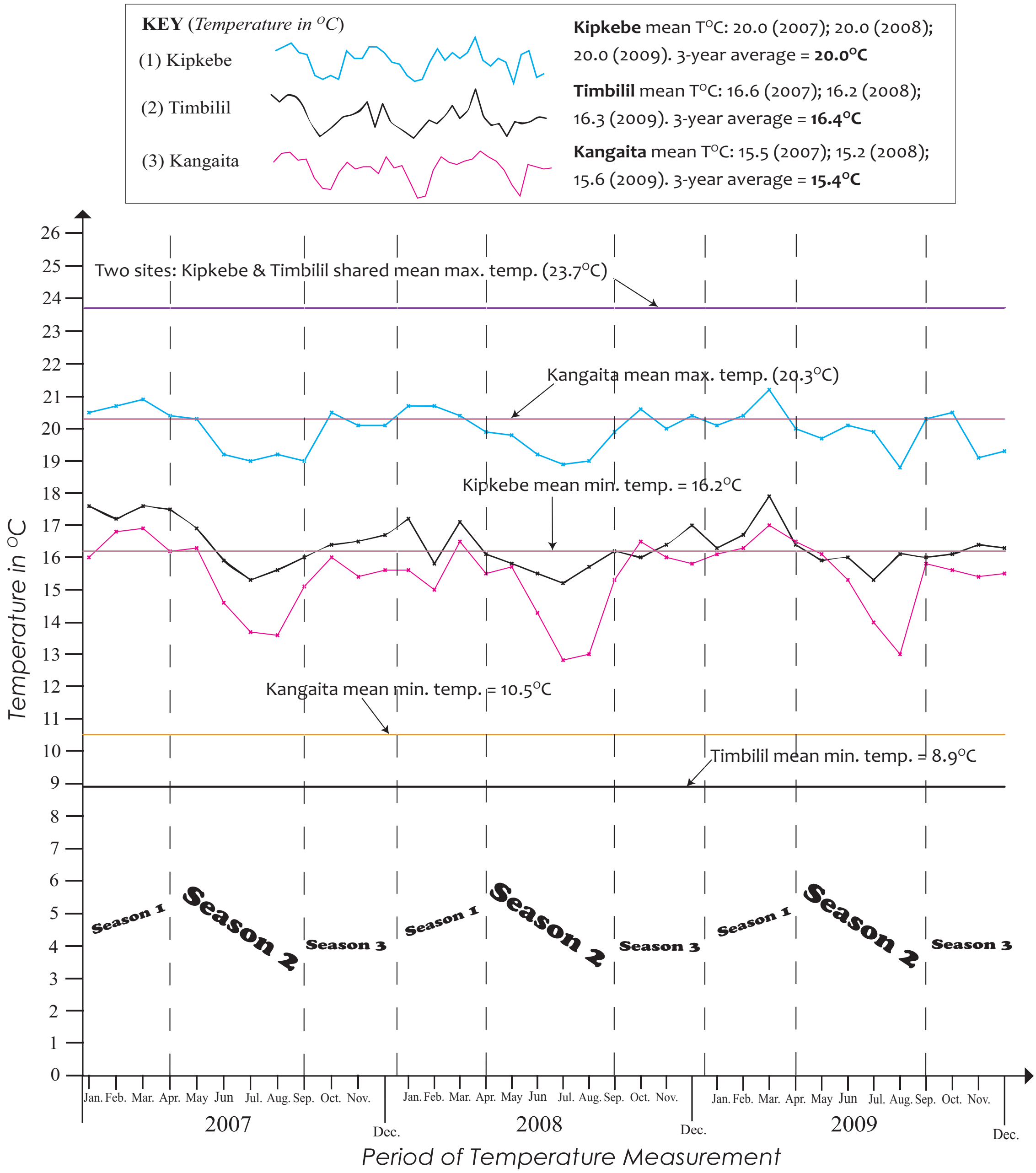


Fig. 4.5: Testing ***conformity of air T°C at Kangaita, Kipkebe and Timbilil to 3 tea seasonal patterns****, Jan. 2007-Dec. 2009 trial period.*

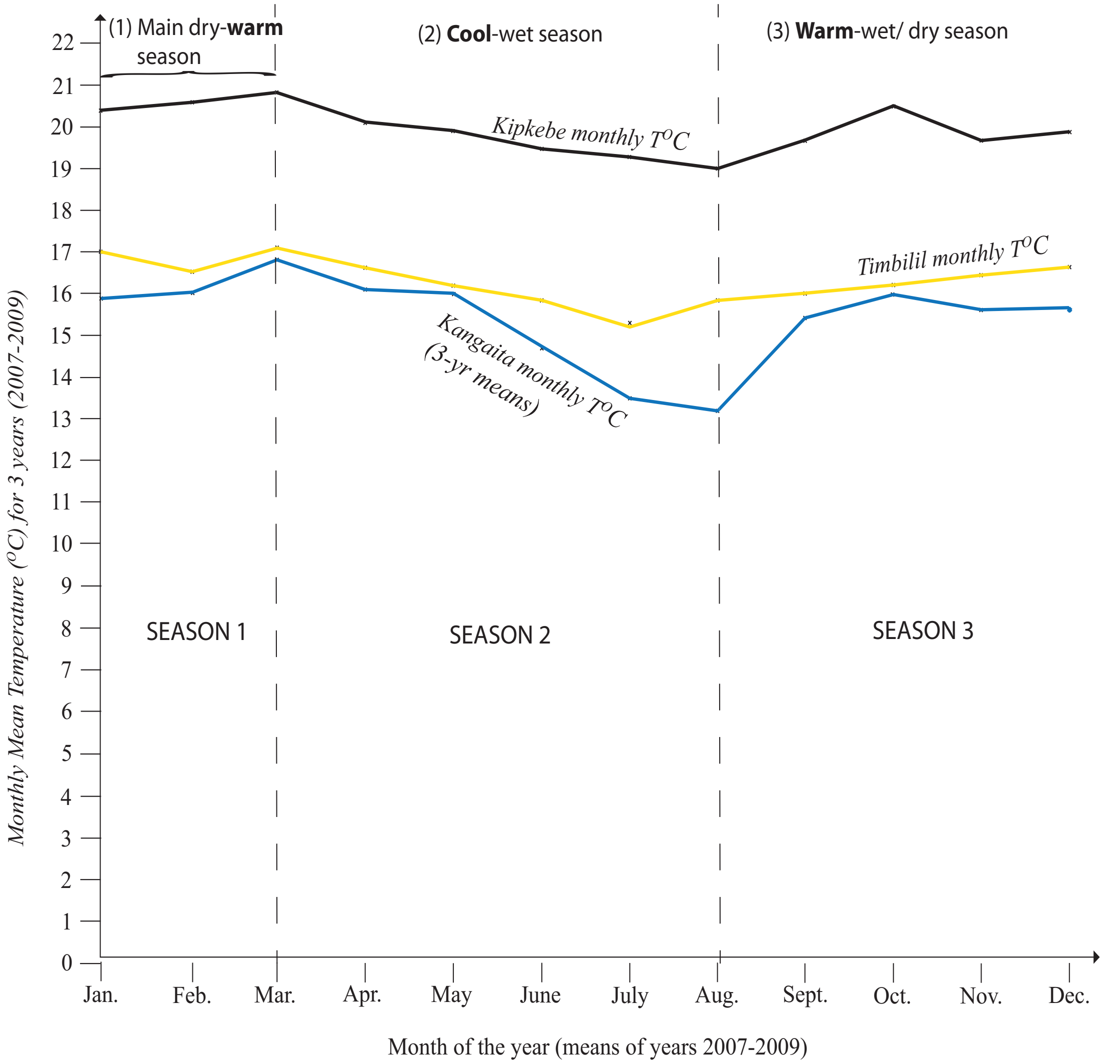


Fig. 4.6: The 3-year mean daily temperatures presented on monthly basis for Kangaita, Kipkebe and Timbilil.

4.5.3. Rainfall results

The Jan. 2007 - Dec. 2009 monthly rainfall measurements for the two trial and reference sites is given alongside temperature data in Appendices 8.17 (Kangaita), 8.18 (Kipkebe) and 8.19 (Timbilil). Since one of the specific objectives of this study was to measure rainfall and test the concept's conformity to the three seasonal cycles experienced in the tea growing zones of Kenya, measurements recorded on monthly basis was divided into three seasons of the year as suggested by Stephens *et al.* (1992) and Ng'etich *et al.* (1995). The 3 seasonal patterns experienced annually for three years cummulatively in the tea growing regions were marked in a graph and data carried in Table 4.14 extrapolated to test conformity. Graph given by Fig. 4.7 shows records of rainfall for the two trial (Kangaita and Kipkebe) and the reference (Timbilil) sites conformed to the three seasonal patterns.

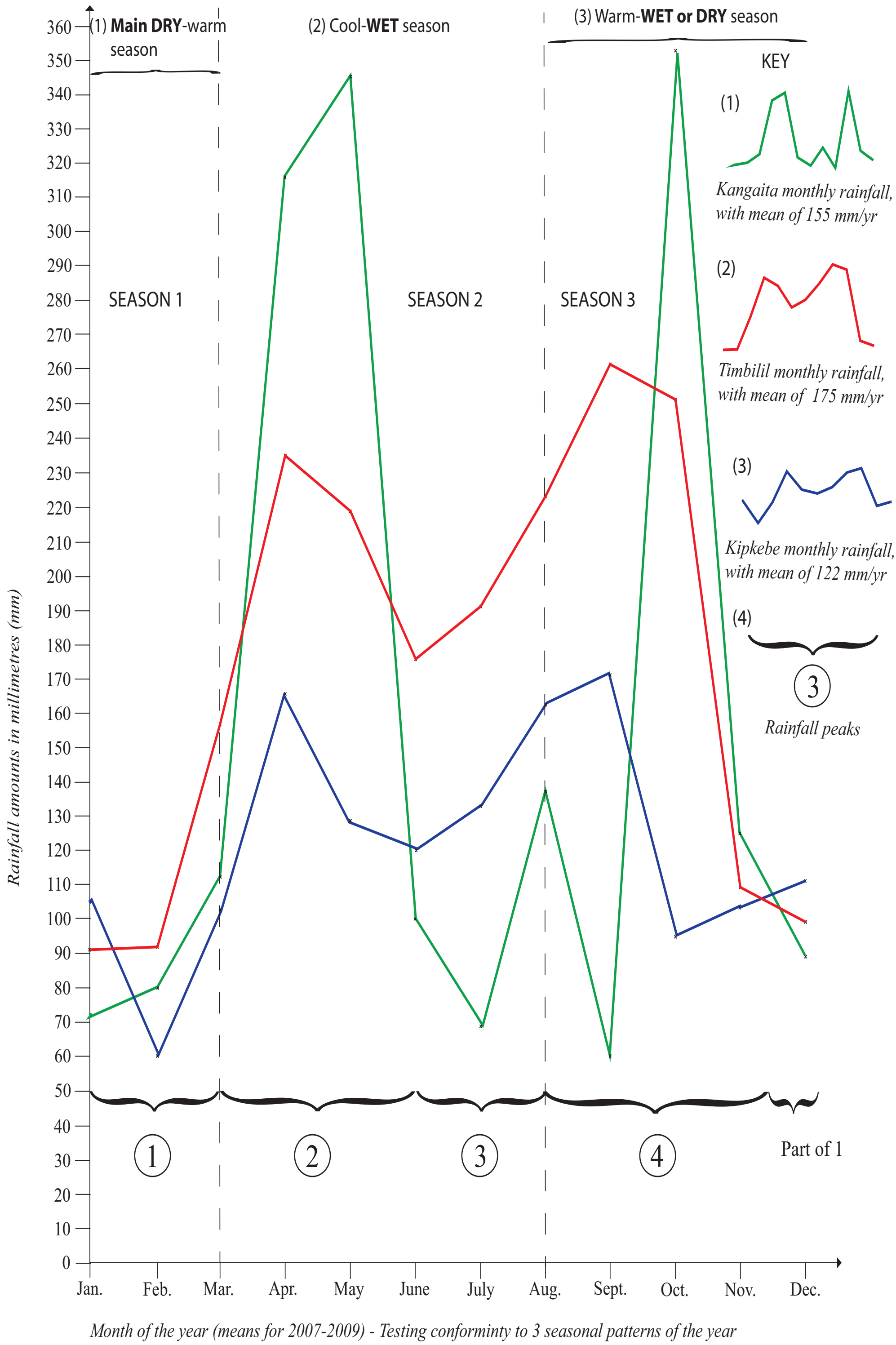


Fig. 4.7:Testing ***conformity of rainfall to 3 seasonal patterns****: The 3-yr rainfall monthly means for Kangaita, Kipkebe and Timbilil.*

(a) ANOVA: temperature across locations

GenStat (2012) was used to determine temperature ANOVA with location as treatment structure and season as block (Table 4.16).

Table 4.16: ANOVA of temperature across the locations (Variate: Temperature)

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Season stratum	2	26.0298	13.0149	27.24	
Location	2	416.5785	208.2893	435.91	<0.01**
Residual	103	49.2158	0.4778		
Total	**107**	**491.8241**			

**: *Statistical significant difference exists at ≤ 0.01.*

Temperature across locations was found to be statistically different from each other with F ratio ≤ 0.01. Temperature at Kipkebe site was found to be significantly different from that of both Timbilil and Kangaita.

(b) Statistical analysis of rainfall across seasons and locations

ANOVA (GenStat, 2012) was carried out with rainfall (variate) across seasons and locations (factors), using data measured from January 2007 to December 2009. Season 1 constituted rainfall data recorded from January to March, season 2 from April to August, while season 3 was precipitation received from September to December. The statistically analysed result is presented in Table 4.17.

Table 4.17: ANOVA of rainfall across the 3 locations and seasons (Variate: Rainfall)

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Location	2	51259	25630	2.94	
Season	2	109312	54656	6.27	0.003**
Season. Location	4	16294	4074	0.46	0.767
Residual	103	898323	8722		
Total	**107**	**058895**			

**: *The mean difference is significant at 0.05 level.*

Statistical outcome showed that rainfall was significantly different between seasons at $p \leq 0.05$. Rainfall data subjected to multiple comparison tests between seasons revealed that significance came from the difference between seasons 1 and 2. There was no difference though of rainfall between locations.

(c) Statistical analysis of yield between clones

ANOVA (GenStat, 2012) was carried to determine significance of yield between clones (as blocks). Treatments were the 2 sites and 3 years, while yield (tons $ha^{-1}yr^{-1}$) was the only variate (Table 4.18).

Table 4.18: ANOVA of clonal yield within and across sites (Variate: Yield)

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Clone stratum	3	0.7110	0.2370	0.68	
Site	1	0.5011	0.5011	1.45	0.248
Site.Year	4	11.7848	2.9462	8.50	≤ 0.01**
Residual	15	5.1995	0.3466		
Total	**23**	**18.1965**			

***: Statistical significant difference exists at <0.01.*

From results in Table 4.18, it is evident that yield across sites within the year was not different statistically, but highly significant (F ratio ≤ 0.01) across the 2 sites during the 3-year measurement.

4.6 Soil Temperature Determination and Modified Hillel's Model

4.6.1. Timbilil and Kangaita: Soil and air temperature relations

The 11-year (2000-2010) soil and air temperatures measured at Timbilil and Kangaita were used in this study. Measurements for the first 7 years (2000-2006) were obtained from TRFK's Agromet Station, while the rest (2007-2010) were measured alongside radiation data measurements. A graph plotted using Timbilil data (extracted from Appendix 8.20) reflected a close, consistent relationship between air and soil temperature parameters, with air temperature recording a uniform, constant figure below soil temperature (Fig. 4.8).

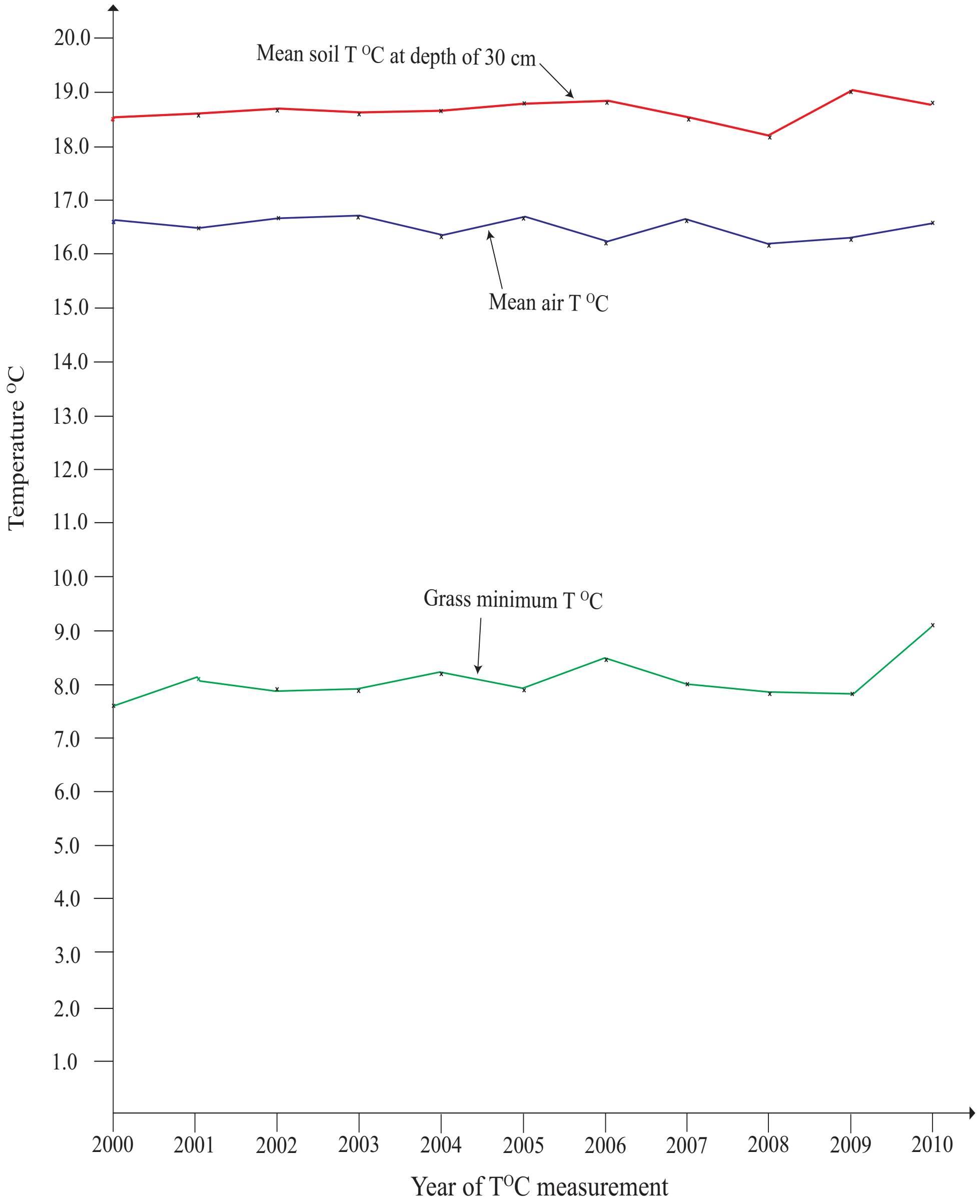


Fig. 4.8: Graphical representation of measured annual mean soil, air and grass minimum temperatures (^{O}C) taken at Timbilil trial site between 2000 and 2010 (11 years), being one of the parameters used to develop Model 1.

Kangaita soil (T_{EST}) and air (T_{MM}) temperature differences was calculated for the purpose of comparing and contrasting with those of Timbilil (extracted from Appendix 8.23). Table 4.19 (a) and (b) enumerates Timbilil and Kangaita ($T_{EST}-T_{MM}$) differences respectively.

Table 4.19 (a): Timbilil monthly means of differences between soil temperature (T_{EST}) at d=30cm and air temperature (T_{MM})

Month	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Means	SED
$(T_{EST}-T_{MM})$ (^{O}C)	1.9	2.1	2.0	1.9	2.4	2.1	2.6	1.9	2.0	2.7	2.2	2.1636	0.2838

Table 4.19 (b): Kangaita monthly means of differences between soil temperature (T_{EST}) at d=30cm and air temperature (T_{MM})

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Means	SED
$(T_{EST}-T_{MM})$ (^{O}C)	6.5	7.6	5.7	4.4	3.2	4.3	3.9	3.2	3.5	2.6	4.7	5.8	4.6167	1.5081

4.6.2. Analysis of variance

The Timbilil and Kangaita soil and air temperature differences were subjected to ANOVA (GenStat, 2012) to determine whether either of the two findings could be used to estimate Kipkebe soil temperature using measured air temperature. The T_{EST}^{O}C analysis across sites and different periods of measurement is depicted in Table 4.20.

Table 4.20: ANOVA of T_{EST} between Kangaita and Timbilil measurements (Variate: $T_{EST}$$^{O}C$)

Source of variation	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Period stratum	10	10.491	1.049	0.73	
Site	1	31.680	31.680	22.06	<0.01**
Residual	10	14.360	1.436		
Total	**21**	**56.531**			

***: Statistical significant difference exists at $F \leq 0.01$; SED=0.511.*

Analysis showed that soil and air temperature measurements across the two sites (Kangaita and Kipkebe) was statistically different from each other at F pr $\leq$ 0.01. The analysis outcome, therefore, rejects use of a universal air temperature to calculate ***[dT_{mb} - dT_{mm}]*** at *d*=30 cm for blanket tea growing zones. Having proved that empirical models are site specific, soil temperature of each site has to be measured/ calculated independently.

4.6.3. Hillel's model modification: Estimation of soil temperature (T_{EST}) at Timbilil and Kangaita using air temperature

Having discounted the general use of one formula to calculate soil temperature in all the tea growing locations using measured air temperature statistically (Table 4.20), the study came up with a modified scheme - *Model 1* (Fig. 4.9). *Eq. 5.1*, expressions provided by *Eq. 3.7* and published works by Hillel (1982), Wu and Nofziger (1999), Salamene *et al*., (2010); Smith *et al.* (1998) were used in this study to come up with Fig. 4.9. The authors above had applied their models on soil not covered extensively by vegetation. This modified model, specifically developed for Timbilil and Kangaita at *d*=30 cm, only applies when measured air temperature is available. Conversely, it can be used to estimate air temperature for a particular location when soil temperature is measured.

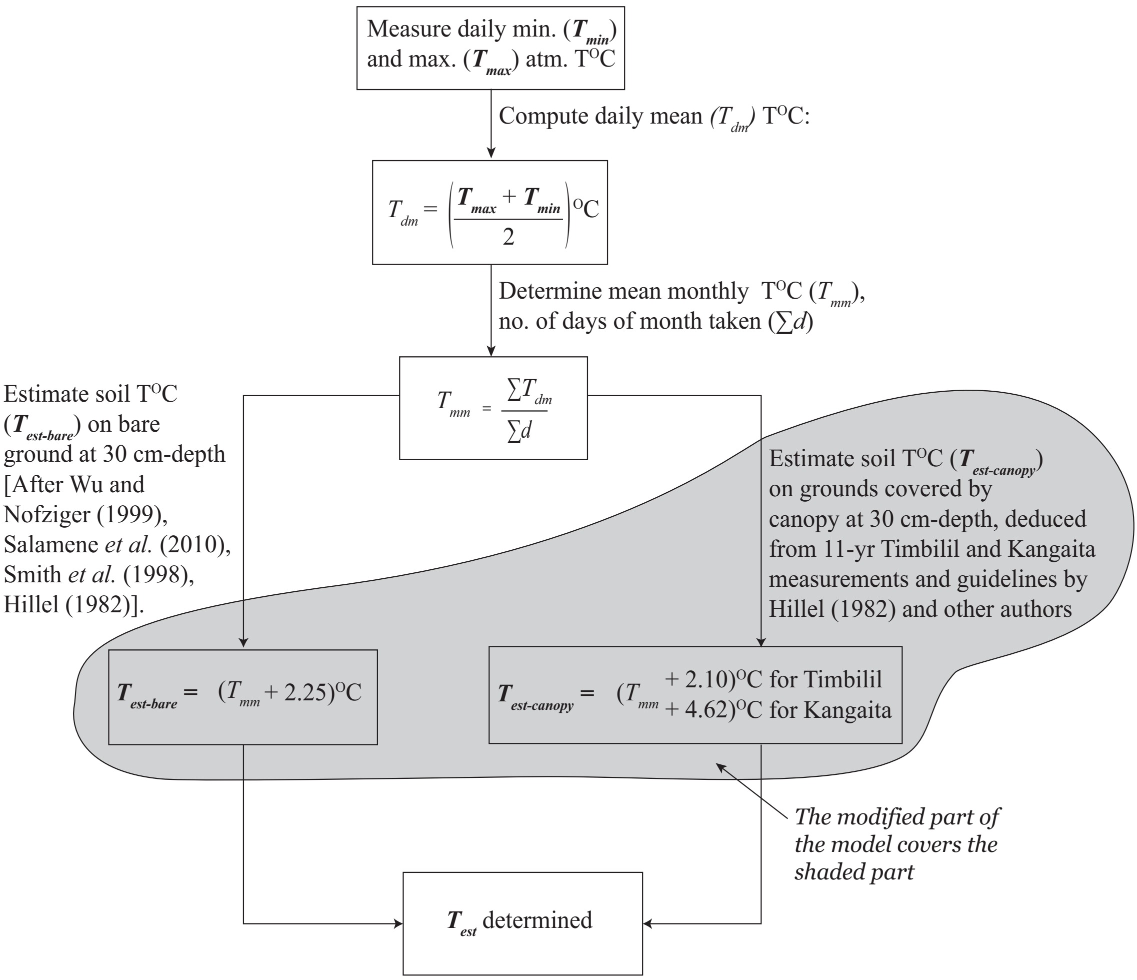


Fig. 4.9: Model 1: A model used to estimate soil temperature at d=30 cm on grounds covered by canopy - Timbilil and Kangaita.

The outcome of *Model 1* (Fig. 4.9) shows that differences between air and soil temperatures is higher by 0.15-0.45^{O}C for bare grounds compared to canopy-covered Timbilil fields. This factor is far much higher (over 2.50^{O}C) at Kangaita. The modified part of this model is given by the shaded region.

4.7 Yield Measurements

Fresh leaf weights (grammes - *g*) in 3 reps were taken in the field and mean determined. To convert *green leaf mass (g)* to *dry matter,* the mean so determined was multiplied by the TRFK factor of 0.225 *(kg* ha^{-1} y^{-1}*)* or divided by 1,000 *(t* ha^{-1} y^{-1}*)*. The later was used to calculate the results.

Individual clone yields calculated annually for Kangaita and Kipkebe are given in Table 4.21.

Table 4.21: The 2007 to 2009 yield, temperature and rainfall at Kangaita and Kipkebe

Year	Clone	Kangaita			Kipkebe			Mean clonal yield
		Yield (tons $ha^{-1}y^{-1}$)	Temp. (^{O}C)	Rainfall (mm)	Yield (tons $ha^{-1}y^{-1}$)	Temp. (^{O}C)	Rainfall (mm)	
2007	301/5	2.207	186.2	2196.5	2.454	239.9	1339.2	2.3305
	31/37	2.230			3.207			2.7185
	31/8	2.280			2.379			2.3295
	TN14-3	1.603			2.302			1.9525
	Total	**8.320**	**186.2**	**2196.5**	**10.342**	**239.9**	**1339.2**	
	Means	**2.080**	**15.5**	**183.0**	**2.586**	**20.0**	**111.6**	
2008	301/5	5.678	182.0	1764.8	2.512	239.5	1543.7	4.095
	31/37	4.163			3.571			3.867
	31/8	4.627			3.384			4.006
	TN14-3	3.231			3.237			3.234
	Total	**17.699**	**182.0**	**1764.8**	**12.704**	**239.5**	**1543.7**	
	Means	**4.425**	**15.2**	**147.1**	**3.176**	**20.0**	**128.6**	
2009	301/5	2.397	186.6	1613.0	2.571	239.4	1607.0	2.484
	31/37	3.629			3.136			3.383
	31/8	2.772			2.921			2.847
	TN14-3	3.544			3.219			3.382
	Total	**12.342**	**186.6**	**1613.0**	**11.847**	**239.4**	**1607.0**	
	Means	**3.086**	**15.6**	**134.4**	**2.962**	**20.0**	**134.0**	
3-yr means	301/5	3.427	15.4	154.8	2.512	20.0	124.7	2.970
	31/37	3.341			3.305			3.323
	31/8	3.226			2.895			3.061
	TN14-3	2.793			2.919			2.856
	Total	**12.787**	**46.3**	**464.5**	**11.631**	**60.0**	**374.2**	
	Means	**3.197**	**15.4**	**154.8**	**2.908**	**20.0**	**124.7**	

Season 3 clonal PAR statistical analysis and its correlation with yield

Since clonal PAR measurements for season 3 was measured uninterrupted for three continuous years (2007-09), this set of data was used to come up with a 2-way univariate general linear model (GLM). The plotted graph of the 3-yr mean PAR versus genotypes is given by Fig. 4.10.

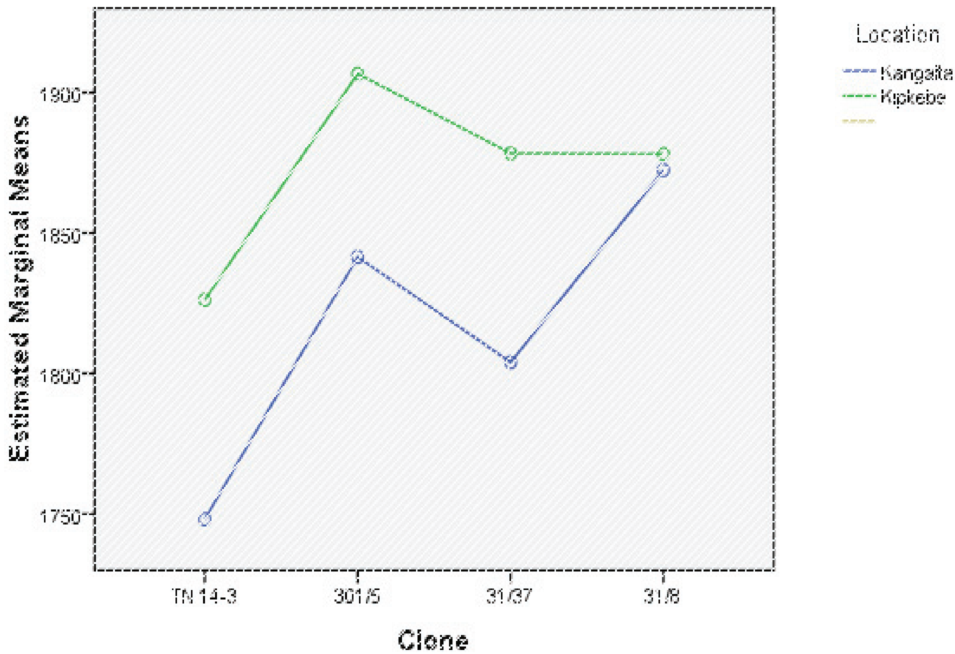


Fig. 4.10: Estimated marginal means of PAR at season 3 (September to December) for the period 2007-2009 using a 2-way GLM.

Correlation coefficient (r) analysis: Total solar radiation versus yield

Correlation coefficient (r) analysis between clonal yield (Table 4.21) measured from 2007 to 2009 in relation to Timbilil total radiation (Table 4.3) returned r = 0.53, representing a strong positive correlation between the two variables (yield and solar radiation).

4.8 Statistical Correlations: Interactions Between Yield, Location, Genotype (PAR), Year, Temperature and Rainfall

The measured variables were subjected to bivariate correlation coefficient analysis, and results reflected in Table 4.22.

Table 4.22: Use of bivariate 2-tailed correlation (Pearson) method to determine correlations between variables

Parameter interactions	Yield	Location/ Site	Genotype PAR	Year	Temperature	Rainfall
Yield	1	-0.166	-0.078	0.324	-0.197	-0.173
Location/ Site	-0.166	1	0.000	0.000	0.999**	-0.684**
Genotype PAR	-0.078	0.000	1	0.000	0.000	0.000
Year	0.324	0.000	0.000	1	0.009	-0.244
Temperature	-0.197	0.999**	0.009	0.009	1	-0.682**
Rainfall	-0.173	-0.684**	-0.244	-0.244	-0.682**	1

** : *Correlation is significant at the 0.01 level (2-tailed).*

Results carried in Table 4.16 deduced that temperature across the 3 sites (Kipkebe, Timbilil and Kangaita) was significantly different from each other at the 0.01 level. The temperature variation exist across locations owing to differences in radiation as temperature is driven by solar radiation. Further bivariate correlation analysis (Table 4.22) between variables showed a significant strength of association between location and temperature (0.999). Their association and correlation coefficient is highly significantly different from zero ($P \leq 0.01$). Correlation coefficient of rainfall across the 3 locations was also found to be (highly) statistically different from zero ($P \leq 0.01$) as well.

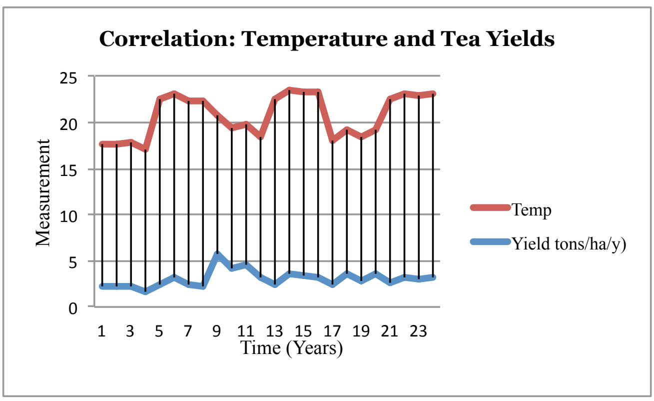


Chart correlation analysis (Fig. 4.11) depicts a positive relationship between temperature and yield.

Fig. 4.11: Correlation analysis between temperature and yield.

CHAPTER FIVE

DISCUSSIONS

5.1 Soil Characterization

(a) Physical characterization

(i) Kipkebe soils

The Kipkebe soil was observed to be darkish-brown within the shallow depths of the surface horizons to reddish-brown as depth increased to deeper layers. The percentage levels of sand (25%) and clay (46%) across all the soil depths was, on average, uniform (Table 4.1). Silt percentage levels (29%) across all the entire site were shown to be high when compared with Kangaita (12%) and Timbilil (11%) (Reference data in Appendix 8.4).

(ii) Kangaita soils

From data shown on Table 4.1, the Kangaita trial site soil is generally darkish-brown within the 15-cm depth to reddish-brown at 60-cm. The results of soil analysis from Kangaita revealed that soil is mainly sandy clay loams (20% clay and 64% sand). The results agree with the findings of Wachira *et al*. (2002). It is also gritty, slightly plastic and has high rate of hydraulic conduction of water. This is due to the high level of sand and low level of clay almost across all soil depths. Kangaita soils have poor water holding capacity (high level of sand and low level of clay) compared to Kipkebe's, explaining why soil moisture level is higher at Kipkebe (37%) compared to Kangaita (35%), but lower compared to Timbilil's (40%). This condition makes plants become water stressed during dry spells.

While Kangaita soils are volcanic (poor water retention due to high porosity), Kipkebe soils are mainly clayey (46%). In addition to Table 4.1, reference can also be made to Appendix 8.3 for data on Kangaita soil physical characterization.

(iii) Timbilil soils

Soil samples drawn from Timbilil's Field 7 in August 2009 showed that clay component was the highest (62%) compared to Kikebe's (46%) and Kangaita's (20%). The Timbilil clay soil classification by the study confirms work by Wachira *et al.* (2002). The strong clay character enables soil to hold more moisture and retain it for longer periods as evidenced in the high moisture content (40%) recorded in this study. Soil characterized at Kangaita and Kipkebe over the same period registered lower moisture content levels of 35% and 37% respectively. Timbilil soils share similar characteristics with Kipkebe as both have good porosity, permeability and water holding capacity (Reference data in Appendix 8.5).

(b) Chemical characterization

Optimum tea soil is acid in reaction. The best soil for tea is in the range of 5.0-5.6. As soil pH decreases below 5.0, deficiency of base nutrients (K, Mg, Mn, Ca, *etcetera*) and phosphate are likely to be expressed as a result of pronounced leaching effect. TN 14-3 has been shown to tolerate high soil pH (Tea Growers Handbook, 2002).

Data presented in Table 4.2 shows that the mean soil acidity level is lower at Kangaita (pH of 4.1) and Timbilil (pH of 4.0) when compared with Kipkebe (pH 4.6). It is also evident from the analysis that Kangaita soils have lower content of the bases: K (276 ppm), Ca (130 ppm), Mg (43 ppm), Mn (46 ppm) at the rhizosphere region (0-10 cm) compared to both Kipkebe (622 ppm K, 1117 ppm Ca, 231 ppm Mg and 84 ppm Mn) and Timbilil (290 ppm K, 725 ppm Ca, 107 ppm Mg and 64 ppm Mn). Bases are the most deficient (lowest) at Kangaita when compared to the other two locations due to extensive leaching effect that took place because its soil is mainly sandy (64%) in texture (Table 4.1).

Kipkebe and Timbilil soils are significantly deficient in P (7 ppm P Kipkebe and 9 ppm P Timbilil at the rhizosphere), while Kangaita's contents are below optimal quantities (82 P ppm at the top soil level). N-fertilization in commercial tea farms has been over-emphasized at the expense of P-replenishment, explaining why P contents are low in the three locations. Kipkebe (1,153 Ca ppm) and Timbilil (725 Ca ppm) have excess quantities of Ca compared to Kangaita (56 Ca ppm). Higher quantities of K, Ca and Mn bases at Kipkebe arose due to lower acidity levels (high pH), while long-term application of NPK (high levels of N) fertilizer at Timbilil has led to lower pH (3.97) in its fields. K is adequate in all the three sites.

5.2 Measurement of Total Radiation (MJm^{-2}) and PAR at two Sites

(a) Total radiation at Timbilil

For significant production to be realized, Squire (1977) emphasizes that tea requires at least 5 sunshine hours per day, because tea yields drop drastically under cloudy conditions. The 3-year solar radiation results met this threshold.

From the summarised data (Table 4.3), the 2007 mean daily sunshine hours (measuring 6.2 hr) were lower than in subsequent years (7.0 hr in 2008 and 7.1 hr in 2009) with standard error of deviation (SED) of ±0.493. Monthly direct solar radiation measurements for 3 years running (2007-2009) showed no significant difference, with radiation mean monthly output of 21.2 MJm^{-2} and SED = ±0.757.

Ethical Tea Partnership (2011) reported that Kenya's tea growing areas are witnessing changing weather patterns, which include increasing temperatures, decreasing rainfall and increases in the propensity of hail, droughts and frosts. More specifically, CIAT (2011) predicts in a model that maximum temperature for the year will increase from 26.6 ^{O}C to 29.0 ^{O}C while the warmest quarter gets hotter by 2.3 ^{O}C in 2050. This is confirmed in Table 4.3 where a steady rise in both daily sunshine hours and radiation in 3 years running is attributed to temperature increase. Since temperature is driven by solar radiation (ISR), its long-term effect leads to climate change.

Yield data given on Table 4.21 shows that 2007 produced least mean clonal outputs for both Kangaita (2.1 t $ha^{-1}y^{-1}$) and Kipkebe (2.6 t $ha^{-1}y^{-1}$), compared to the subsequent years. It was determined in 2008 and 2009 that the number of sunshine hours went up by a digit (7.0 hr; 20.3 MJm^{-2} and 7.1 hr; 21.7 MJm^{-2} respectively), evidently giving rise to higher yields, i.e. 4.4 t $ha^{-1}y^{-1}$ for Kangaita and 3.2 t $ha^{-1}y^{-1}$ for Kipkebe in 2008. More cloudy days on average were recorded in this study in 2007 than in the 2 subsequent years (Appendix 8.10). The low total radiation in 2007 (20.3 MJm^{-2}) is therefore, attributed to higher cloud cover experienced in 2007 compared to 2008 and 2009, resulting in reduced yield. The outcome depicts close relationship between total radiation and yield.

(b) Kangaita and Kipkebe direct (E_{dir}) and intercepted radiation ($\sum RSi$)

(i) E_{dir}

Direct radiation (E_{dir}) reaching the top canopy of tea crops per site at any given time should be the same irrespective of the recipient genotype. Results, however, showed that E_{dir} measurements varied from clone to clone per location owing to spatial time taken while taking measurements across the reps. E_{dir} for the two sites was the least in 2007 compared to 2008 and 2009.

Kangaita

From the daily E_{dir} top leaf harvest of solar energy (Appendix 8.15[b]), it can be seen that the smallest quantity of this energy was realized in 2007 (502 Wm^{-2}), compared to 2008 (793 Wm^{-2}) and 2009 (716 Wm^{-2}) as given in Fig. 4.1. This result agrees with Timbilil's E_{dir} findings (Section 4.2, Table 4.3) whose radiation measurement was also lowest during the 2007 period (20.3 MJm^{-2}). The 2007 Kangaita radiation findings agree with Kipkebe data as well since higher cloud cover recorded during first year of this study in the two sites resulted in lower radiation capture by tea crop canopy. This low radiation energy appears to have impacted negatively on tea crop yields, since in subsequent years when E_{dir} was higher, higher yields (4.4 t $ha^{-1}y^{-1}$ in 2008, and 3.1 t $ha^{-1}y^{-1}$ in 2009) were realized.

There was E_{dir} capture difference among the tea clones in that clone 31/8 gave the largest E_{dir} (134 Wm^{-2}) on average in a period of 3 years. The topmost part of clone 31/37 captured the least irradiance (124 Wm^{-2}).

Kipkebe

It was shown that $\boldsymbol{E_{dir}}$ energy intercepted by top part of tea bushes across the clones was lowest in 2007 across the sites, with Kipkebe realizing 513 Wm^{-2} while Kangaita had 502 Wm^{-2} (Appendix 8.15[b and c]). The 2008 (669 Wm^{-2}) and 2009 (692 Wm^{-2}) measurements were similarly higher than that of 2007, as was the case with Kangaita. This agrees with Timbilil's $\boldsymbol{E_{dir}}$ trial as well (Section 4.2, Table 4.3) where radiation measurements were lowest in 2007 (20.3 MJm^{-2}). It shows that radiation intensity was highest in 2008 (793 Wm^{-2}) while the highest peak of 692 Wm^{-2} was realized at Kipkebe in 2009 (Fig. 4.1). Cloudless skies contributed to higher $\boldsymbol{E_{dir}}$ in 2008 as opposed to 2007 where more cloudy days were recorded.

(ii) $\sum$***RSi***

Kangaita (Table 4.4)

It was expected that progressive canopy formation should have hindered more light penetration to maintenance layer in 2009, raising the $\sum$***RSi*** ratio. The canopy allowed the highest intensity of ISR (21%) to penetrate into the lower layers of the leaves compared to the first 2 years (2007 and 2008) of the trial. This could have been due to reduced interception of light caused by water stress. Rainfall facilitates tea canopy establishment, contributing to maximum ISR interception. Low mean monthly rainfall at Kangaita (Appendix 8.17) in 2009 (134 mm) compared to the first 2 years (183 mm in 2007 and 147 mm in 2008) of this trial, coupled with fewer number of rainy days recorded the same year (134 days) compared to the preceding 2 years led to moisture content deficit in the soil, causing senescent leaves to fall off. Limited number of young leaves was, therefore, unable to shield the lower layers and allowed more light to penetrate to the base of the plant (maintenance layer), resulting in reduced harvestable leaves, hence lower yield.

Kipkebe (Table 4.5)

Irradiance penetration to the maintenance layer beneath the top canopy was more pronounced in 2007 (60% on average across the treatments) compared to the subsequent years (78% in 2008 and 83% in 2009) (Table 4.5). Two reasons may have led to less radiation interception in 2007, hence less dense canopy: (i) Insufficient rainfall in 2007 (mean monthly of 112 mm) (Appendix 8.18) compared to Kangaita (183 mm) may have resulted in slow growth of the vegetative parts of the plants leading to reduced canopy density, poor ground cover formation as was the case with the Kangaita case (sub-section 4.3.1); (ii) Slow recovery of the clones following pruning carried out in February 2007.

Unlike the Kangaita trial where more light energy penetrated into the maintenance layer (reduced light interception) in the third year (2009) of trial due to leaf fall, the Kipkebe experiment followed the expected solar interception cycle. Light interception indicated a progressive canopy development such that by 2009, a more dense canopy had been formed, resulting in more interception of light than in the 2 preceding years (Table 4.5), in which more light was intercepted with time as a result of build-up of denser canopy (Table 4.5).

Low $\boldsymbol{E_{dir}}$ in 2007 resulted in low yields (2.6 t $ha^{-1}y^{-1}$) compared to 2008 and 2009 and (3.2 t $ha^{-1}y^{-1}$ and 3.0 t $ha^{-1}y^{-1}$ respectively). TN 14-3 was the most effective in irradiation interception (78%), while clone 301/5 allowed most of $\boldsymbol{E_{dir}}$ to the maintenance layer (73%).

(c) $\boldsymbol{E_{dir}}$ (Wm^{-2}) across locations

Results shown in Table 4.6 indicate that higher $\boldsymbol{E_{dir}}$ energy values was intercepted on top of tea bushes at Kangaita (670 Wm^{-2}) compared to Kipkebe (625 Wm^{-2}). Conversely, measurements at the base of tea plants shows that Kipkebe tea plants allowed more light at the base as a result of inadequate canopy cover that arose from pruning that took place in February 2007, a few months prior to commencement of experiment. The clones had slow recovery, explaining why there was less irradiance at the base of the plants in Kangaita (bigger canopy cover - 127 Wm^{-2}) compared to Kipkebe (157 Wm^{-2}).

Irradiance at the base do not necessarily determine the productivity level of the crop, but is equally important because it stores the crop's food reserves used to maintain the crop. Leaves on this layer play an equally important role as those located at the top in that food reserves are stored here and used to maintain the crop. Harvest of light on top is more critical as harvestable tender leaves are located at the top part of the canopy structure. The growth habit (erectness) of a clone determines efficiency in ***Si*** interception to a large extent. The larger the crop canopy size, the higher the solar rays intercepted as more photosynthesizing leaves have access to direct solar irradiance which translates to higher outputs of photosynthates, hence more harvestable yield. A clone with a good frame and hard branches like TRFK 12/12, having horizontal spread and semi-erect leaves realises higher harvest of solar irradiance than a clone that exhibits vertical growth habits (Wachira *et al.* 2002). In addition, the crown architecture (the totality of the plant's above-ground parts) and leaf mosaics are important in carbon-fixation (Valladares and Pearcy, 2000).

In this study, Kangaita's E_{dir} of 670 Wm^{-2} realised a higher annual made tea yield of 3.2 t $ha^{-1}y^{-1}$ on average compared to Kipkebe's lower irradiance (625 Wm^{-2}) that gave made tea yield of 2.9 t $ha^{-1}y^{-1}$ over the same period.

(d) E_{dir} and *Si* across seasons and clones

(i) E_{dir}

Computation carried on Table 4.7 shows that season 1 (mid-December to end of March) recorded the *largest* irradiance (R_S) on top of tea canopy with a mean of 857 Wm^{-2} at Kangaita and 730 Wm^{-2} at Kipkebe. According to Stephens *et al.* (1992) and Ng'etich *et al.* (1995), this season is *dry and warm*, explaining why this trial recorded the highest R_S.

The *least* direct solar energy (R_S) measurement intercepted on top of tea plants in the two locations was in season 2, where Kangaita recorded 630 Wm^{-2} while Kipkebe's was 592 Wm^{-2}. According to Stephens *et al.* (1992) and Ng'etich *et al.* (1995), this season (2) is supposed to be *cool and wet*, and runs from April to August each year. Kipkebe recorded the least irradiance (84 Wm^{-2}) in season 2 for the measurement taken at the bottom of tea bushes.

Irradiance intensity of season 3 lies between that of seasons 1 and 2, with both sites receiving equal quantities of irradiance intensities, i.e. Kangaita 656 Wm^{-2} and Kipkebe 657 Wm^{-2}. Published works from earlier authors have it that season 3 should be *warm and wet*, or *warm and dry*, and runs from September to mid-December. Once more, the findings of this trial further confirms conformity of this experiment with the three seasonal patterns advanced by Stephens *et al.* (1992) and Ng'etich *et al.* (1995).

(ii) ***∑RSi ratio***

The mean solar radiation values (***∑RSi***) for the two sites put together further supports the 3-season theory in that 82% of irradiance was captured at the top canopy of tea bushes in season 1, while 81% was captured in season 2 and 78% in season 3. Higher solar radiation was intercepted during the dry spell (season 1) compared to the other 2 seasons (seasons 2 and 3).

(iii) ***Clonal solar interception***

Although Kangaita and Kipkebe clones under study were planted at the same time in June 1998, the 10-year old clones showed significant variations in canopy cover across the sites as given in Fig. 4.3. Overally, the ratio of solar interception was higher at Kangaita (81%) compared to Kipkebe (75%) by a 6%-point.

5.3 The Ratio Between PAR and Total Radiation in Tea

(a) Timbilil trial

Ceptometer (PAR) findings (column 2) carried in Table 4.9 reveal that the sun reaching the earth's surface differ in intensity at different times of the day. Some of the days, the skies were cloudy at 1400 hours, partly explaining why radiation values obtained at 1400 hr were low (1,095 mol $m^{-2} s^{-1}$). The highest irradiance was captured at 1200 hours (1435 mol $m^{-2} s^{-1}$), owing to the high intensity of heat and clearer skies during this time compared to morning and afternoon hours.

The ε concept, formalized by Monteith (1977) on experimental and theoretical grounds, was conceived as a robust and appropriate modelling approach to describe crop growth. Despite the preference for ε-based growth-engines, they still suffer from many drawbacks (Kiniry *et al.*,1989; Sinclair and Muchow, 1999; Albrizio and

Steduto, 2005). Criticisms include: inconsistent and variable estimates of ε within and between crop species, and even between C_3 and C_4 crop groups; unpredictable ε between locations and years; and unreliable attempts to normalize ε for climate. Furthermore, ε often loses its linearity under water stress (Azam-Ali *et al.*, 1984) and nutrient deficit conditions (Muchow and Davis, 1988; O'Connell *et al.*, 2004).

As for $\boldsymbol{Q_p{:}R_s}$ (ε value) ratio, Table 4.9 shows that the lowest ratio was recorded at 1200 hours (ε = 43.03%), while radiation measurement on top of tea bushes at 1400 hours gave the highest ε of 47.89%. The trial's top of bushes radiation ε mean measurement was **0.4541 (45%)**, with standard error of deviation (SED) of ±0.0243.

The top canopy 'ε' mean (PAR to total radiation) of **0.45** computed in this study is comparable to the global value published by Gonzalez and Calbo (2002); McCree (1972); Howell *et al.* (1983) and Meek *et al*. (1984). The idea was to use the calculated factor to convert direct radiation measurements (represented here by R_S) at Kangaita and Kipkebe to PAR (denoted by Q_P).

(b) Conversion of $\boldsymbol{R_S}$ Kangaita and Kipkebe measurements to *PAR*

Since the experiment involved measuring radiation on top and bottom canopy of at least 3 bushes per clone per rep per site, the exercise took upto an hour to complete measurements of all the 3 replications. Under perfect conditions, radiation measurements should be taken at once in all the treatments, blocks and sites. This was not possible as readings were recoreded sequentially starting from block 1 treatment 1, all the way from blocks 1 to 3. As measurement exercise from one clone to the next took time, solar intensities were bound to vary owing to differences in cloud cover conditions.

From Table 4.11, the largest PAR (Q_P) at Kangaita was recorded on top of canopy of clone 31/8 (1,432 mol m^{-2} s^{-1}), while the least was in clones 31/37 and TN14-3 where 1,358 mol m^{-2} s^{-1} was recorded. These measurements were higher than Kipkebe's where 1,298 mol m^{-2} s^{-1} was captured on top of clone TN14-3 while 1,290 mol m^{-2} s^{-1} was recorded in clone 301/5. The difference in PAR measurements within clones in a given location was not significant.

Timbilil's highest PAR measurement of 1,435 mol $m^{-2} s^{-1}$ (top of canopy) (Table 4.9) compares favourably with the two sites. The outcome depicting TN 14-3 as among the highest recipients of PAR (1,358 mol $m^{-2} s^{-1}$ for Kangaita and 1,298 mol $m^{-2} s^{-1}$ for Kipkebe) did not translate to equally higher yield (Table 4.21).

5.4 Air Temperature and its Conformity to Seasonal Patterns in the Tea Zones

Starting with the specific years, three sites compared, the highest daily mean maximum temperature recorded in 2007 was in Timbilil in March (25.7^{O}C), while in 2008 and 2009, the highest was 25.7^{O}C in January (Timbilil) and 27.4^{O}C in March (Timbilil) respectively. In all the 3 years, the highest daily mean maximum temperatures was either in January or March (season 1). It can be deduced from these measurements that although Timbilil recorded the highest daily mean maximum temperature, the highest overall daily mean temperature over the same period was in March (20.8^{O}C) at Kipkebe. It can also be seen in Fig. 4.5 that the mean monthly temperature curve consistently shoots above the mean annual temperature line in all the 3 years in season 1 (January to March), while the same curve reduces drastically in season 2. In season 3, it more-or-less levels off.

On the other hand, the 3-yr overall daily mean air temperature given in Table 4.14 and Fig. 4.5 (and Appendices 8.17, 8.18 and 8.19) shows that peak was recorded in the month of March in all the three trial sites, where 16.8^{O}C was recorded in Kangaita, Kipkebe registering 20.8^{O}C and Timbilil recording 17.1^{O}C. Temperature means for season 1 in the 3 sites was the highest compared to seasons 2 and 3 (Table 4.14). The outcome of this study agrees with that suggested by Stephens *et al.* (1992) and Ng'etich *et al.* (1995) on this season (1) as it is expected to experience the highest temperatures during the year, i.e. between mid-December and March. On the other hand, the lowest mean temperature was experienced in the month of August at Kangaita (13.2^{O}C) and Kipkebe (19.0^{O}C), while Timbilil's lowest temperature was recorded in the month of July (15.3^{O}C). Further analysis on temperature means for season 2 showed that it is the least compared to the other two seasons. Season 2 commences in April and comes to a close in the month of September each year. This season has been described by authors as '*cool*' (Stephens *et al.*, 1992 and Ng'etich *et al.*, 1995), hence lowest annual mean temperatures recorded in this study was expected during this period in the three sites. Between September and mid-December, moderately high temperatures in October at Kangaita (16.0^{O}C), Kipkebe (20.5^{O}C) and Timbilil (16.2^{O}C) were recorded. The lowest mean temperatures were recorded at Kangaita (15.4^{O}C), while Kipkebe's measurement was the highest (20.0^{O}C). Timbilil's mean daily temperature between January 2007 and December 2009 was 16.3^{O}C. Further, the 3-year mean daily temperature summary (Fig. 4.5) presents Kipkebe as the hottest site with a mean of 20.0^{O}C followed by Timbilil (16.3^{O}C), while Kangaita emerged the coldest with 15.4^{O}C. Based on the tabulated research findings (Table 4.14) and the wavy illustration presented by Figs. 4.5 and 4.6, it is evident that temperature situations at Kangaita, Kipkebe and Timbilil sites follow the weather seasonal pattern described by Stephens *et al.* (1992) and Ng'etich *et al.* (1995).

5.5 Clonal Yields at two Sites

(a) Correlation between PAR and yield

The clonal PAR correlation results (Fig. 4.11) showed that the least radiation was recorded on TN 14-3 at both locations, with Kangaita giving lower PAR values compared to Kipkebe's. On the other hand, clone 301/5 recorded the highest PAR values at both locations, with Kipkebe recording the highest peak comparatively. The highest PAR value at Kangaita was recorded by clone 31/8. A close scrutiny of Table 4.21 and Fig. 4.10 indicated a positive correlation between PAR quantities and yield volumes in both locations. While the lowest PAR measurements at Kangaita was recorded on TN 14-3 (2.8 t $ha^{-1}y^{-1}$), the highest PAR for the 3-yr means was recorded in clone 301/5, which corresponded with the highest clonal yield of 3.4 t $ha^{-1}y^{-1}$. A positive correlation was depicted between PAR and yield in all the 4 clones. The marginal means of PAR for clone 31/8 converged at one point, clearly indicating that this is a universal clone.

(b) Yield across the sites

If ***i*** is known, yield provides a good representative of DM. Based on the 3-year means, it can be deduced from Table 4.21 that clone 301/5 produced higher yield at Kangaita

(3.4 t $ha^{-1}y^{-1}$) than Kipkebe (2.5 t $ha^{-1}y^{-1}$). Least clone yields were recorded in clone TN 14-3 at Kangaita (2.8 t $ha^{-1}y^{-1}$) and 301/5 (2.5 t $ha^{-1}y^{-1}$) at Kipkebe. The highest annual yield was recorded on clone 301/5 in Kangaita in 2008 (5.7 t $ha^{-1}y^{-1}$), while 2.5 t $ha^{-1}y^{-1}$ was harvested at Kipkebe in the same clone during this period. The lowest yield was witnessed in 2007 at Kangaita where clone TN 14-3 gave only 1.6 t $ha^{-1}y^{-1}$. ANOVA (Table 4.18) indicated that yield across sites and years differed significantly at p=0.01.

5.6 The Relationship Between Rainfall and Yield in Tea

(i) Kangaita

Precipitation amount is a critical factor that influence crop yield (Stephens *et al*., 1992). In the Kangaita trial however, the experiment produced the following results: in 2007, a total of 2197 mm was received, while the average clonal yield comprised 2.1 t $ha^{-1}y^{-1}$, 1765 mm in 2008 (4.4 t $ha^{-1}y^{-1}$) and 1613 mm in 2009 (3.1 t $ha^{-1}y^{-1}$) (Fig. 4.7 and Appendix 8.17). From these findings, periods that had lower rainfall amounts gave higher yields. Higher rainfall amounts did not translate to higher yields compared to the impact the E_{dir} had on the tea crop yield. Interception directly impacted on tea crop yield.

(ii) Kipkebe

Contents of Tables 4.14 (precipitation) and 4.21 (yield) shows that the 2007 monthly precipitation of 112 mm realized a clonal average yield of 2.6 t $ha^{-1}y^{-1}$, while the 2008 (129 mm) and 2009 (128 mm) gave bigger yields of 3.2 $ha^{-1}y^{-1}$, and 3.0 $ha^{-1}y^{-1}$, respectively. While rainfall amounts at Kangaita did not seem to have significantly influenced yield, rainfall was a significant factor at Kipkebe in that it contributed towards determination of yield volume as suggested by Stephens *et al*. (1992).

5.7 Conformity of PAR and Rainfall to the Three Seasonal Cycles in the Tea Growing Zones

Weather is bound to change. The 3-seasonal pattern conformity theory study was carried out not to disapprove it but to provide further information on weather patterns of tea growng areas of Kenya.

(a) Conformity of PAR to the three seasonal patterns

In Table 4.12, season 1 (mid-December to end of March) PAR gave 1,571 mol m^{-2} s^{-1} at Kangaita and 1,510 mol m^{-2} s^{-1} for Kipkebe, the *highest* PAR ($\boldsymbol{Q_p}$) values on top canopy of tea bushes, all the three seasons compared. This was expected as mean temperature at the end of season 1 in all the three sites was equally the highest as given in Table 4.14. The *lowest* PAR measurement was in season 2 (Table 4.12), where Kangaita recorded 1,304 mol m^{-2} s^{-1}, Kipkebe's 1,226 mol m^{-2} s^{-1}. The least PAR (1,226 mol m^{-2} s^{-1}) was in season 2, taken at Kipkebe. The intensities of measurements of seasons 3's PAR lied in between seasons 1 and 2 (Kangaita 1,358 mol m^{-2} s^{-1} and Kipkebe 1.360 mol m^{-2} s^{-1}). While more solar energy was intercepted by the top canopy at Kangaita in seasons 1 (90%) and 3 (89%), Kipkebe harvested more in season 2 (92%) as Kangaita recorded 88%.

(b) Conformity of rainfall to the three seasonal patterns

Reference is made to Table 4.14, Fig.4.7 and tea growing zones' seasonal patterns described by Stephens *et al.* (1992) and Ng'etich *et al.* (1995). Starting with Kangaita (Appendix 8.17), peak rainfall amounts in the months of April (382 mm in 2007), May (497 mm in 2007 and 305 mm in 2009), August (243 mm in 2007) and October (384 mm in 2008 and 489 mm in 2009). These months are either placed in seasons 2 or 3. This pattern is replicated at Kipkebe (211 mm in July 2008) and Timbilil (372 mm in October 2009) sites. Seasons 2 and 3 are described by Stephens *et al.* (1992) and Ng'etich *et al.* (1995) as *wet* (season 2) and *wet or dry* (season 3), while season 1 is classified as *main dry*. This study further validates the weather pattern concept in that the *least (driest)* precipitation amounts (Table 4.14) recorded at Kangaita was in the month of September (60mm), while similar amount (60 mm) was recorded at Kipkebe in February. The driest month at Timbilil was January where a 3-year mean of 91mm was measured. The 3-year rainfall summary (Fig. 4.7) gave peak precipitation in May (345 mm in season 2) and October (353 mm in season 3) at Kangaita. Kipkebe also had duo peaks: 166 mm in April (season 2) and 171 mm (season 3) in September, while the highest rainfall measurements was recorded at Timbilil in 3 peaks: 235 mm in April (season 2), 261 mm in September and 251 mm in October both of these months being in season 3.

5.8 Computed Soil Temperature Using Air Temperature for Tea Growing Areas

From Fig. 4.8 and *Eq. 3.7*, it is deduced that:

$$T_{est\text{-}canopy} = (T_{mm} + [dT_{mb} - dT_{mm}]) \qquad (Eq\ 5.1)$$

It (*Eq. 5.1*) showed that mean air temperature for Timbilil was **2.2^{O}C** $[dT_{mb} - dT_{mm}]$ below soil temperature at *d*=30cm, while that for Kangaita was **4.6^{O}C**, making it impossible to generalize soil temperature at different sites as the difference between these two values is huge. The Timbilil findings compares favourably with work carried out by Smith *et al*. (1998) where annual mean air temperature remained about 2.0-2.5^{O}C uniformly below soil temperature at 50cm depth, and 1.0-2.0^{O}C below soil temperature at 150cm depth, and Wu and Nofziger (1999) whose model consistently underestimated soil temperatures by about 2^{O}C. The Kangaita mean finding (4.6^{O}C), however, was at variance not only with the Timbilil measurements, but also with work carried out by authors mentioned above.

Higher soil temperature amount recorded at Kangaita seems to have influenced made tea yield. Output of 3.2 tons $ha^{-1}\ y^{-1}$ (Table 4.21) harvested at Kangaita was higher than Kipkebe's (2.9 tons $ha^{-1}\ y^{-1}$).

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATION

6.1 CONCLUSIONS

1. There was a steady rise in total radiation per annum at Timbilil between 2007 and 2009. A strong positive relationship exists between total solar radiation (hence PAR) and yield.

2. Using equation $\boldsymbol{Q_P = \varepsilon R_S}$ (*Eq. 3.3*), this study computed PAR to total solar radiation ratio ['ε' (epsilon)] in tea over Kericho to be 0.45. This ratio was similar in all the sites where the trial was conducted.

3. Rainfall influenced yield amounts significantly at both Kipkebe and Kangaita.

4. Kangaita soil temperature was significantly higher than Kipkebe's. This factor seems to have influenced yield as higher soil temperature resulted in more yield on average in the three year period. Rhizosphere soil temperature greatly influenced yield.

6.2 RECOMMENDATION

The study findings on the relationship between PAR and total radiation ratio of **0.45** is recommended for use in tea highland regions of Africa to use evaluate clones for radiation use efficiency.

7.0 REFERENCES

Ahmad M. F. and Rasul G. (2008). Prediction of soil temperature by air temperature, a case study of Faisalabad. Pakistan Journal of Meteorology, Vol. 5 Issue 9, pp. 19-27.

Albrizio R. and Steduto P. (2005). Resource use efficiency of fieldgrown sunflower, sorghum, wheat and chickpea. I. Radiation use efficiency. Agricultural and Forest Meteorology **130**, 254–268.

Anderson J. M. (1986). Photoregulation of the composition, function and structure of thylakoid membranes. Annual Review of Plant Physiology **37**: 93–136.

Anon (1998). Human nutrition in Tropical Africa. pp. 229-230.

Anon (1962). Historical notes on tea introduction in Africa. In: Tea Estates in Africa (Compiled by Wilson, Smithett and Co). London: Mabey and Fitzclarence Ltd, pp. 6-9.

Azam-Ali S.N., Gregory P.J. and Monteith J.L. (1984). Effects of planting density on water use and productivity of pearl millet (Pennisetum typhoides) grown on stored water. II. Water use, light interception and dry matter production. Exp. Agr. **20**, 215–224.

Bandyopadhyay, T. (2011). Molecular marker technology in genetic improvement of tea. International Journal of Plant Breeding and Genetics, pp. 1-2.

Banerjee, B. (1992). Selection and breeding criteria. In: Willson, K. C. and Clifford, M. N. (Eds). Tea: Cultivation to consumption. Chapman & Hall, 2-6 Boundary Row, U.K., London. pp. 53-81.

Barua, D.N. (Ed.) (1989). Science and Practice in Tea Culture. Tea Research Association, Calcutta, Jorhat, India pp. 509.

Bezbaruah, H. P. (1988). Release of biclonal stock TS 491. Two and a Bud **35**, 55.

Bhagat R. M., Baruah R. D. and Safique S. (2010). Climate and tea [*Camellia sinensis* (L.) O. Kuntze] production with special reference to North Eastern India: A review. Journal of Environmental Research and Development Vol. 4 No. 4, pp. 1017-1028.

Bhardwaj, H.L. and A.S. Bhagsari (1989). Harvest index, yield, and physiological characteristics of soybean as related to seed size. Soybean Genetics Newsletter. **16**:133-136.

Bonheure, D. (1990). Tea: The tropical agriculture series. CTA, Macmillan Educational Ltd., London, pp. 102.

Bore, J. K. (2008). Physiological responses of grafted (*Camellia sinensis*) to water stress. PhD. Thesis, Egerton University, Njoro, Kenya.

Brisson N., Gary C., Justes E., Roche R., Mary B., Ripoche D., Zimmer D., Sierra J., Bertuzzi P, Burger P, Bussiere F., Cabidoche Y. M., Cellier P., Debaeke P., Gaudillere J. P., Henault C., Maraux F., Seguin B. and Sinoquet H. (2003). An overview of the crop model STICS. European Journal of Agronomy: 309–332.

Burgess, P. J. (1992). Response of tea clones to drought in Southern Tanzania. PhD thesis, Granfield Institute of Technology, Silsoe College, UK.

Campbell, G. S. and Norman J. M. (1989). The description and measurement of plant canopy structure. In: Rusell G., Marshall B. and Jarvis P. G. eds. Plant Canopies: The Growth, Form and Function. Cambridge University Press, Cambridge, New York, New Rochelle, Melbourne, Sydney, pp.1-19.

Cannell, M. G. R. (1985). Dry matter partitioning in tree crops. In: *Atrributes of Trees as Crop Plants*, 160-193 (Eds: M. G. R. Cannell and J. E. Jackson). Huntingdon: ITE/ NERC.

Carr, M. K. V. and Stephens, W. (1992). Climate, weather and yield of tea in "Tea: Cultivation to consumption". (Eds. K. C. Willson and M. N. Clifford), London: Chapman and Hall.

Chen, H., Fong, C. H. (1994). Drought damages and related factors in tea (*Camellia sinensis*) in Taiwan. Chinese Journal of Agrometeorology **1**, 133-141.

Cheruiyot, E. K. (2008). The influence of soil water content and nitrogen supply on growth, yield and polyphenol content of selected tea (*Camellia sinensis* [L.] O. Kuntze) cones in Kenya. PhD Thesis, Egerton University, Kenya.

CIAT (Centro Internacional de Agricultura Tropical) International Center for Tropical Agriculture (2011). Future Climate Scenarios for Kenya's Tea Growing Areas; Final report, Cali, Managua: April, 2011 A.A. 6713, Colombia. pp. 1-8.

Cochran C. C. (2010). Soil moisture-temperature correlation and classification model. 19th World Congress of Soil Science, Soil Solutions for a Changing World,1-6 August 2010, Brisbane, Australia.

Cooper, J. D. (1979). Water use of a tea estate from soil moisture measurements. East African Agriculture and Forestry Journal. **43**: 102 - 121.

Corley, R. H. V. (1983). Potential productivity of tropical perennial crops. Experimental Agriculture **19**, 217-237.

Donald C. M. and Hamblin J. (1976). The biological yield and harvest index of cereals as agronomic and plant breeding criteria. Adv. Agron., **28**, 361-405.

Eeles, C. W. O. (1979). Soil moisture under montane forest and tea. East African Agriculture & Forestry Journal. **43**: 122 - 138.

Ehleringer, J. R. and Cerling, T. E. (2002). C_3 and C_4 photosynthesis. In: Volume 2, The Earth System: Biological and Ecological Dimensions of Global Environmental Change. Eds: Mooney H. A. and Canadell J. G. pp 186–190.

Ellis, R. T. (1978). Clones or seed. TRFCA Quarterly Newsletter **50**, 8-10.

Ethical Tea Partnership (2011). Climate change adaptation in the Kenyan tea sector. Report from the adaptation workshop held in Kericho on the 16th of May 2011.

Evans, J. R. (1999). Leaf anatomy enables more equal access to light and CO_2 between chloroplasts. Environmental Biology Group, Research School of Biological Sciences, Australian National University, GPO Box 475, Canberra, ACT 2601, Australia. Publication of New Phytol.: **143**, 93-104.

Evett S.R., Matthias A. D. and Warrick A.W. (1994). Energy balance model of spatially variable evaporation from bare soil. Soil Sci. Soc. Amer. J. 58:1604-1611.

Food and Agricultural Organisation (2012). Report for inception workshop for FAO project on climate change and the tea sector in Kenya: Economic and social impact assessment organized by FAO in collaboration with Ministry of Agriculture, Nakuru, Kenya.

Food and Agricultural Organisation (2006). World Agriculture Trade Matrix, Key statistics of food and agriculture external trade. Economic and Socila Department, The Statistics Division, FAO.

Gardner, W. H. (1986). Water content. In Arnold Klute (ed.), Methods of Soil Analysis Part I. Physical and Mineralogical Methods, 2nd edition. Agronomy 9, American Society of Agronomy, Madison, Wisconsin 493-544.

GenStat (2012). GenStat for Windows 10th Edition. VSN International, 5 The Waterhouse, Waterhouse Street, Hemel Hempstead, Hertfordshire HP1 1ES, UK.

Gonzalez, J. A. and Calbo (2002). Modelled and measured ratio of PAR to global radiation under cloudless skies. Agricultural and Forest Meteorology **110**, 319-325.

Gorthi, S. (2011). Prediction Models for Estimation of Soil Moisture Content, Master of Science in Electrical Engineering thesis, Utah State University, Logan, Utah, USA.

Government of Kenya (2008). Kenya Vision 2030: First Medium Term Plan (2008-2012).

Government of Kenya (2010). Agricultural Sector Development Strategy: 2010-2020.

Green, M. J. (1971). An evaluation of some criteria used in selecting large yielding tea clones. Journal of Agricultural Science, Cambridge **76**, 143 - 156.

Hall, H. E. (2001). Crop responses to environment. 2000 N.W. Corporate Boulevard, Boca Raton, Florida 33431.

Hatch, M. D. (1999). C_4 photosynthesis: a historical overview. In Sage R. F., Monson R. K., eds, C_4 Plant Biology. Academic Press, San Diego, pp 17–46.

Hillel, D. (1982). Introduction to soil physics. Academic Press, San Diego, CA.

Howell T. A., Meek D. W. and Hatfield J. L. (1983). Relationship of photosynthetically active radiation to shortwave radiation in the San Joaquin valley. Agricultural and Forest Meteorology **28**: 157–175.

http://www.ghcc.msfc.nasa.gov/landprocess/lp_home.html. Accessed in September 2011.

http://www.tearesearch.or.ke. Accessed in October 2010.

Huemmrich, K. F. (2013). Simulations of Seasonal and Latitudinal Variations in Leaf Inclination Angle Distribution: Implications of Remote Sensing. Advances in Remote Sensing 2, 93-101.

International Atomic Energy Agency - IAEA (2008). Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation and Sensor Technology. Wagramer Strasse 5 P.O. Box 100 A-1400 Vienna, Austria.

International Tea Committee (2011). Annual Bulletin of Statistics 2011. Carlton House Terrace, London SW1Y5DB, United Kingdom.

International Tea Committee (2009). Annual Bulletin of Statistics 2009. ISBN 0305-2370, Carlton House Terrace, London SW1Y5DB, United Kingdom.

Jacob, H. and Clarke G. (2002). Methods of Soil Analysis, Part 4. Physical Method, Soil Science Society of America, Inc, Madison, Wisconsin, USA, p. 1692.

Jones H. G. (1992). Plants and microclimate - A quantitative approach to environmental plant physiology. Second edition. Cambridge University Press, Cambridge CB2 IRP, 9-45.

Kaleita A. L., Tian L., and. Yao H (2003). Soil moisture estimation from remotely sensed data. American Society of Agricultural Engineers Annual International meeting, Las Vegas, NV, July 27-30 2003.

Kamau D. M., (2008). Productivity and resource use in ageing tea plantations. PhD thesis, Wageningen University, Wageningen, The Netherlands, pp. 40.

Kamunya, S.M., F.N. Wachira, R.S. Pathak, R.C. Muoki and R.K. Sharma. (2012). Tea Improvement in Kenya. In: L. Chen, Z. Apostolides, and Z.M. Chen (eds). Global Tea Breeding; Achievements, Challenges and Perspectives. Zhejiang University Press, Springer. pp 177-226.

Kamunya, S. M. and Msomba S. (2011). Performance of improved tea clones at seven locations in Kenya and Tanzania. In: clonal selection for high productivity, a joint TRFK and Tea Research of Tanzania (TRIT) study, p. 15-19.

Kamunya, S. (2012). Tea News - A quarterly publication of the Tea Board of Kenya, July- September 2012, p. 20-21.

Kigalu, J. M., Kimambo, E., Msite, I. and Gembe, M. (2008). Drip irrigation of tea (*Camellia sinensis L.*): 1. Yield and crop water productivity responses to irrigation. Agricultural Water Management, Vol. **95**, issue 11, pp. 1253-1260.

Kilel, E. C., Wanyoko, J. K., Faraj, A.K. and Wachira, F. N. (2013). Plain black tea quality parameters of purple leaf coloured tea clones in Kenya. International Journal of Research in Chemistry and Environment Vol. **3** Issue 3, p. 81-88.

Kiniry, J. R., Jones, C. A., O'Toole, J. C., Blanchet, R., Cabelguenne, M. and Spanel, D.A. (1989). Radiation-use efficiency in biomass accumulation prior to grain-filling for five grain-crop species. Field Crops Res. **20**, 51–64.

Kool M. T. N., Westerman A. D., Rou-Haest C. H. M. (1996). Importance and use of carbohydrate reserves in above-ground stem parts of rose cv. Montrea. Journal of Horticultural Sciences, **71**, 893-900.

Kumar A, Pandey V., Shekh A. M. and Kumar M. (2008). Radiation use efficiency and weather parameter influence during life cycle of soybean (*Glycine max*. [L] Mirrll) production as well accumulation of dry matter. American-Eurasian Journal of Agronomy **1 (2):** 41-44.

Lakshmi V., Jackson T. J. and Zehrfuhs D. (2003). Soil moisture–temperature relationships: results from two field experiments. Hydrol. Process. **17**, 3041–3057.

Lal, R. (1979). Physical characteristics of soils of the tropics: determination and management . In: R. Lal and D. J. Greenland (Editors), Soil Physical Properties and Crop Production in the Tropics, John Waley, Chichester, Ch. 1.2, pp. 7-44.

Li H. L., Luo Y., and Ma J. H. (2011). Radiation-use efficiency and the harvest index of winter wheat at different nitrogen levels and their relationships to canopy spectral reflectance. Crop and Pasture Science, **62**, 208–217.

Magambo, M. J. S. (1981). Dry matter production and partitioning. Tea **2(1)**, 5-7.

Magambo, M. J. S. and Cannell, M. G. R. (1981). Dry matter production and partition in relation to yield in tea. Experimental Agriculture **17**, pp. 33-38.

Magambo, M. J. S. (1983). Dry matter production and partitioning in clonal (*Camellia sinensis* L.) in Kenya. PhD Thesis, University of Nairobi.

Mahilum, B. C. (2004). Basic soil science and concepts in tropical soils. Trop Ag Hawaii Inc., POB 1213 Honokaa, HI 96727-1213, USA.

Marimuthu, S., Kumar, R. R. and Manivel, L. (1994). Factors affecting partitioning of assimilates in tea. J. Nuclear Agric. Biol., **23(4)**: 219-223.

Matthews, R. B., Stephens, W. (1998). Cuppa-Tea: A simulation model describing seasonal yield variation and potential production of tea. I. Shoot development and extension. Experimental Agriculture **34**, 345-367.

Marshall, T. J. and J. W. Holmes (1988). Soil Physics. 2nd ed. Cambridge Univ. Press, New York.

Marx, E. S., Hart, J., and Stevens, R. G. (1999). Soil Test Interpretation Guide. EC 1478. OR: Oregon State University, Corvallis.

McLean, E. O. (1982). Methods of soil analysis, Part 2: Chemical and Microbiological Properties, In A. L. Page (ed.), pp. 199-224, 986-988. American Soc. of Agronomy, Madison, WI, USA

McCree, K. J. (1972). Test of current definitions of photosythetically active radiation against leaf photosynthesis data. Agricultural and Forest Meteorology **10,** 443-453.

McCree, K. J. (1981). Photosynthetically active radiation. In Encyclopedia of Plant Physiology, New Series, Vol. **12A**, O. L. Lange, P. S. Nobel, C. B. Osmond, and H. Zeigler, eds., Springer, Berlin, pp. 41–55.

Meek D. W., Hatfield J. L., Howell T. A., Idso S. B., Reginato R. J. (1984). A generalized relationship between photosynthetically active radiation and solar radiation. Agronomy Journal 76: 939–945.

M'Imwere, Z. K (1997). Tea production in the smallholder sector in Kenya - achievements, problems and prospects. Tea **18(2)**, 75-86.

Ministry of Agriculture (2007). Task Force Report on the Tea Industry.

Mondal T. K., Bhattacharya A., Laxmikumaran M., Ahuja P. S. (2004). Recent advances of tea (*Camellia sinensis*) biotechnology. Plant Cell, Tissue and Organ Culture **76**, 195-254.

Monteith, J. L. (1977). Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal Society of London - Biological Sciences **281**:277–294.

Moon, P. (1940). Proposed standard solar radiation curves for engineering use. Journal of The Franklin Institute **230**: 583-618.

Muchow R.C. and Davis R. (1988). Effect of nitrogen supply on the comparative productivity of maize and sorghum in a semi-arid tropical environment. II. Radiation interception and biomass accumulation. Field Crops Research **18**, 17–30.

Muthumania T., Vermab D. P., Venkatesanc S. and Kumard R. S. S. (2013). Influence of climatic seasons on quality of south Indian black teas. Journal of Natural Product and Plant Resources. Scholars Research Library **3 (1)**:30-39.

Mwebesa, M. M. N. (1970). East African observer's handbook. East African Meteorological department. A handbook of standard procedures for surface weather observing and recording of climatological data. 1st ed. p. 110-133.

Ng'etich, W. K. (1995). An evaluation of the responses of some Kenyan tea clones to environment in Kenya; Ph.D. thesis, Cranfield University, Silsoe Campus, Institute of Water and Environment, U.K.

Ng'etich, W. K. (1997). Response of tea to environment. Tea **18(2)**, 149-155.

Ng'etich W. K., Stephens W. and Othieno C. O. (1995). Clonal tea response to altitude in Kericho. II. Weather, climate analysis and soil water deficits. Tea **16(2)**, 86-98.

Ng'etich W. K., Stephens W. and Othieno C. O. (2001). Response of tea to environment in Kenya. 3. Yield and yield distribution. Experimental Agriculture, **37**, 361-372.

Ng'etich W. K., Stephens W. and Othieno C. O. (2001a). Response of tea to environment in Kenya. 1. GxE interactions for total dry matter and yield. Experimental Agriculture, **37**, pp. 333-342.

Ng'etich W. K. (2002). Weather and the tea plant. The 2002 TRFK technical report. Tea Board of Kenya. Pg. 7-8.

Nixon, D. J., Burgess, P. J., Sanga, B. N. K., Carr, M. K. V. (2001). A comparison of the responses of mature and young clonal tea to drought. Experimental Agriculture **37**, 391-402.

Obaga S. O., Othieno C. O., Lang'at, J. K. (1989). Observations on the effects of altitude on yield attributes of some tea clones - growth and density of shoots. Tea **10**, 73-79.

Obaga S. O., Squire G. R., Lang'at J. K. (1988). Altitude, temperature and the growth rate of tea shoots. Tea **9(1)**, 28-33.

O'Connell M.G., O'Leary G.J., Whitfield D.M. and Connor D.J. (2004). Interception of photosynthetically active radiation and radiation-use efficiency of wheat, field pea and mustard in a semi-arid environment. Field Crops Res. **85**, 111–124.

Odhiambo, H. O., Nyabundi, J. O., Chweya, J. (1993). Effects of soil moisture and vapour pressure deficits on shoot growth and yield of tea in the Kenyan highlands. Experimental Agriculture **29**, 341-350.

Olsen, S. R., and Sommers, L. E. (1982). Phosphorus. P. 403- 430. In A. L. Page (ed), Methods of soil analysis, Agron. No. 9, Part 2: Chemical and microbiological properties, 2nd ed., Am. Soc. Agron., Madison, WI, USA.

Onduru, D.D., De Jager, A., Hiller, S. and Van den Bosch, R. (2012). Sustainability of smallholder tea production in developing countries: Learning experiences from farmer field schools in Kenya. International Journal of Development and Sustainability. Vol. **1** No. 3.

Othieno C. O. (1976). Annual total dry matter production in young clonal tea in Kenya. Tea in East Africa **16(2)**: 10 - 12.

Othieno C. O., Stephens W., Carr M. K. V. (1992). Yield variability at the Tea Research Foundation of Kenya. Agricultural and Forest Meteorology. **61**: 237-252. Elsevier Science Publishers B. V., Amsterdam.

Owuor P. O., Obanda M., McLean G. and Kisinyo P. O. (1999). Fermentability variations of popular clones from Nandi Hills, Kenya. Tea **20(1)**, 5-11.

Oyamo, J. (1992). The golden clone in a golden field. Tea **13(1)**.

Pallant, J. (2011). SPSS survival manual. A step by step guide to data analysis using the SPSS programme. 4th edition.

Roberts, A.G., Santa Cruz, S., Boevink, P., Roberts, I. M., Sauer, N., and Oparka, K. J. (1999). The sink-source transition in leaves – new insights. In, Scottish Crop Research Institute, Annual Report 1998/99, pp.76-79

Rong L., Volenec J. J., Joern B. C. and Cunniham S. M. (1996). Seasonal changes in non-structural carbohydrates, protein and micronutrients in roots of alfalfa, red clover, sweet clover and birds foot trefiol. Crop Science Journal **36**, 617-623.

Salamene S., Francelino M. R., Santana R. M., Gonçalves C. E., Schaefer R., Setzer A. W. (2010). Correlation between atmospheric physical factors and soil temperature of Keller Peninsula, King George Island, Antarctica. The 19th World Congress of Soil Science, Soil Solutions for a Changing World, 1 – 6 August 2010, Brisbane, Australia.

Satyanarayana, N. (1994). Source-sink relationship and production and partition of dry matter in tea. Planters Chronicles, **89**, 485-487.

Shanmugarajah, V. (1999). Clones recommended for upcountry. In: Plant Propagation and Breeding Division, annual report, Tea Research Institute of Sri Lanka, pp. 130.

Schapendonk A., Stol W., van Kraalingen D.W.G., Bouman B.A.M. (1998). LINGRA, a sink/source model to simulate grassland productivity in Europe. European Journal of Agronomy **9**:87–100.

Seurei P., Wachira F. N., Njuguna C. K. (1997). Cambod Tea: The potential for commercial exploitation in Kenya. Tea **18(1)**, 6-10.

Sinclair T. R. and Muchow R. C. (1999). Radiation use efficiency. Advanced Agronnomy **65**: 215–265.

Skye Instruments Ltd (2012). Light Guidance Notes, SIL-UK. Appendix 3 on Conversion of measurements between mmolm^{-2}sec^{-1} and Wm^{-2}. Pp. 12.

Smith C. A. S., Burn C. R., Tarnocai C., Sproule B. (1998). Air and soil temperature relations along an ecological transect through the permafrost zones of North-Western Canada. 7th International Conference, No. 55, pp. 1009-1015.

Soil Survey Staff (1999). Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. Second edition. USDA-Soil Conservation Service. United Staes Government Printing Office, Washington, D. C.

SPSS Statistics 17.0 (2011). www.spss.com. SPPS Incorporation.

Spencer, A.G. (1950). Flame photometry. Lancet. Nov 25; **2**(6639):623–627.

Squire, G. R. (1977). Seasonal changes in photosynthesis of tea (*Camellia sinensis*). Journal of Applied Ecology **14**: 303 - 316.

Squire, G. R. (1985). Ten years of tea physiology. Tea **6(2)**, 43-48.

Squire, G. R. (1990). The Physiology of Tropical Crop Production. Published CAB International.

Squire G. R., Obaga S. M. O., Othieno, C. O. (1993). Altitude, temperature and shoot production of tea in the Kenyan highlands. Experimental Agriculture **29**, 107-120.

Stephens W. and Carr M. K. V. (1993). Responses of tea (*Camellia sinensis*) to irrigation and fertilizer. III. Shoot extension and development. Experimental Agriculture **29**, 323-339.

Stephens W., Othieno C. O., Carr M. K. V. (1992). Climate and weather variability at the Tea Research Foundation of Kenya. Agricultural and Forest Meteorology **61**: 219-235.

Stern R., Arnold G., Coe R. and Buysse W., (2001). Using GenStat for Windows in Agriculture and Experimental Biology, 5th Edition. ICRAF Nairobi, Kenya. pp. 204.

Stigter C. J., Mwampaja A. R. and Othieno C. O. (1984). An interpretation of temperature patterns under mulched tea at Kericho, Kenya. Agricultural and Forest Meteorology, 31, pp. 231-239.

Taiz L. and Zeiger E. (2011). A Companion to Plant Physiology, 5th Edition. Published by Pallgrave Macmillan.

Tan K. H. (1996). Soil sampling preparation and analysis. New York: Marcel Dekker.

Tanton, T. W. (1979). Some factors limiting yield of tea (*Camellia sinensis*). Experimental Agriculture **15**, 187-191.

Tanton, T. W. (1982a). Environmental factors affecting yield of tea (*Camellia sinensis*). I. Effects of air temperature. Experimental Agriculture **18**, 47-52.

Tanton, T. W. (1982b). Environmental factors affecting yield of tea (*Camellia sinensis)*. II. Effects of soil temperature, daylength and dry air. Experimental Agriculture **18**, 53-63.

Tanui, J., Fang, W., Feng, W., Zhuang, P. and Li, X. (2012). World black tea markets: Relationships and implications for the global tea industry. Journal of International Food and Agribusiness Marketing. **24**(2):148-168.

Tea Board of Kenya (2012). Kenya tea industry performance report for 2011 and projections for 2012. A publication by the Tea Board of Kenya, Naivasha Road, off Ngong Road, Nairobi, Kenya.

Tea Board of Kenya (2013). 10-year Kenya tea export. http://www.teaboard.or.ke/statistics/exports.html - Accessed in September 2013.

Tea Board of Kenya (2014). Kenya tea exports in 2013. http://www.teaboard.or.ke/statistics/exports.html. Accessed in June 2014.

Tea Growers Handbook (2002). A publication of Tea Research Foundation of Kenya, 5th Edition, sponsored by Tea Board of Kenya, Nairobi, Kenya.

Tea Map of Kenya (2003). Tea growing regions, east and west of the Rift Valley, Tea Board of Kenya. Compiled and drawn by Tourist Maps (K) Ltd, Revised 2003.

Tea News (2012). A quarterly publication of the Tea Board of Kenya, July - September 2012. pp. 3-4, 19-21.

Tea Research Foundation of Kenya (2002). Annual Technical Report. Tea Research Foundation of Kenya (TRFK), Tea Board of Kenya, pp.20-28.

Tea Research Foundation of Kenya (2005). Twenty five years of technological achievement on research in tea: The 2005 TRFK technical report for the Open Day held on 19th October, 2005. A publication of the TRFK, Kericho, Kenya.

Tea Research Foundation of Kenya (2006). Technical Report. A publication of Tea Research Foundation of Kenya, Kericho, Kenya.

Tea Research Foundation of Kenya (2010a). Annual Technical Report for the Year 2010. Published by Tea Research Foundation of Kenya, Kericho, Kenya.

Tea Research Foundation of Kenya (2010b). Carbon sequestration, Carbon and nutrient stocks and Safe use of pesticides. TRFK Institute Seminar. Proceedings of TRFK Institute Seminar held at the TRFK Training Centre, Kericho on 23rd June 2010. pp. 4-8.

Tea Research Foundation of Kenya (2011). The 2010 – 2015 Strategic Plan, 2nd Edition.

Ueno O. (2001). Environmental regulation of C_3 and C_4 differentiation in the amphibious sedge *Eleocharis vivipara*.

Valladares F. and Pearcy R. W. (2000). The role of crown architecture for light harvesting and carbon gain in extreme light environments assessed with a structurally realistic 3-D model. Anales Jard. Bot. Madrid **58(1)**: 3-16.

Wachira, F. N. (2001). Tea improvement in Kenya: An overview of research achievements, prospects and limitations. In: Tea Board of Kenya, Board of Directors Open Day Proceedings, 29 January 2001. Tea Research Foundation of Kenya pp. 12-24.

Wachira, F. N. (2002). Enhancing the use of tea genetic resources in Kenya through research. The 2002 TRFK technical report. Tea Board of Kenya. pp. 9-17.

Wachira, F. N. and Ng'etich, W. K. (1999). Dry matter production and partition in diploid, triploid and tetraplod tea. Journal of Horticultural Science and Biotechnology **74(4)**, 507 – 517.

Wachira F. N., Tanaka J. and Takeda Y. (2001). Genetic variation and differentiation in tea (Camellia sinensis) germplasm revealed by RAPD and AFLP variation. J. Hortic. Sci. Biotechnol. **76**:557-563.

Wachira F., Ng'etich W., Omolo J. and Mamati G. (2002). Genotype × environment interactions for tea yields. Euphytica **127**: 289 -296.

Waheed A., Hamid 1, F. S., Ahmad H., Aslam S., Ahmad N., Akbar A. (2013). Different limatic data observation and its effect on tea crop. Journal of Material and Environmental Science, **4 (2)** pp. 299-308

Walker J. P.,Willgoose G. R. and Kalma J. D. (2004). *In situ* measurement of soil moisture: a comparison of techniques. Journal of Hydrology 293. pp. 85–99.

Walkley, A. and Black, I. A. (1934). An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Science, Vol. **37**, pp. 29-38.

Wanyoko, J. K. (1988). Magnesium and nitrogen fertilizer application to moribund tea. Preliminary results. Acta Horticulture, **218**, 191 - 206.

Wanyoko, J. K. (1999). Use of soil ammendments to improve yields of tea (*Camellia sinensis* [L.] O. Kuntze) grown in strongly acidic soils. Ph.D thesis, Moi University, Eldoret, Kenya.

White D., Howden H., Mark S. (2009), Climate and its effects on crop productivity and management, in Crop and Soil Sciences, edited by Willy H. Verheye, in Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, EOLSS Publishers, Oxford ,UK.

Willson, K. C. and Clifford, M. N. (1992). Tea: cultivation to consumption. Published by Chapman and Hall, 2-6 Boundary Row, U.K., London SE1 8HN. 31-40, 87-123, 128-141.

World Meteorological Organization (2013). A summary of current climate change findings and fugures. In: http://www.wmo.int/pages/mediacentre/factsheet/documents/ClimateChange.

Wu, J. and D. L. Nofziger (1999). Incorporating temperature effects on pesticide degradation into a management model. Journal of Environmental Quality **28**:92-100.

Yamori, W., Hikosaka, K. and Way, D. A. (2013). Temperature response of photosynthesis in C_3, C_4, and CAM plants: temperature acclimation and temperature adaptation.

Zheng, D. E. R., Hunt, Jr. and Running, S.W. (1993). A daily soil temperature model based on air temperature and precipitation for continental application. Climate Research **2**: 183-191.

8.0 APPENDICES

APPENDIX 8.1: WORLD LEADING COUNTRIES IN TEA PRODUCTION, 1999 - 2008 (METRIC TONNES). FIGURES REPRESENT MADE TEA (mt)

Country	Year									
	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
China	675,871	683,324	701,699	745,374	768,140	835,231	934,857	1,028,064	1,140,000	1,200,000
India	825,935	846,922	853,923	838,474	878,129	892,965	945,974	981,805	944,678	980,818
Kenya	248,709	236,286	294,631	287,102	293,671	324,608	323,497	310,578	369,606	345,817
Sri Lanka	284,149	306,794	296,301	310,604	303,254	308,089	317,196	310,822	304,613	318,697
Vietnam	65,000	63,700	76,800	89,440	106,950	119,050	133,350	142,500	148,270	166,375
Turkey	170,563	130,671	142,900	142,000	155,000	165,000	135,000	142,000	178,000	155,000
Indonesia	161,003	162,586	166,868	162,194	169,819	164,817	156,273	146,847	137,248	137,499
Japan	88,512	89,309	90,371	83,677	91,930	100,262	100,000	99,500	92,111	93,000
Argentina	70,973	67,973	67,120	66,778	67,278	64,871	80,000	88,000	87,000	72,000
Bangla-desh	46,365	52,639	56,820	53,624	58,298	55,627	60,600	53,265	57,955	58,818
Uganda	24,730	29,282	33,255	33,831	36,475	35,706	37,734	36,726	44,913	42,752
Malawi	38,469	42,114	36,770	39,185	41,693	50,090	37,978	45,010	48,141	41,639
Tanzania	23,490	23,897	24,745	27,511	29,482	30,688	30,362	31,348	34,863	31,606
Myanmar	16,800	17,000	17,200	17,300	17,700	17,900	18,000	18,300	18,400	18,600
Iran	68,501	44,233	59,000	49,500	58,051	40,000	25,000	20,000	17,000	18,000
Taiwan	22,555	20,349	19,837	20,345	20,675	20,192	18,803	19,345	17,502	17,384
Rwanda	12,970	14,391	17,809	14,948	15,484	14,181	16,457	16,973	17,700	17,300
Nepal	11,000	11,200	11,500	12,000	12,600	13,000	13,300	13,688	15,168	16,127

Source: The International Tea Committee (2009). Annual Bulletin of Statistics 2009.

APPENDIX 8.2: EXPORTS OF KENYAN TEA SHOWING MAJOR COUNTRIES OF DESTINATION AND VALUE

Year	Weight of tea exported (Metric tonnes)	Amount earned by Kenya (US$ '000)	Deviation from previous year (US$ '000)	Major consumers of Kenyan tea exports (over 50,000 mt year^{-1})			
				Importing country	*Metric tonnes (mt)*	*Value in US$ ('000)*	*% Revenue compared to entire export*
2004	332,502	536,150	-	Pakistan Egypt UK	84,340 84,106 53,338	142,680 128,324 83,659	
				Sub-total	**221,784**	**354,663**	**66%**
2005	348,276	555,456	+19,306	Pakistan Egypt UK	98,301 77,931 53,217	165,092 114,317 80,152	
				Sub-total	**229,449**	**359,561**	**65%**
2006	312,156	644,997	+89,541	Pakistan Egypt UK	84,498 78,789 46,429	178,583 156,372 95,075	
				Sub-total	**209,716**	**430,030**	**67%**
2007	343,703	685,625	+40,628	Pakistan Egypt UK	79,818 67,421 58,501	163,606 128,940 108,263	
				Sub-total	**205,740**	**400,809**	**58%**
2008	383,445	899,160	+213,535	Egypt UK Pakistan	99,638 69,211 61,299	235,704 150,359 142,727	
				Sub-total	**230,148**	**528,790**	**58%**
Mean	**344,061**	**664,278**			**219,367**	**414,771**	**63%**

Source of the information: The International Tea Committee (2009). Annual Bulletin of Statistics 2009, & author's own calculations from data.

APPENDIX 8.3: KANGAITA SOIL PHYSICAL CHARACTERIZATION

Soil Textural Classes: October 2009

Tea clone	Rep	Depth (cm)	% Sand	% Clay	% Silt	Soil textural class
31/37	A	0-30	34.7	20.8	14.5	Sandy clay loam
		30-60	72.7	20.4	6.9	Sandy clay loam
	B	0-30	64.6	14.1	21.3	Sandy loam
		30-60	68.8	22.2	9.0	Sandy clay loam
	C	0-30	66.7	18.1	15.2	Sandy loam
		30-60	66.7	24.0	9.3	Sandy clay loam
31/8	A	0-30	56.7	24.1	19.2	Sandy clay loam
		30-60	72.7	22.0	5.3	Sandy clay loam
	B	0-30	68.6	18.0	13.4	Sandy loam
		30-60	7.07	22.0	7.3	Sandy clay loam
	C	0-30	64.7	24.0	11.3	Sandy clay loam
		30-60	62.7	15.8	21.5	Sandy loam
TN 14/3	A	0-30	67.0	14.3	15.2	Sandy clay loam
		30-60	70.7	19.8	9.5	Sandy loam
	B	0-30	66.7	18.3	15.0	Sandy loam
		30-60	72.0	20.4	7.6	Sandy clay loam
	C	0-30	66.0	20.3	13.7	Sandy clay loam
		30-60	70.2	24.2	3.6	Sandy clay loam
301/5	A	0-30	56.2	20.0	23.8	Sandy clay loam
		30-60	72.0	22.0	6.0	Sandy clay loam
	B	0-30	68.2	16.0	15.8	Sandy loam
		30-60	74.8	21.7	3.5	Sandy clay loam
	C	0-30	66.8	19.8	13.4	Sandy clay loam
		30-60	68.8	23.6	7.6	Sandy clay loam

APPENDIX 8.4: KIPKEBE PHYSICAL SOIL CHARACTERIZATION

Soil Textural Classes: October 2009

Site	Depth (cm)	% Sand	% Clay	% Silt	Soil textural class
A	0-10	28.92	41.28	29.80	Clay
	10-20	27.24	41.28	31.48	Clay
	20-30	26.88	47.28	25.84	Clay
	30-60	23.56	47.34	29.10	Clay
B	0-10	29.08	41.64	29.28	Clay
	10-20	28.76	39.64	31.60	Clay
	20-30	24.72	41.64	33.64	Clay
	30-60	28.40	42.00	29.60	Clay
C	0-10	28.36	40.00	31.64	Clay
	10-20	28.16	40.00	31.84	Clay loam
	20-30	24.36	42.00	33.64	Clay
	30-60	24.28	48.00	27.72	Clay
D	0-10	30.28	50.00	19.72	Clay
	10-20	26.00	40.00	34.00	Clay
	20-30	28.04	42.36	29.60	Clay
	30-60	26.40	48.36	25.24	Clay
E	0-10	26.84	42.00	31.16	Clay
	10-20	21.84	52.00	26.16	Clay
	20-30	20.56	54.00	24.90	Clay
	30-60	17.12	56.88	26.00	Clay
F	0-10	29.12	38.88	32.00	Clay loam
	10-20	24.20	42.16	33.64	Clay
	20-30	29.00	38.52	32.48	Clay loam
	30-60	24.20	46.52	29.28	Clay

APPENDIX 8.5: TIMBILIL PHYSICAL SOIL CHARACTERIZATION

Soil Textural Classes: August 2009

Field 7

Site	Depth (cm)	% Sand	% Clay	% Silt	Soil textural class
A	0-10	42.18	46.18	11.64	Clay
	10-20	30.18	60.12	9.70	Clay
	20-30	19.38	70.20	10.42	Clay
	30-60	14.24	72.46	13.30	Clay
B	0-10	46.20	47.16	6.64	Sandy clay
	10-20	40.30	50.38	9.32	Clay
	20-30	26.00	68.40	5.60	Clay
	30-60	14.00	74.30	11.70	Clay
C	0-10	42.00	50.00	8.00	Clay
	10-20	27.80	62.24	9.96	Clay
	20-30	24.20	64.52	11.28	Clay
	30-60	15.00	72.80	12.20	Clay
D	0-10	42.36	48.40	9.24	Clay
	10-20	24.40	62.36	13.24	Clay
	20-30	18.16	72.00	9.84	Clay
	30-60	19.66	72.16	8.18	Clay
E	0-10	38.40	46.28	15.32	Clay
	10-20	34.60	47.40	18.00	Clay
	20-30	18.40	70.20	11.40	Clay
	30-60	16.60	72.60	10.80	Clay

APPENDIX 8.6: KANGAITA CHEMICAL SOIL CHARACTERIZATION

Bot Genet 6/8

Date: October 2009

Site	Depth (cm)	pH	Moisture (%)	P ppm	K ppm	Ca ppm	Mg ppm	Mn ppm
A	0-10	4.13	33.33	102	395	47	41	48
	20-30	4.02	32.62	14	204	24	15	50
	40-60	4.10	35.72	18	126	14	10	44
B	0-10	4.16	35.67	99	344	315	92	59
	20-30	4.16	33.31	10	150	31	19	44
	40-60	4.23	34.15	6	166	23	12	18
C	0-10	4.02	36.96	80	276	184	42	34
	20-30	4.08	34.98	17	343	24	10	44
	40-60	4.06	33.70	12	289	22	9	21
D	0-10	3.89	32.71	104	190	91	30	74
	20-30	4.32	31.63	13	198	15	9	48
	40-60	4.02	34.09	8	134	10	9	22
E	0-10	4.36	35.73	65	244	38	26	27
	20-30	4.12	34.92	14	144	16	11	26
	40-60	4.12	36.66	16	139	12	9	47
F	0-10	4.02	37.63	44	208	103	26	31
	20-30	4.18	35.77	19	250	23	11	32
	40-60	4.16	37.61	11	120	17	8	18
G	0-10		34.51					
	20-30		36.81					
	40-60		37.72					

APPENDIX 8.7: KIPKEBE CHEMICAL SOIL CHARACTERIZATION

Bot Genet 6/8

Date: October 2009

Site	Depth (cm)	pH	Moisture (%)	P ppm	K ppm	Ca ppm	Mg ppm	Mn ppm
A	0-10	4.74	30.43	5	644	1036	216	70
	10-20	4.42	33.34	5	494	1348	262	50
	20-30	4.38	35.45	7	408	1352	291	43
	40-60	4.36	36.64	7	322	1287	282	35
B	0-10	4.23	34.23	6	510	1474	277	45
	10-20	4.32	34.44	6	365	1070	236	48
	20-30	4.30	36.62	6	215	988	191	35
	40-60	4.40	37.51	9	215	1390	251	27
C	0-10	4.40	31.23	4	301	918	193	49
	10-20	4.49	33.37	5	301	860	203	50
	20-30	4.66	35.07	7	301	1083	209	41
	40-60	4.80	35.47	9	258	1542	300	18
D	0-10	4.63	36.67	9	687	1066	188	26
	10-20	4.80	35.89	8	601	1375	268	30
	20-30	4.85	38.49	7	580	1220	256	28
	40-60	4.92	41.39	9	515	1331	241	24
E	0-10	4.70	31.53	8	429	942	243	50
	10-20	4.63	34.11	7	365	1092	334	52
	20-30	4.70	37.02	4	279	911	266	25
	40-60	4.80	39.07	8	408	1038	287	18
F	0-10	4.48	39.12	9	1160	1268	268	263
	10-20	4.66	37.12	7	752	1251	251	61
	20-30	4.59	42.03	7	623	896	204	55
	40-60	4.42	44.89	10	429	943	214	43

APPENDIX 8.8: TIMBILIL CHEMICAL SOIL CHARACTERIZATION

August 2009

Field 7

Site	Depth (cm)	pH	Moisture (%)	P ppm	K ppm	Ca ppm	Mg ppm	Mn ppm
A	0-10	3.77	41.84	8	200	282	43	145
	10-20	3.90	36.58	7	198	155	43	36
	20-30	4.04	39.12	9	199	157	40	27
	40-60	4.10	40.21	8	176	121	36	20
B	0-10	3.70	36.87	13	222	210	49	25
	10-20	3.50	41.31	8	264	111	36	106
	20-30	3.51	39.92	11	266	167	40	85
	40-60	3.66	40.19	11	290	124	44	72
C	0-10	3.96	43.46	7	320	529	89	68
	10-20	3.60	41.92	8	221	411	77	56
	20-30	3.57	42.84	10	222	289	57	50
	40-60	3.79	40.01	13	270	152	42	41
D	0-10	4.42	37.96	8	397	1190	136	31
	10-20	4.27	36.73	10	290	235	61	76
	20-30	4.46	39.34	6	266	290	55	9
	40-60	4.64	41.53	10	244	360	65	9
E	0-10	4.41	38.69	8	311	1412	217	53
	10-20	3.99	39.48	9	265	315	75	17
	20-30	4.05	41.87	11	243	277	66	17
	40-60	4.02	39.81	6	220	152	60	6

APPENDIX 8.9: MONTHLY (GUNN BELLANI) RADIATION MEASUREMENTS AT TIMBILIL (MJm^{-2}), JAN. 2007 - DEC. 2009

Timbilil						
Year	**2007**		**2008**		**2009**	
Radiation (Gunn Bellani)	**Mean daily sunshine hours**	**Monthly means (MJm^{-2})**	**Mean daily sunshine hours**	**Monthly means (MJm^{-2})**	**Mean daily sunshine hours**	**Monthly means (MJm^{-2})**
Jan.	7.7	22.81	8.6	24.26	7.8	22.81
Feb.	7.8	23.92	8.3	24.69	8.5	24.69
Mar.	8.7	25.29	6.8	22.21	8.3	24.90
Apr.	5.9	20.07	7.0	21.95	6.8	21.61
May	6.8	20.41	6.7	20.41	6.5	20.11
June	3.0	14.25	5.9	18.31	8.8	22.76
July	3.6	15.45	6.9	19.94	6.9	19.94
Aug.	5.3	18.74	5.6	19.08	6.2	20.20
Sept.	5.2	19.17	5.9	20.33	6.6	21.82
Oct.	6.2	21.22	5.1	19.30	5.0	18.96
Nov.	5.5	19.56	8.2	23.62	6.6	21.40
Dec.	8.2	22.81	8.8	24.26	6.7	21.01
Totals	**73.9**	**243.7**	**83.8**	**258.36**	**84.7**	**260.21**
Means	**6.2**	**20.3**	**7.0**	**21.53**	**7.1**	**21.68**

APPENDIX 8.10: OCTOBER 2007 TO NOVEMBER 2009 MONTHLY RADIATION SUMMARY (MILLIVOLTS - *mV*) FOR BOTH KANGAITA & KIPKEBE SITES (BOT/GENET 8)

No.	Month	Site	TN 14-3 (*mV*)		301/5 (*mV*)		SC 31/37 (*mV*)		31/8 (*mV*)	
			Top	Base	Top	Base	Top	Base	Top	Base
1.	Oct. 2007	Kangaita	-	-	-	-	-	-	-	-
		Kipkebe	*5.7375*	*2.1368*	*5.8207*	*2.3506*	*5.7572*	*2.5998*	*5.9599*	*2.6502*
2.	Nov. 2007	Kangaita	5.0770	1.1003	5.1777	1.1190	4.2690	0.9180	5.3643	1.1503
		Kipkebe	*6.3882*	*2.2011*	*6.1843*	*2.2915*	*5.9749*	*2.2987*	*6.1787*	*2.5239*
3.	Dec. 2007	Kangaita	6.4680	0.9613	7.2830	0.9930	6.6200	1.0210	6.7610	1.0953
		Kipkebe	-	-	-	-	-	-	-	-
4.	Jan. 2008	Kangaita	8.7833	1.5050	9.4550	1.4950	8.7433	1.3926	10.1217	1.5200
		Kipkebe	-	-	-	-	-	-	-	-
5.	May 2008	Kangaita	-	-	-	-	-	-	-	-
		Kipkebe	*5.5202*	*1.6216*	*5.8234*	*1.9459*	*5.7318*	*1.5793*	*5.9433*	*1.3326*
6.	Oct. 2008	Kangaita								
		Kipkebe	*9.0632*	*1.5338*	*9.0240*	*1.7053*	*9.2481*	*1.7233*	*8.8086*	*1.7343*
7.	Nov. 2008	Kangaita	7.5382	1.5106	7.3694	1.4080	8.1102	1.5243	7.8963	1.6202
		Kipkebe	*7.3702*	*1.6054*	*7.3214*	*1.8124*	*7.3259*	*1.6644*	*7.2768*	*1.7519*
8.	Dec. 2008	Kangaita	10.0350	1.7700	11.2405	1.8937	10.9063	1.9757	11.1387	1.9648
		Kipkebe	*9.1716*	*1.7621*	*9.1992*	*2.0940*	*9.2670*	*1.9703*	*9.1441*	*1.9604*
9.	Jan. 2009	Kangaita	11.7417	1.8743	11.9190	1.7753	11.9357	2.0253	12.2467	1.9173
		Kipkebe	*7.9930*	*1.3530*	*7.7983*	*1.6562*	*7.8336*	*1.5540*	*7.7985*	*1.5055*
10.	Feb. 2009	Kangaita	-	-	-	-	-	-	-	-
		Kipkebe	*8.1081*	*1.3747*	*7.9939*	*1.7686*	*8.2845*	*1.7216*	*8.1324*	*1.6510*
11.	Mar. 2009	Kangaita	-	-	-	-	-	-	-	-
		Kipkebe	*8.9629*	*1.3031*	*8.8345*	*1.9213*	*8.9053*	*1.7501*	*8.6806*	*1.6385*
12.	Apr. 2009	Kangaita	-	-	-	-	-	-	-	-
		Kipkebe	*5.7393*	*0.5746*	*5.3014*	*0.7620*	*5.4953*	*0.6974*	*5.5468*	*0.6690*
13.	May 2009	Kangaita	-	-	-	-	-	-	-	-
		Kipkebe	*7.9308*	*0.9449*	*7.7441*	*1.5843*	*7.8330*	*1.3694*	*7.8714*	*1.2094*
14.	June 2009	Kangaita	7.5740	1.6943	7.4390	1.6963	7.5803	1.6787	7.8553	1.7403
		Kipkebe	*9.2167*	*1.1682*	*9.0468*	*2.0501*	*9.2562*	*1.7693*	*9.2456*	*1.6457*

15.	July 2009	Kangaita	7.0691	1.4642	6.9997	1.4552	7.1294	1.5039	7.1576	1.5494
		Kipkebe	*8.6883*	*1.0342*	*8.5498*	*2.0170*	*8.7024*	*1.6475*	*8.5665*	*1.5562*
16.	Aug. 2009	Kangaita	8.2700	2.3433	7.0533	1.7000	6.9667	1.7100	7.3433	2.1900
		Kipkebe	*7.4910*	*0.8935*	*7.3346*	*1.3745*	*7.3041*	*1.2235*	*7.4330*	*1.2100*
17.	Sept. 2009	Kangaita	-	-	-	-	-	-	-	-
		Kipkebe	*9.8241*	*1.0907*	*9.8517*	*2.0304*	*9.8178*	*1.6236*	*9.7828*	*1.6113*
18.	Oct. 2009	Kangaita	7.7237	1.6852	7.4674	1.9541	8.0715	1.8633	7.9841	2.0189
		Kipkebe	*9.7016*	*1.1504*	*9.5708*	*2.1701*	*9.5891*	*1.6505*	*9.5379*	*1.6495*
19.	Nov. 2009	Kangaita	-	-	-	-	-	-	-	-
		Kipkebe	*6.3594*	*0.4677*	*6.2739*	*1.2396*	*6.3550*	*0.8654*	*6.1400*	*0.8061*

APPENDIX 8.11: OCTOBER 2007 TO NOVEMBER 2009 MONTHLY RADIATION MEASUREMENTS FOR THE 4 TREATMENTS (*Wm*$^{-2}$) PER LOCATION FOR TWO LOCATIONS - KANGAITA & KIPKEBE

The converted light measurements are in *Watts per square metre* (*Wm*$^{-2}$).

Key:

Kang = Kangaita

Kipk = Kipkebe

No.	Month	Site	TN 14-3 (*Wm*$^{-2}$)		301/5 (*Wm*$^{-2}$)		SC31/37 (*Wm*$^{-2}$)		31/8 (*Wm*$^{-2}$)		Mean (*Wm*$^{-2}$)	
			Top	**Base**	**Top**	**Base**	**Top**	**Base**	**Top**	**Base**	**Top**	**Base**
1.	Oct. 2007	Kang	-	-	-	-	-	-	-	-	-	-
		Kipk	*490.38*	*182.64*	*497.50*	*200.91*	*492.07*	*222.21*	*509.39*	*226.51*	*477*	*208*
2.	Nov. 2007	Kang	433.93	94.04	442.54	95.64	364.87	78.46	458.49	98.32	425	92
		Kipk	*546.00*	*188.13*	*528.57*	*195.85*	*510.68*	*196.47*	*528.09*	*215.72*	*528*	*199*
3.	Dec. 2007	Kang	552.82	82.16	622.49	84.87	565.81	87.26	577.86	93.62	580	87
		Kipk	-	-	-	-	-	-	-	-		
4.	Jan. 2008	Kang	750.71	128.63	808.12	127.78	747.29	119.03	865.10	129.91	793	126
		Kipk	-	-	-	-	-	-	-	-		
5.	May 2008	Kang	-	-	-	-	-	-	-	-		
		Kipk	*471.81*	*138.60*	*497.73*	*166.32*	*489.90*	*134.98*	*507.97*	*113.90*	*492*	*138*
6.	Oct. 2008	Kang	-	-	-	-	-	-	-	-		
		Kipk	*774.63*	*131.09*	*771.28*	*145.75*	*790.44*	*147.29*	*752.87*	*148.23*	*772*	*143*
7.	Nov. 2008	Kang	644.29	129.11	629.86	120.34	693.18	130.28	674.90	138.48	661	130
		Kipk	*629.93*	*137.21*	*625.76*	*154.91*	*626.15*	*142.26*	*621.95*	*149.74*	*626*	*146*
8.	Dec. 2008	Kang	857.69	151.28	960.73	161.85	932.16	168.86	952.03	167.93	926	162
		Kipk	*783.90*	*150.61*	*786.26*	*178.97*	*792.05*	*168.40*	*781.55*	*167.56*	*786*	*166*
9.	Jan. 2009	Kang	1003.56	160.20	1018.72	151.74	1020.15	173.10	1046.73	163.87	1022	162
		Kipk	*683.16*	*115.64*	*666.52*	*141.56*	*669.54*	*132.82*	*666.53*	*128.68*	*671*	*130*
10.	Feb. 2009	Kang	-	-	-	-	-	-	-	-		
		Kipk	*693.00*	*117.50*	*683.24*	*151.16*	*708.08*	*147.15*	*695.08*	*141.11*	*695*	*139*
11.	Mar. 2009	Kang	-	-	-	-	-	-	-	-		
		Kipk	*766.06*	*111.38*	*755.09*	*164.21*	*761.14*	*149.58*	*741.93*	*140.04*	*756*	*141*
12.	Apr. 2009	Kang	-	-	-	-	-	-	-	-		
		Kipk	*490.54*	*49.11*	*453.11*	*65.13*	*469.68*	*59.61*	*474.09*	*57.18*	*472*	*58*
13.	May 2009	Kang	-	-	-	-	-	-	-	-		
		Kipk	*677.85*	*80.76*	*661.89*	*135.41*	*669.49*	*117.04*	*672.77*	*103.37*	*671*	*109*
14.	June 2009	Kang	647.35	144.81	635.81	144.98	647.89	143.48	671.39	148.74	651	146
		Kipk	*787.75*	*99.85*	*773.23*	*175.22*	*791.13*	*151.22*	*790.22*	*140.66*	*786*	*142*

15.	July 2009	Kang	604.20	125.15	598.26	124.38	609.35	128.54	611.76	132.43	606	128
		Kipk	*742.59*	*88.39*	*730.75*	*172.39*	*743.79*	*140.81*	*732.18*	*133.01*	*737*	*134*
16.	Aug. 2009	Kang	706.84	200.28	602.85	145.30	595.44	146.15	627.63	187.18	633	170
		Kipk	*604.26*	*76.37*	*626.89*	*117.48*	*624.28*	*104.57*	*635.30*	*103.42*	*623*	*100*
17.	Sept. 2009	Kang	-	-	-	-	-	-	-	-		
		Kipk	*839.67*	*93.22*	*842.03*	*173.54*	*839.13*	*138.77*	*836.14*	*137.72*	*839*	*136*
18.	Oct. 2009	Kang	660.15	144.03	638.24	167.02	689.87	159.26	682.40	172.56	668	161
		Kipk	*829.20*	*98.32*	*818.02*	*185.48*	*819.58*	*141.07*	*815.21*	*140.98*	*821*	*141*
19.	Nov. 2009	Kang	-	-	-	-	-	-	-	-		
		Kipk	*543.54*	*39.97*	*536.23*	*105.95*	*543.16*	*73.97*	*524.79*	*68.90*	*537*	*72*

APPENDIX 8.12: REP MEANS IRRADIATION (Wm^{-2}) MEASUREMENTS, PER LOCATION PER SEASON, KANGAITA AND KIPKEBE TRIAL SITES, OCT. 2007 TO NOV. 2009

Period	Season	Site	Rep	TN 14-3 (Wm^{-2})		301/5 (Wm^{-2})		31/37 (Wm^{-2})		31/8 (Wm^{-2})	
				Top	Base	Top	Base	Top	Base	Top	Base
1 Oct. - 15 Dec. 2007	3	Kangaita	A	486.81	80.46	623.91	100.64	399.51	86.53	558.28	107.62
			B	428.87	77.71	447.21	78.36	472.69	73.65	452.17	84.44
			C	445.28	76.92	410.85	70.06	398.19	62.50	403.26	67.43
		Kipkebe	*A*	*513.24*	*182.54*	*519.91*	*204.91*	*531.01*	*212.41*	*542.31*	*244.56*
			B	*519.53*	*184.05*	*542.46*	*193.38*	*530.29*	*224.35*	*536.74*	*215.01*
			C	*521.82*	*189.55*	*476.74*	*196.85*	*442.74*	*191.25*	*477.19*	*203.79*
Mid. Dec. 2007 - March 2008	1	Kangaita	A	799.57	127.21	928.63	131.70	861.04	113.72	926.64	141.74
			B	738.03	122.51	707.91	113.89	746.94	135.12	834.69	142.38
			C	738.97	125.00	740.46	116.60	612.82	112.39	684.76	108.05
		Kipkebe	*A*	*474.44*	*37.97*	*474.44*	*86.17*	*500.36*	*48.21*	*506.38*	*31.94*
			B	*608.12*	*58.45*	*608.12*	*56.04*	*508.79*	*46.40*	*612.34*	*37.97*
			C	*500.36*	*42.18*	*500.36*	*24.10*	*506.38*	*40.38*	*500.36*	*43.99*
1 Sept. - 15 Dec. 2008	3	Kangaita	A	884.92	157.43	1032.92	175.13	965.39	187.49	995.55	200.70
			B	745.27	153.39	799.25	164.01	826.68	157.79	901.46	160.29
			C	742.66	148.93	749.36	138.23	742.31	137.93	687.47	138.35
		Kipkebe	*A*	*725.51*	*138.34*	*726.79*	*161.58*	*729.47*	*147.93*	*715.93*	*157.70*
			B	*727.91*	*138.25*	*726.51*	*157.66*	*732.54*	*152.44*	*714.91*	*154.90*
			C	*726.55*	*136.66*	*730.44*	*160.89*	*741.82*	*154.04*	*712.38*	*148.03*
16 Dec. - 31 March 2009	1	Kangaita	A	918.50	158.25	991.84	139.32	1024.10	181.67	1024.19	168.08
			B	911.54	140.21	912.31	151.71	915.21	163.63	939.91	149.83
			C	865.94	137.44	908.55	136.11	912.05	140.09	918.76	148.03
		Kipkebe	*A*	*731.02*	*127.62*	*718.82*	*160.50*	*730.97*	*151.78*	*724.23*	*146.72*
			B	*734.52*	*125.01*	*721.81*	*157.91*	*742.21*	*149.56*	*726.38*	*145.39*
			C	*735.39*	*122.89*	*727.33*	*158.13*	*736.52*	*149.77*	*723.05*	*144.59*

1 April - 31 August 2009	2	Kangaita	A	675.22	169.31	598.56	132.24	626.85	137.92	653.14	184.96
			B	635.74	144.56	624.30	142.56	634.47	144.85	675.85	149.50
			C	647.42	156.38	614.07	139.85	591.37	135.39	581.81	133.89
		Kipkebe	*A*	*671.27*	*80.56*	*652.45*	*134.08*	*663.32*	*115.87*	*663.00*	*108.61*
			B	*667.15*	*78.90*	*650.29*	*133.25*	*658.97*	*114.74*	*659.46*	*106.68*
			C	*664.97*	*77.22*	*644.79*	*132.05*	*656.73*	*113.33*	*660.28*	*107.31*
1 Sept. - 30 Nov. 2009	3	Kangaita	A	714.53	164.29	692.88	156.48	740.45	163.25	699.62	166.35
			B	590.12	116.52	556.50	170.94	658.97	147.58	658.40	187.66
			C	675.79	151.28	665.33	173.13	670.18	166.95	689.17	168.66
		Kipkebe	*A*	*732.78*	*79.57*	*732.83*	*155.50*	*732.21*	*121.22*	*723.53*	*119.17*
			B	*736.77*	*76.68*	*731.42*	*155.20*	*732.64*	*117.36*	*725.08*	*115.50*
			C	*742.85*	*75.27*	*732.03*	*154.27*	*737.02*	*115.22*	*727.52*	*112.92*

APPENDIX 8.13: KANGAITA AND KIPKEBE DAILY E_{DIR} (Wm^{-2}) CATEGORIZED INTO 3 TEA GROWING SEASONS OF THE YEAR

Season	Location	Rep	TN 14-3 (Wm^{-2})		301/5 (Wm^{-2})		31/37 (Wm^{-2})		31/8 (Wm^{-2})		Rep Means (Wm^{-2})	
			Top	Base	Top	Base	Top	Base	Top	Base	Top	Base
1	Kangaita	A	859	143	960	136	943	148	975	155	**934**	**146**
		B	825	131	810	133	831	149	887	146	**838**	**140**
		C	802	131	825	126	762	126	802	128	**798**	**128**
		Clone means	**829**	**135**	**865**	**132**	**845**	**141**	**888**	**143**	**857**	**138**
	Kipkebe	*A*	*731*	*128*	*719*	*161*	*731*	*152*	*724*	*147*	***726***	***147***
		B	*735*	*125*	*722*	*158*	*742*	*150*	*726*	*145*	***731***	***145***
		C	*735*	*123*	*727*	*158*	*737*	*150*	*723*	*145*	***731***	***144***
		Clone means	***734***	***125***	***723***	***159***	***737***	***151***	***724***	***146***	***730***	***145***
2	Kangaita	A	675	169	599	132	627	138	653	185	**639**	**156**
		B	636	145	624	143	634	145	676	150	**643**	**146**
		C	647	156	614	140	591	135	582	134	**609**	**141**
		Clone means	**653**	**157**	**612**	**138**	**617**	**139**	**637**	**156**	**630**	**148**
	Kipkebe	*A*	*573*	*59*	*563*	*110*	*582*	*82*	*585*	*70*	***576***	***80***
		B	*638*	*69*	*629*	*95*	*584*	*81*	*636*	*72*	***622***	***79***
		C	*583*	*60*	*573*	*78*	*582*	*77*	*580*	*151*	***580***	***92***
		Clone means	***598***	***63***	***588***	***94***	***583***	***80***	***600***	***98***	***592***	***84***
3	Kangaita	A	695	134	783	144	702	146	751	158	**733**	**146**
		B	588	116	601	138	653	126	671	144	**628**	**131**
		C	621	126	609	127	604	122	593	125	**607**	**125**
		Clone means	**635**	**125**	**664**	**136**	**653**	**131**	**672**	**142**	**656**	**134**
	Kipkebe	*A*	*657*	*133*	*660*	*174*	*664*	*161*	*661*	*174*	***661***	***161***
		B	*661*	*133*	*667*	*169*	*665*	*165*	*659*	*162*	***663***	***157***
		C	*664*	*134*	*646*	*171*	*641*	*154*	*639*	*155*	***648***	***154***
		Clone means	***661***	***133***	***658***	***171***	***657***	***160***	***653***	***164***	***657***	***157***

APPENDIX 8.14: KANGAITA AND KIPKEBE DAILY *PAR* ($molm^{-2}s^{-1}$) MEASUREMENTS CATEGORIZED INTO 3 TEA GROWING SEASONS OF THE YEAR

Season	Location	Rep	PAR Measurements in mol $m^{-2}s^{-1}$									
			TN 14-3		301/5		31/37		31/8		Rep Means	
			Top	Base	Top	Base	Top	Base	Top	Base	Top	Base
1	Kangaita	A	3951	658	4416	626	4338	681	4485	713	**4298**	**670**
		B	3795	603	3726	612	3823	685	4080	672	**3856**	**643**
		C	3689	603	3795	580	3505	580	3689	589	**3670**	**588**
		Clone means	**3812**	**621**	**3979**	**606**	**3889**	**649**	**4085**	**658**	**3941**	**634**
	Kipkebe	*A*	*3363*	*589*	*3307*	*741*	*3363*	*699*	*3330*	*676*	***3341***	***676***
		B	*3381*	*575*	*3321*	*727*	*3413*	*690*	*3340*	*667*	***3364***	***665***
		C	*3381*	*566*	*3344*	*727*	*3390*	*690*	*3326*	*667*	***3360***	***663***
		Clone means	***3375***	***577***	***3324***	***732***	***3389***	***693***	***3332***	***670***	***3355***	***668***
2	Kangaita	A	3105	727	2755	607	2884	635	3004	851	**2937**	**705**
		B	2926	667	2870	658	2916	653	3110	690	**2956**	**667**
		C	2976	718	2824	644	2719	621	2677	616	**2799**	**650**
		Clone means	**3002**	**704**	**2816**	**636**	**2840**	**636**	**2930**	**719**	**2897**	**674**
	Kipkebe	*A*	*2636*	*271*	*2590*	*506*	*2677*	*377*	*2691*	*322*	***2649***	***369***
		B	*2935*	*317*	*2893*	*437*	*2686*	*373*	*2926*	*331*	***2860***	***365***
		C	*2682*	*276*	*2636*	*359*	*2677*	*354*	*2668*	*695*	***2666***	***421***
		Clone means	***2751***	***288***	***2706***	***434***	***2680***	***368***	***2762***	***449***	***2725***	***385***
3	Kangaita	A	3197	616	3602	662	3229	672	3455	727	**3371**	**669**
		B	2705	534	2765	635	3004	580	3087	662	**2890**	**603**
		C	2857	580	2801	584	2778	561	2728	575	**2791**	**575**
		Clone means	**2920**	**577**	**3056**	**627**	**3004**	**604**	**3090**	**655**	**3017**	**616**
	Kipkebe	*A*	*3022*	*612*	*3036*	*800*	*3054*	*741*	*3041*	*800*	***3038***	***738***
		B	*3041*	*612*	*3068*	*777*	*3059*	*759*	*3031*	*745*	***3050***	***723***
		C	*3054*	*616*	*2972*	*787*	*2949*	*708*	*2939*	*713*	***2979***	***706***
		Clone means	***3039***	***613***	***3025***	***788***	***3021***	***736***	***3004***	***753***	***3022***	***722***

APPENDIX 8.15: IRRADIATION MONTHLY MEANS PER YEAR IN *WATTS PER SQUARE METER* (*Wm*$^{-2}$) FOR THE 4 TREATMENTS PER LOCATION (KANGAITA AND KIPKEBE), OCTOBER 2007 TO NOVEMBER 2009

(a)

Site	Parametre	Period	Position	Treatment mean measurements			
				301/5	**31/37**	**31/8**	**TN 14-3**
Kangaita	Direct solar radiation, E_{dir} (Wm^{-2}): Mean monthy	2007	Top	532.5	465.3	518.2	493.4
			Base	90.3	82.9	96.0	88.1
		2008	Top	799.6	790.9	830.7	750.9
			Base	136.7	139.4	145.4	136.3
		2009	Top	698.8	712.5	728.0	724.4
			Base	146.7	150.1	161.0	154.9
		Mean for Top		***677.0***	***656.2***	***692.3***	***656.2***
		Mean for Base		***124.6***	***124.1***	***134.1***	***126.4***
Kipkebe	Direct solar radiation, E_{dir} (Wm^{-2}): Mean monthy	2007	Top	513.0	501.4	518.7	518.2
			Base	198.4	209.3	221.1	185.4
		2008	Top	670.3	674.6	666.1	665.1
			Base	161.5	148.2	144.9	139.4
		2009	Top	686.1	694.5	689.5	696.1
			Base	144.3	123.3	117.7	88.2
		Mean for Top		***623.1***	***623.5***	***624.8***	***626.5***
		Mean for Base		***168.1***	***160.3***	***161.2***	***137.7***

(b) *Kangaita daily mean* E_{dir} *(Wm*$^{-2}$*) for top and beneath canopy of tea bushes measured between 2007 and 2009.*

Parametre	Year	Position	Treatment (tea clones)				
			301/5	**31/37**	**31/8**	**TN 14-3**	**Annual Mean**
Direct solar radiation (E_{dir}) (Wm^{-2}): Daily Means	2007	Top	533	465	518	493	**502**
		Base	90	83	96	88	**89**
	2008	Top	800	791	831	751	**793**
		Base	137	139	145	136	**139**
	2009	Top	699	713	728	724	**716**
		Base	147	150	161	155	**153**
	Mean for Top		***677***	***656***	***692***	***656***	**670**
	Mean for Base		***125***	***124***	***134***	***126***	**127**

(c) *Kipkebe daily mean E_{dir} (Wm^{-2}) for top and beneath the canopy of tea bushes computed between 2007 and 2009.*

Parametre	Year	Position	Treatment (tea clones)				
			301/5	**31/37**	**31/8**	**TN 14-3**	**Annual Mean**
Direct solar radiation (***E_{dir}***) (Wm^{-2}): Daily Means	2007	Top	513	501	519	518	**513**
		Base	198	209	221	185	**203**
	2008	Top	670	675	666	665	**669**
		Base	162	148	145	139	**149**
	2009	Top	686	695	690	696	**692**
		Base	144	123	118	88	**118**
	Mean for Top		***623***	***624***	***625***	***627***	**625**
	Mean for Base		***168***	***160***	***161***	***138***	**157**

APPENDIX 8.16: PAR AND DIRECT IRRADIANCE TAKEN AT TIMBILIL, APRIL 2012

Broadband measurements are measured in *millivolts (mV)* while PAR measurements are given in *mol* $m^{-2}s^{-1}$

Position	**Time**	**PAR (Ceptometer) quantum units (mol $m^{-2}s^{-1}$)**	**PAR converted to E_{dir} (Wm^{-2}) *[Eq. 3.5]*: Q_P**	**Solarimeter (broadband) readings *(mV)***	**Conversion from solarimeter *(mV)* to direct solar irradiance *(Wm^{-2}) [Eq. 3.1], cf=0.706)*: R_S**
Top	1000 hrs	1,268	276	10.1	609
Base	1000 hrs	340	74	5.4	327
Top	1200 hrs	1,435	312	12.0	725
Base	1200 hrs	474	103	7.0	421
Top	1400 hrs	1,095	238	8.2	497
Base	1400 hrs	340	74	4.9	295
Top	**Mean**	**1,266**	**275**	**10.1**	**610**
Base	**Mean**	**385**	**84**	**5.8**	**348**

APPENDIX 8.17: KANGAITA TEMPERATURE (°C) AND RAINFALL (*MILLIMETERS - mm*) MEASUREMENTS, JANUARY 2007 - DECEMBER 2009, BOT/GENET 8 EXPERIMENTAL SITE

Year	Month	Daily mean mxm. T°C	Daily mean min. T°C	Overall daily mean T°C	Monthly rainfall totals (mm)	No. of rain days (> trace)
2007	Jan.	21.9	10.0	16.0	105.5	9
	Feb.	23.3	10.3	16.8	83.6	7
	Mar.	23.0	10.7	16.9	72.2	10
	Apr.	21.0	11.3	16.2	381.5	16
	May	20.1	12.4	16.3	496.6	23
	June	18.3	10.8	14.6	150.5	12
	July	16.9	10.5	13.7	86.8	19
	Aug.	16.7	10.4	13.6	243.3	24
	Sept.	19.7	10.5	15.1	84.8	10
	Oct.	20.4	11.5	16.0	187.3	12
	Nov.	20.6	10.1	15.4	186.6	12
	Dec.	21.2	10.0	15.6	117.8	9
	Totals	**243.1**	**128.5**	**186.2**	**2,196.5**	**163**
	Means	**20.3**	**10.7**	**15.5**	**183.0**	**13.6**
2008	Jan.	21.7	9.5	15.6	77.2	9
	Feb.	22.0	8.0	15.0	152.5	4
	Mar.	22.0	11.0	16.5	198.6	15
	Apr.	20.2	10.8	15.5	343.7	16
	May	19.6	11.7	15.7	232.7	19
	June	17.7	10.9	14.3	75.6	15
	July	16.2	9.3	12.8	101.4	20
	Aug.	16.7	9.3	13.0	87.2	20
	Sept.	20.4	10.2	15.3	51.3	8
	Oct.	20.6	12.3	16.5	384.0	18
	Nov.	21.2	10.8	16.0	60.3	8
	Dec.	21.9	9.6	15.8	0.30	0
	Totals	**240.2**	**123.4**	**182**	**1,764.8**	**152**
	Means	**20.0**	**10.3**	**15.2**	**147.1**	**12.7**

2009		Daily mean mxm. T°C	Daily mean min. T°C	Overall daily mean T°C	Monthly rainfall totals (mm)	No. of rain days (> trace)
	Jan.	22.5	9.7	16.1	31.9	5
	Feb.	22.5	10.0	16.3	3.1	1
	Mar.	24.0	10.0	17.0	64.0	3
	Apr.	21.3	11.7	16.5	224.2	16
	May	19.5	12.7	16.1	305.2	18
	June	19.3	11.2	15.3	74.4	12
	July	17.7	10.2	14.0	19.9	8
	Aug.	16.2	9.7	13.0	81.5	13
	Sept.	20.2	11.3	15.8	42.8	10
	Oct.	20.7	10.5	15.6	489.0	20
	Nov.	20.8	9.9	15.4	127.3	15
	Dec.	20.9	10.0	15.5	149.7	13
	Totals	**245.6**	**126.9**	**186.6**	**1,613.0**	**134**
	Means	**20.5**	**10.6**	**15.6**	**134.4**	**11.2**

APPENDIX 8.18: KIPKEBE TEMPERATURE (^{O}C) AND RAINFALL (*mm*) MEASUREMENTS, JAN. 2007 - DEC. 2009, BOT/GENET 8)

Year	Month	Daily mean mxm. T^{O}C	Daily mean min. T^{O}C	Daily overall mean T^{O}C	Monthly rainfall totals (mm)	No. of rain days (> trace)
2007	Jan.	23.5	17.4	20.5	165.2	17
	Feb.	24.0	17.3	20.7	107.1	11
	Mar.	25.0	16.7	20.9	130.5	21
	Apr.	23.6	17.2	20.4	94.9	16
	May	22.8	17.1	20.3	153.1	18
	June	22.7	15.6	19.2	160.7	16
	July	21.7	16.3	19.0	71.1	17
	Aug.	21.5	16.8	19.2	118.9	18
	Sept.	22.3	16.8	19.0	142.4	17
	Oct.	24.7	16.3	20.5	63.1	11
	Nov.	23.7	16.4	20.1	54.6	13
	Dec.	23.8	16.4	20.1	77.6	6
	Totals	**279.3**	**200.3**	**239.9**	**1,339.2**	**181**
	Means	**23.3**	**16.7**	**20.0**	**111.6**	**15.1**
2008	Jan.	25.0	16.3	20.7	32.9	7
	Feb.	24.9	16.5	20.7	34.4	4
	Mar.	24.3	16.5	20.4	189.5	20
	Apr.	23.2	16.6	19.9	193.7	21
	May	22.7	16.8	19.8	88.3	11
	June	21.6	16.8	19.2	110.3	10
	July	21.9	15.9	18.9	211.2	20
	Aug.	21.5	16.4	19.0	164.6	13
	Sept.	22.8	16.9	19.9	175.2	17
	Oct.	24.3	16.8	20.6	105.1	12
	Nov.	23.2	16.7	20.0	181.6	17
	Dec.	24.2	16.5	20.4	56.9	7
	Totals	**279.6**	**198.7**	**239.5**	**1,543.7**	**159**
	Means	**23.3**	**16.6**	**20.0**	**128.6**	**13.3**

2009	Month	Daily mean mxm. $T^{O}C$	Daily mean min. $T^{O}C$	Daily overall mean $T^{O}C$	Monthly rainfall totals (mm)	No. of rain days (> trace)
	Jan.	23.3	16.8	20.1	117.2	11
	Feb.	23.9	16.8	20.4	38.0	8
	Mar.	25.2	17.1	21.2	105.9	11
	Apr.	22.8	17.1	20.0	208.1	23
	May	22.3	17.0	19.7	146.7	13
	June	23.4	16.7	20.1	88.8	12
	July	26.2	13.5	19.9	115.8	8
	Aug.	26.2	11.3	18.8	204.1	14
	Sept.	25.3	15.3	20.3	195.3	18
	Oct.	25.7	15.3	20.5	116.4	17
	Nov.	24.8	13.3	19.1	71.3	10
	Dec.	25.8	12.8	19.3	119.4	21
	Totals	**294.9**	**183.0**	**239.4**	**1,607.0**	**166**
	Means	**24.6**	**15.3**	**20.0**	**134.0**	**13.8**

APPENDIX 8.19: TIMBILIL AIR T°C, SOIL T°C AT 0.3M AND RAINFALL (*mm*) MEASUREMENTS, JANUARY 2007 - DECEMBER 2009

Year	Month	Daily mean mxm. T°C	Daily mean min. T°C	Daily overall mean T°C	Soil T°C at 0.3m depth	Monthly rainfall totals (mm)	No. of rain days (> trace)
2007	Jan.	24.2	9.7	17.6	19.2	132.7	10
	Feb.	24.5	9.8	17.2	19.2	123.3	9
	Mar.	25.7	9.4	17.6	19.3	99.7	5
	Apr.	24.5	10.4	17.5	18.9	239.5	20
	May	23.6	10.2	16.9	19.3	254.0	24
	June	21.5	10.3	15.9	18.8	202.9	23
	July	21.3	9.3	15.3	18.0	240.5	24
	Aug.	21.8	9.4	15.6	17.6	277.3	28
	Sept.	22.5	9.5	16.0	17.7	302.3	20
	Oct.	23.7	9.1	16.4	18.1	145.7	17
	Nov.	23.2	9.7	16.5	18.3	33.7	7
	Dec.	24.6	8.7	16.7	18.1	34.7	8
	Totals	**281.1**	**115.5**	**199.2**	**222.5**	**2,086.3**	**195**
	Means	**23.4**	**9.6**	**16.6**	**18.5**	**173.9**	
2008	Jan.	25.7	8.7	17.2	18.0	24.1	6
	Feb.	24.9	8.2	15.8	18.5	105.3	8
	Mar.	25.1	9.0	17.1	18.3	337.9	16
	Apr.	23.8	8.4	16.1	18.1	166.3	14
	May	23.3	8.3	15.8	18.8	172.8	24
	June	22.0	8.9	15.5	18.1	211.5	17
	July	21.6	8.8	15.2	18.0	236.6	21
	Aug.	22.3	9.1	15.7	17.4	244.8	23
	Sept.	23.6	8.7	16.2	18.2	291.5	23
	Oct.	23.1	8.8	16.0	17.8	371.5	23
	Nov.	24.0	8.8	16.4	18.2	212.2	16
	Dec.	25.3	8.6	17.0	18.8	23.7	7
	Totals	**284.7**	**104.3**	**194.0**	**218.2**	**2,398.2**	**198**
	Means	**23.7**	**8.7**	**16.2**	**18.2**	**199.9**	

2009	Month	Daily mean mxm. T°C	Daily mean min. T°C	Daily overall mean T°C	Soil T°C at 0.3m depth	Monthly rainfall totals (mm)	No. of rain days (> trace)
	Jan.	24.2	8.3	16.3	18.6	114.9	8
	Feb.	25.9	7.6	16.7	18.8	47.2	3
	Mar.	27.4	8.4	17.9	19.5	34.0	4
	Apr.	24.4	8.3	16.4	19.5	298.8	25
	May	22.9	8.9	15.9	18.9	230.0	20
	June	24.1	7.9	16.0	19.1	114.6	14
	July	23.0	7.7	15.3	18.3	96.6	16
	Aug.	23.5	8.7	16.1	18.5	147.5	15
	Sept.	23.0	8.9	16.0	19.8	190.6	26
	Oct.	22.8	9.3	16.1	18.7	236.1	18
	Nov.	24.3	8.5	16.4	18.7	81.1	7
	Dec.	23.2	9.3	16.3	18.7	239.5	16
	Means	**24.1**	**8.5**	**16.3**	**227.1**	**152.6**	**172**
	Totals	**288.7**	**101.8**	**195.4**	**19.0**	**1,830.9**	

APPENDIX 8.20: CRITICAL AIR & SOIL T^{O}C MEASUREMENTS SPANNING 11 YEARS (2000-2010) AT TIMBILIL

Parameter	Year											11-yr mean
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	
Mean daily soil T^{O}C (0.3m)	18.5	18.6	18.7	18.6	18.7	18.8	18.8	18.5	18.2	19.0	18.8	***18.7***
Mean daily air T^{O}C	16.6	16.5	16.7	16.7	16.3	16.7	16.2	16.6	16.2	16.3	16.6	***16.5***
Mean daily grass min. T^{O}C	7.6	8.1	7.9	7.9	8.2	7.9	8.5	8.0	7.8	7.8	9.1	***8.1***

Variance and standard error:

Source	Soil temperature	Air temperature
Mean	18.655	16.491
N	11	11
Standard deviation	0.2115	0.2023
Standard error of mean	0.0638	0.0610
Variance	0.045	0.041

APPENDIX 8.21: *Qp:Rs* RATIO (PAR AND DIRECT IRRADIANCE) AT TIMBILIL, APRIL 2012

Date	Position	Time	Ceptometre Photon System readings (*mol* $m^{-2}s^{-1}$) - PAR quantum units,	Conversion of PAR (*mol* $m^{-2}s^{-1}$) to direct radiation (E_{dir} in Wm^{-2}) (*Col.1÷4.6*) (*Eq. 3.5*) **Qp**	Corresponding solarimeter broadband radiation (*mV*) field readings	Converted *mV* to Energy System (E_{dir}) (Wm^{-2}), i.e. *Eq. 3.1* (*cf = 0.706*) **Rs**	Ratio **Qp:Rs**
13 April 2012	Top	1000 hrs	1432	311	13.6	821	0.38
	Base	1000 hrs	356	77	8.9	537	0.14
	Top	1200 hrs	1549	337	15.6	941	0.36
	Base	1200 hrs	471	102	8.9	537	0.19
	Top	1400 hrs	1221	265	12.4	748	0.35
	Base	1400 hrs	312	68	7.6	459	0.15
16 April 2012	Top	1000 hrs	1069	232	9.4	567	0.41
	Base	1000 hrs	275	60	4.3	259	0.23
	Top	1200 hrs	1172	255	12.6	760	0.34
	Base	1200 hrs	489	106	8.2	497	0.21
	Top	1400 hrs	1312	285	10.5	634	0.45
	Base	1400 hrs	302	66	7.2	434	0.15
17 April 2012	Top	1000 hrs	1549	337	13.4	809	0.42
	Base	1000 hrs	371	81	7.0	422	0.19
	Top	1200 hrs	1770	385	15.6	941	0.41
	Base	1200 hrs	542	118	8.0	483	0.24
	Top	1400 hrs	842	183	6.8	410	0.45
	Base	1400 hrs	475	103	4.0	241	0.43
18 April 2012	Top	1000 hrs	1172	255	9.7	585	0.44
	Base	1000 hrs	312	68	4.7	284	0.24
	Top	1200 hrs	1765	384	15.6	941	0.41
	Base	1200 hrs	456	99	8.8	531	0.19
	Top	1400 hrs	872	190	6.2	374	0.51
	Base	1400 hrs	284	62	4.3	259	0.24

19 April 2012	Top	1000 hrs	1250	272	8.7	525	0.52
	Base	1000 hrs	320	70	5.4	326	0.21
	Top	1200 hrs	1062	231	7.2	434	0.53
	Base	1200 hrs	296	64	5.7	344	0.19
	Top	1400 hrs	432	94	2.9	175	0.54
	Base	1400 hrs	236	51	1.3	78	0.66
24 April 2012	Top	1000 hrs	642	140	6.4	386	0.36
	Base	1000 hrs	246	53	3.3	199	0.27
	Top	1200 hrs	882	192	7.2	434	0.44
	Base	1200 hrs	376	82	4.4	266	0.31
	Top	1400 hrs	868	189	7.1	428	0.44
	Base	1400 hrs	266	58	3.6	217	0.27
26 April 2012	Top	1000 hrs	2395	521	12.4	748	0.70
	Base	1000 hrs	476	103	2.8	350	0.30
	Top	1200 hrs	2365	514	13.6	821	0.63
	Base	1200 hrs	764	166	7.2	434	0.38
	Top	1400 hrs	2130	463	11.8	712	0.65
	Base	1400 hrs	505	110	6.2	374	0.29
28 April 2012	Top	1000 hrs	637	138	7.2	434	0.32
	Base	1000 hrs	362	79	4.0	241	0.33
	Top	1200 hrs	932	203	8.8	531	0.38
	Base	1200 hrs	396	86	4.6	278	0.31

APPENDIX 8.22: PAR (*mol* $m^{-2}s^{-1}$) FOR THE 4 TREATMENTS PER LOCATION, OCT. 2007 TO NOV. 2009

Direct radiation measurements (Wm^{-2}) were converted to PAR by multiplying it by a factor 4.6 (*Eq. 3.5*).

Site	Parameter	Period	Position	Treatment mean measurements				Mean
				301/5	31/37	31/8	TN 14-3	
Kangaita	PAR (*mol* $m^{-2}s^{-1}$)	2007	Top	2450	2140	2384	2270	2311
			Base	415	381	442	405	411
		2008	Top	3678	3638	3821	3454	3648
			Base	629	641	669	627	642
		2009	Top	3214	3278	3349	3332	3293
			Base	675	690	741	713	705
		Mean for Top		***3114***	***3019***	***3185***	***3019***	***3084***
		Mean for Base		***573***	***571***	***617***	***582***	***586***
Kipkebe	PAR (*mol* $m^{-2}s^{-1}$)	2007	Top	2360	2306	2386	2384	2359
			Base	913	963	1017	853	937
		2008	Top	3083	3103	3064	3059	3077
			Base	743	682	667	641	683
		2009	Top	3156	3195	3172	3202	3181
			Base	664	567	541	406	545
		Mean for Top		***2866***	***2868***	***2874***	***2882***	***2872***
		Mean for Base		***773***	***737***	***742***	***633***	***722***

APPENDIX 8.23: KANGAITA MEAN AIR T^{O}C (T_{MM}) & SOIL T^{O}C AT 0.3M (T_{EST}), 2007-2008

Year	Month	Mean daily air T^{O}C (T_{MM})	T_{EST} (^{O}C) (d=0.3m)	$T_{EST} - T_{MM}$
2007	Jan	16.0	21.3	5.3
	Feb	16.8	22.1	5.3
	Mar	16.9	21.5	4.6
	Apr	16.2	20.0	3.8
	May	16.3	19.3	3.0
	June	14.6	19.0	4.4
	July	13.7	17.1	3.4
	Aug	13.6	17.0	3.4
	Sept	15.1	20.3	5.2
	Oct	16.0	19.5	3.5
	Nov	15.4	20.9	5.5
	Dec	15.6	23.0	7.4
	Mean	**15.5167**	**20.0833**	**4.5667**
	SED	**± 1.0920**	**±1.8419**	**±1.2543**
2008	Jan	15.6	23.3	7.7
	Feb	15.0	24.9	9.9
	Mar	16.5	23.3	6.8
	Apr	15.5	20.5	5.0
	May	15.7	19.1	3.4
	Jun	14.3	18.5	4.2
	Jul	12.8	17.1	4.3
	Aug	13.0	16.0	3.0
	Sept	15.3	17.0	1.7
	Oct	16.6	18.3	1.7
	Nov	16.0	19.9	3.9
	Dec	15.8	20.0	4.2
	Mean	**15.175**	**19.825**	**4.65**
	SED	**± 1.2285**	**± 2.7805**	**± 2.4194**

APPENDIX 8.24: KIPKEBE MEAN AIR T^{O}C (T_{MM}), 2000-2010

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Mean	SED
Air temp. (^{O}C)	17.6	17.5	18.7	19.9	20.0	20.4	20.1	20.0	20.0	20.0	19.6	19.4	± 1.0269