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An evaluation of the responses of some tea clones to environment in Kenya.

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ABSTRACT

An evaluation of the responses of some Kenyan tea clones to environment in Kenya.

An experiment set up at four sites in Kericho, Kenya was used to investigate Genotype x Environment interactions of four tea clones of commercial and scientific interest.

Small differences in environment resulted in large variations in dry matter production and yield between sites and clones. The largest dry matter was from clone TN14/3 (29 t ha⁻¹) but it had low yield (2.1 t ha⁻¹ y⁻¹). By contrast, the largest yield was from clone S15/10 (3.8 t ha⁻¹ y⁻¹), which gave the smallest dry matter (18 t ha⁻¹). These contrasting responses in dry matter and yield were analysed in terms of the interception of solar radiation, radiation use efficiency, partition of dry matter and components of yield. The differences in clonal dry matter production were attributed to site to site variability in solar radiation and temperature which affected the rates of ground cover development and the solar radiation interception. The differences in yield were attributed mainly to differences in air temperature and saturation deficits of the air between the sites which affected the shoot replacement cycles through rates of shoot extension and development.

Differences in measured and derived environmental variables between the sites were found. Incident solar radiation differed between the sites by up to 2.4 MJ m⁻² d⁻¹. Differences in mean air and soil temperatures between the extreme sites were 2.5 °C and 3 °C respectfully. A lapse rate of 6.1 °C km⁻¹ for mean air temperature was found. Annual rainfall amounts also differed between the sites by up to 700 mm. There were no differences in wind speeds, but there were large differences were in saturation deficits (0.5 kPa) and evapotranspiration (1 mm d⁻¹).

During the course of the experiment light interception ranged from less than 5% at planting to more than 80% in April 1994. Radiation use efficiencies for dry matter ranged from 0.30 to 0.45 g MJ⁻¹ in the clones studied and appeared conservative with respect to temperature across the sites.

Clone TN14/3 had the lowest base temperature for shoot extension (6.1 °C), while clone BB35 had the highest (10.4 °C). The base temperatures for shoot extension were 1.3 to 2.9 °C higher than those for development, hence the differences in shoot lengths between sites. Shoot replacement cycle ranged from 57 days to 110 days between the sites and was the main determinant of yield.

The dry matter content of shoots varied between sites and seasons and ranged from 18% to 33%. Mean shoot dry mass was inversely proportional to temperature, ranging from 6 to 12% difference between extreme sites.

Loss in yield due to water stress during the dry seasons ranged from 14 to 20% across the sites. Yield losses due to 'hut sites' ranged from 10 to 50%, while that from hail damage accounted for up to 20% of annual yields.

These results are discussed in the light of other work in Kericho and southern Tanzania. The thesis concludes by considering the implication of the results for the tea industry.

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I would like to thank the Overseas Development Administration for the scholarship to undertake this training and The British Council for administration of the scholarship. I would also like to thank the Director and Board of Directors of Tea Research Foundation for allowing me to undertake this study and for providing the funds to run the experiment in Kenya.

Many thanks to AHP Co. Ltd., and the management at Kipketer and Kaproret estates; George Williamson Ltd., and management at Changoi and Lelsa estates for allowing the setting up of, and looking after, the experimental plots in their respective estates.

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I cannot forget to thank my colleague, Francis Wachira, with whom we started an experiment earlier, on Genotype x Environment interactions looking at wider environmental range.

I owe lots of thanks to my colleagues at Silsoe; Paul Burgess, Josy Siakantu, Julius Kigalu, Ibok Oduro, Cesareo Landeros and the members of Christian Union to mention but a few, who were a constant source of encouragement.

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LIST OF SYMBOLS AND ABBREVIATIONS

A	function of leaf absorptivity	(dimensionless)
a	Leaf absorptance	(dimensionless)
AWC	Available water content - the water held between field capacity and permanent wilting point	(mm m ⁻¹)
b	Relative rate of leaf change with mass	(g g ⁻¹ leaf ⁻¹)
D	Drainage of water below crop rooting depth	(mm)
d	Root depth of a crop	(m)
d ₀	initial root depth	
d _t	root depth at time t	
DM	Dry mass	(kg)
E _s	Bare soil evaporation	(mm d ⁻¹)
ET _c	Crop transpiration	(mm d ⁻¹)
ET ₀	Reference crop evapotranspiration	(mm d ⁻¹)
f _b	fraction of incident solar radiation that is beam	(dimensionless)
f _s	Proportion of intercepted solar radiation	
GC	Proportion of ground covered by crop	
HI	Harvest index - the proportion of total dry matter that is harvested as the economic product	
k	Extinction coefficient of light in a canopy	
k _r	relative increase in root depth per unit time	(m m ⁻¹ d ⁻¹)
K _c	Crop factor	
K _y	Relative change in yield per unit drought stress	
KSh.	Kenya Shilling	
KTDA	Kenya Tea Development Authority	
L	Shoot length	(mm)
LAI	Leaf area index - Total leaf area per unit ground area	
LAI*	Leaf area index -total canopy leaf area per unit canopy area	
L _f	Final shoot length at harvest	(mm)
L ₀	Initial shoot length	(mm)
N	Nitrogen	
PAR	Photosynthetically Active Radiation - the radiation used by the plants in the process of photosynthesis (400 to 700 nm)	(μmol m ⁻² s ⁻¹)
PWP	Permanent wilting point	(kPa)
R	Rainfall	(mm)

r^2	Percentage variance explained	(%)
RER	Relative shoot extension rate	(mm mm ⁻¹ d ⁻¹)
R_s	Neutron probe count in soil	
R_w	Neutron probe count in water (water constant)	
s.e.	Standard error	
SD	Saturation deficit of the air	(kPa)
SD-time:	defined as the accumulation of stress above a threshold per unit time	(kPa d)
S_i	Intercepted solar radiation	(MJ m ⁻² d ⁻¹)
S_o	Incident solar radiation	(MJ m ⁻² d ⁻¹)
SRC	Shoot replacement cycle - time taken for shoot released from apical dominance to reach three leaves	(d)
SWD	Soil water deficit	(mm)
T	Temperature	(°C)
t	Time	(d)
T_{bd}	Base temperature for extension and development- temperature below which no development occurs	(°C)
T_{be}	Base temperature for extension and development - temperature below which no extension occurs	(°C)
TRFK	The Tea Research Foundation of Kenya	
TRIEA	Tea Research Institute of East Africa	
t_f	Duration of shoot growth	(d)
x	Ratio of horizontal to vertical projected areas of a canopy	
Y_{act}	Actual or observed yields	(kg ha ⁻¹)
Y_{prd}	Predicted tea yields	(kg ha ⁻¹)
τ	fraction of Photosynthetically Active Radiation (PAR) that is transmitted	
ϕ	is the sun's zenith angle	(°)
Θ	Thermal time: time-temperature integral above a specified base	(°C d)
ρ_d	Thermal development rate - increase in development rate per unit increase in air temperature above T_{bd}	(d ⁻¹ °C ⁻¹)
ρ_e	Thermal extension rate - increase in relative extension rate per unit rise in air temperature above T_{be}	(mm mm ⁻¹ d ⁻¹ °C ⁻¹)
ϵ_s	Radiation use efficiency for solar radiation -the ratio of plant dry mass accumulated over a period divided by the intercepted solar radiation over the same period	(g MJ ⁻¹)
θ_v	Volumetric soil water content -	(mm mm ⁻¹)

CHAPTER 1

INTRODUCTION

General

Tea (*Camellia sinensis* L.) is a perennial crop cultivated for its shoots that are used in the manufacture of tea. It is thought to have originated from a region bordering Assam, north Burma, south-west China and Tibet (Barua, 1989). At present, it is grown in latitudes ranging from the equator to 33°S in Natal, South Africa and 49°N in Georgia (Huang, 1989). It also spans a range of altitudes from sea level (Bangladesh) to as high as 2600m above mean sea level (a.m.s.l.) in Kenya. The climates in these different altitudes and latitudes range from Mediterranean to tropical (Carr and Stephens, 1992).

Tea was first introduced into Kenya in the early 1900s and was grown in the Limuru area near Nairobi. The success here led to the subsequent spread into other regions in the country. The first area to benefit from this was Kericho, which grew to be the largest tea growing region in the country and, by 1992, accounted for 32% of the national tea production. Tea was subsequently grown in the highlands west of the rift valley and around Mt. Kenya. These areas in which it is range from 1600 m to 2600 m a.m.s.l. with average annual rainfall between 1300 mm and 2200 mm. The soils in these regions are heavily leached acidic soils of volcanic origin with a pH of about 5.

Tea production in Kenya

The tea industry in Kenya is divided into two main sectors: the large estate sector comprising of multi-national companies and some local companies, having medium to large plantations (up to 7000 ha), and the small-holder sector that is made up of individual small scale farmers with average holdings of about 0.6 ha, whose leaf is collected and processed by the Kenya Tea Development Authority (KTDA). A third but very small sector is known as propriety farmers. These fall somewhat between KTDA and the large estate in the area they have under tea. In terms of crop production, the small-holder sector has steadily increased its share of the annual crop to about 55% in 1990. However the small holder sector covers approximately 66% of the total 87,800 ha of tea in 1988 (Othieno, 1990).

Mean tea yields in the large estate sector in Kenya have risen over the last 40 years from under 1000 kg ha⁻¹ in the 1950s to over 3500 kg ha⁻¹ in the 1990s. Indeed a yield of up to 11000 kg ha⁻¹ has been recorded for a high yielding clone grown commercially at an altitude of 1900 m in Kericho (Oyamo, 1992). The increase in yields in the large estate sector is due to a variety of factors. Over the past 20 years, better planting material in form of clones have been introduced, better management practices have been implemented such as improved fertiliser inputs, better weed control, infilling and the changes in plant spacing to more population. By contrast, the increase in mean yield per unit area was not as dramatic in the small holder sector. This is due to a number of factors, some of which are the different socio-economic backgrounds of individual farmers, which has a bearing on the yield when averaged over the whole tea growing regions.

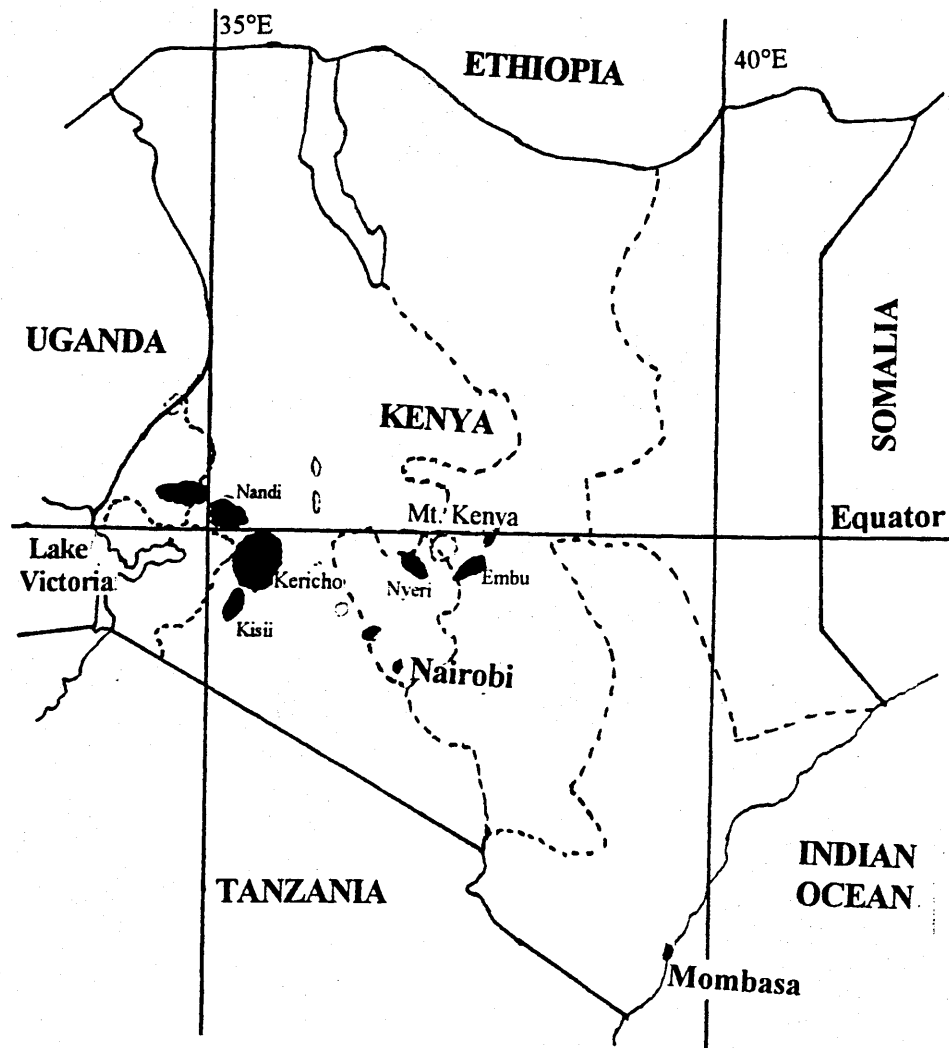


Figure 1.1. Map of Kenya showing the major tea areas.

Kenya is the largest tea producer in Africa and ranks 4th in world tea production, with a 16% share of the world tea export market in 1992 (ITC, 1992). Tea is therefore an important foreign exchange earner for the country and currently is in the lead in agricultural commodities. About 88% of the country's production was exported in 1992 (Tea Board of Kenya, 1992), bringing in an estimated Kshs. 9 billion (about US \$ 200 million). On the domestic front, tea also provides employment and a direct means of livelihood of about 200,000 people (individual small holders and their families) not to mention support industries. Although, there is therefore considerable pressure to expand the area of tea in Kenya, there is now little land for expansion in either the small holder or large estate sectors. For the small holder, a balance between cash crops (in this case tea) and the crops or livestock necessary for self-sufficiency is essential. Optimising the production from such small lands is therefore a priority for these farmers. While the plantation sector is not faced with the same constraints of multiple land-use as the small holder, there is little land left for expansion and hence the same argument of optimisation applies. Expansion is continuing in the present with the available planting material for those farmers with land which can be turned to tea. On the other hand some in the large estate sector are looking to increase yields by uprooting old tea and re-planting with higher yielding clones.

The main areas where future expansion might be possible are in the so-called 'marginal areas for tea' (where rainfall, temperatures and /or soils conditions may be limiting). At present this is being undertaken on a limited scale for example in the Nyayo Tea Zone. Very little research has been carried out to identify cultivars that can grow well in such areas although a number of experiments have been conducted at the Tea Research Foundation of Kenya (TRFK), which is itself a cold area. Neither has there been a study to determine the mechanisms causing the wide variations in yield observed in apparently similar environments in Kenya. There is therefore a need to identify in the short term, existing clones that are adapted to grow in such areas and to understand the mechanisms determining the yield of tea across a wide range of environments and establish the reasons for different clonal responses. In the long term, this may lead to the development of criteria by which new clones can be selected.

Objectives

The main objectives of this study are therefore:

- i) to quantify the effects of climate and weather on variability in dry matter production, partitioning, yield and the components of yield in selected Kenyan tea clones and,
- ii) to identify mechanisms causing any observed differences in response to environment.

FRAMEWORK FOR ANALYSIS OF PLANT RESPONSES TO ENVIRONMENT

The objectives will be met by using a framework for analysis of plant growth and productivity.

The measurement of simple yield responses to the environment does not indicate the mechanisms responsible for high yield and or cold tolerance. Identification of such mechanisms may be possible from an analysis of the physiological processes which determine yield. In his review, Carr (1972) gave the climatic factors which affect the tea plant as : radiation, temperature (both soil and air), humidity, rainfall, hail and wind. Differences in the potential yield of a crop can be caused primarily by both variations in solar irradiance, which provides the energy for production of assimilates and variations in the water and nutrient availability to roots. These two main factors occur in concert with other influential factors e.g. temperature (both soil and air), saturation deficits of the air and wind speeds.

A modification of the framework proposed by Carr and Stephens (1992) is presented below and is used to outline previous work on the environmental physiology of tea. The approach considered in this review is physically based but has the advantage of few inputs when compared to some of the more elaborate physiological models developed for annual crops.

The thesis is then based on the framework for analysis and is outlined below. The framework deals with the wider view of the thesis. A more detailed review of the relevant literature is presented at the introduction of each Chapter.

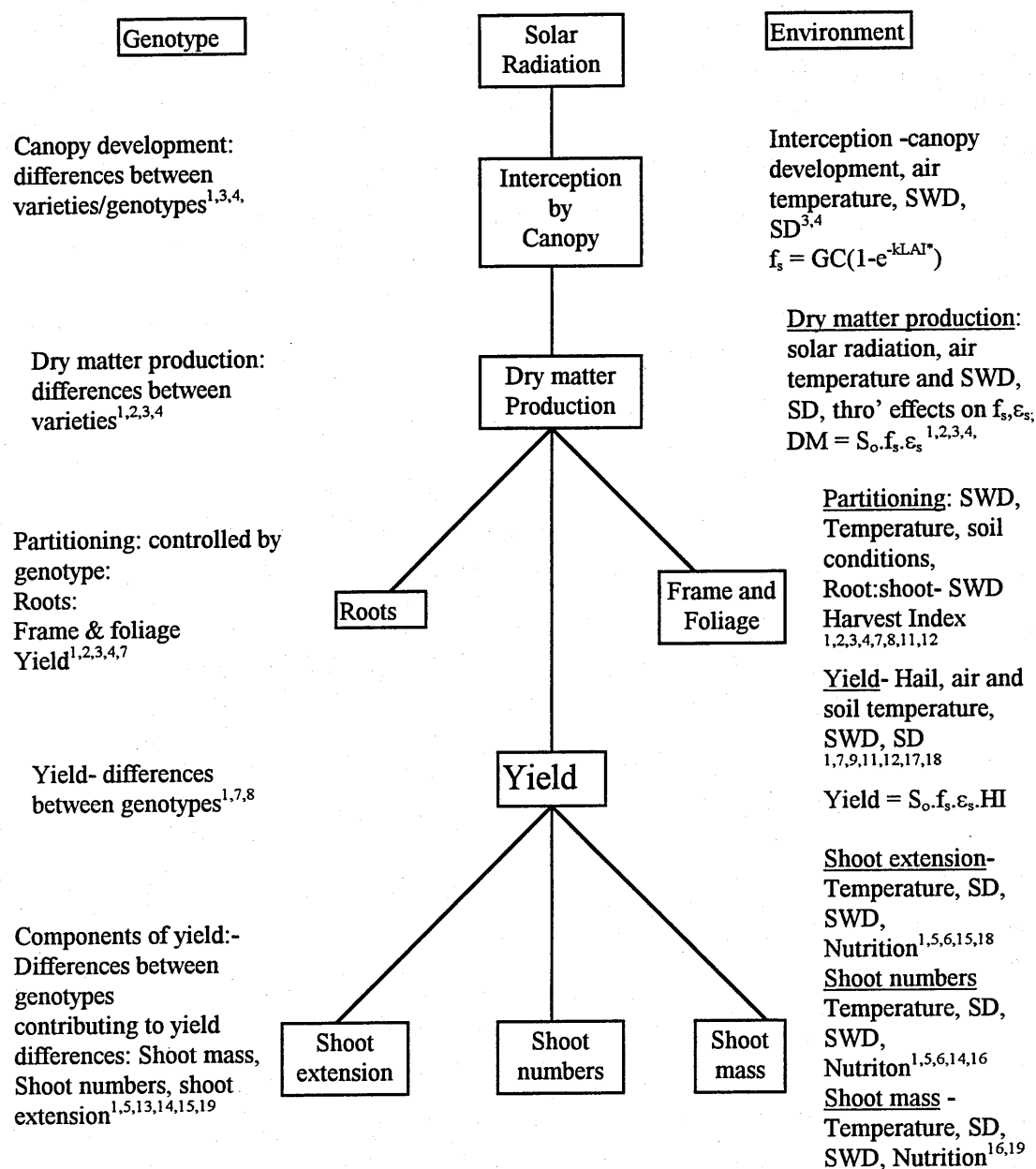


Fig. 1.2. Framework for analysis of effects of environment and genotype on total dry matter production and yield. The control of the plant processes by genotypic and environmental factors are listed alongside, with a selection of references [see text for definition of symbols].

¹Burgess (1992); ²Magambo and Cannell (1981); ³Marshall *et al.* (1992); ⁴Mohamed *et al.* (1988)
^{5,6}Obaga *et al.* (1988, 1989); ^{7,8}Othieno (1978, 1982); ⁹Othieno *et al.* (1992); ¹⁰Smith *et al.* (1990);
^{11,12}Squire (1977, 1979); ¹³Squire *et al.* (1993); ^{14,15,16}Stephens and Carr (1990, 1993, 1994); ^{17,18}Tanton
 (1982a, b); ¹⁹Wachira *et al.* (1990).

Thesis structure

The thesis structure follows the logical flow of the framework for the analysis of plant responses. The thesis can therefore be grouped according to the framework (Fig 1.2) in to four parts. Chapter 1 deals with Introduction and Chapter 2 with the Methodology. These chapters introduce the subject and review what has been done, the areas that need to be addressed, and how these can be met in the present study through the objectives. The experimental design, the sites and clones used are described in Chapter 2.

Chapter 3 on weather, climate and soil water deficits stands on its own and describe the baseline environments in which the experiment was conducted.

The overall findings of the thesis are brought out in Chapter 4 which reports on the Genotype x Environment interactions in both dry matter production and yield. From these analyses, questions are posed as to the factors controlling the observed changes and differences. These questions are then dealt with in more detail in Chapter 5 (dry matter production), Chapter 6 (partitioning), Chapter 7 (yield), Chapter 8 (shoot extension and development) and Chapter 9 (shoot population density and shoot mass).

Chapter 10 summarises the conclusions drawn from the study, highlights the implications for the tea industry in Kenya and makes recommendations for further research.

The references for Chapters 1 to 3 and 10 are collated at the end of the thesis, while those for Chapters 4 to 9 are at the ends of respective chapters. These chapters will be submitted to international journals and are therefore presented in the form of papers.

CHAPTER 2

SITE AND METHODOLOGY

INTRODUCTION

To fulfill the objectives, an experiment was set up using four clones of commercial and scientific interest in eastern Africa and Kenya in particular. Four sites were chosen at different altitudes so as to give a range of temperatures. For ease in monitoring and management of the experiment, the sites were within 20 km from the Tea Research Foundation of Kenya at Timbilil.

This chapter describes the sites, some clonal attributes and, the general experimental methodology. Specific methodologies are dealt with in individual Chapters.

SITE DESCRIPTION

The experiment was set up at four sites within Kericho District, the main tea growing area in Kenya. The sites lie along the gradual incline of the Mau Forest ranges in the Rift Valley, with a distance of about 20 km between two extreme sites.

Table 2.1. *Approximate location (latitude and longitude) and altitude of each experimental site.*

	S	E	Altitude (m)
Timbilil	0°22'	35°21'	2200
Kipketer	0°23'	35°19'	2060
Kaporet	0°27'	35°15'	1900
Changoi	0°29'	35°14'	1800

The highest site, Timbilil, is at an altitude of 2200 m and belongs to the Tea Research Foundation of Kenya (TRFK). The two intermediate sites are Kipketer and Kaporet which both belong to African Highlands Produce Co. Ltd. (AHP). The lowest site, Changoi belongs to George Williamson Kenya Ltd. (GW). The sites were chosen to give as wide a range of altitudes (and therefore temperatures) as possible but with similar

land preparation and cultural practices. The experimental plots were situated adjacent to existing tea on land newly cleared for planting by the Estates.

EXPERIMENTAL DESIGN

A completely randomized block design was used with four treatments (clones) replicated four times at each site. An observation plot immediately adjacent to the experiment, planted with the same four clones, was used for plant dry matter harvests. To investigate the effects of environment on the genotypes, the sites were also used as a factor in the analysis of variance. The layout was the same at each site.

Replicates				Observation block
I	II	III	IV	
S15/10	BB35	6/8	TN14/3	6/8
BB35	TN14/3	S15/10	6/8	BB35
6/8	S15/10	BB35	S15/10	TN14/3
TN14/3	6/8	TN14/3	BB35	S15/10

Figure 2.1. Layout of the experiment

SITE HISTORY

A summary table on some of the prevailing and subsequent cultural practices and land preparations are given in Table 2.2.

Table 2.2. *Summary of some site attributes including previous land use and clearing methods*

Site	Aspect	Estimated slope	Previous land use	Clearing method	Comments
Timbilil	East	< 5%	Forest	Bulldozer	Land was fallow for some time
Kipketer	South	< 5%	Cypress	Bulldozer	Planted same year as the clearing
Kaproret	West	~ 6%	Eucalyptus	Bulldozer	Planted same year as the clearing
Changoi	West	< 5%	Forest	Bulldozer/ manual	Fallow for some time

Land preparation

The Timbilil site was under natural forest until it was cleared in 1989. It was then covered by regenerating shrubs that were cleared in February/March 1991 ready for planting in May/June 1991. The Kipketer site was under cypress plantation before it was cleared in early 1991. The Kaproret site was under Eucalyptus plantation before it was cleared in early 1991, as in the other two sites, by use of bulldozer. The area slopes towards west (Table 2.2). The Changoi site was under natural forest until it was cleared and left fallow for a number of years by which time it was covered by a lot of shrubs. It was cleared again in 1991 in preparation for planting that year.

METHODS

Soils

Soils were sampled from each site and physical (texture and water retention) and chemical (pH and nutrients) analyses were carried out at the Tea Research Foundation of Kenya Laboratory.

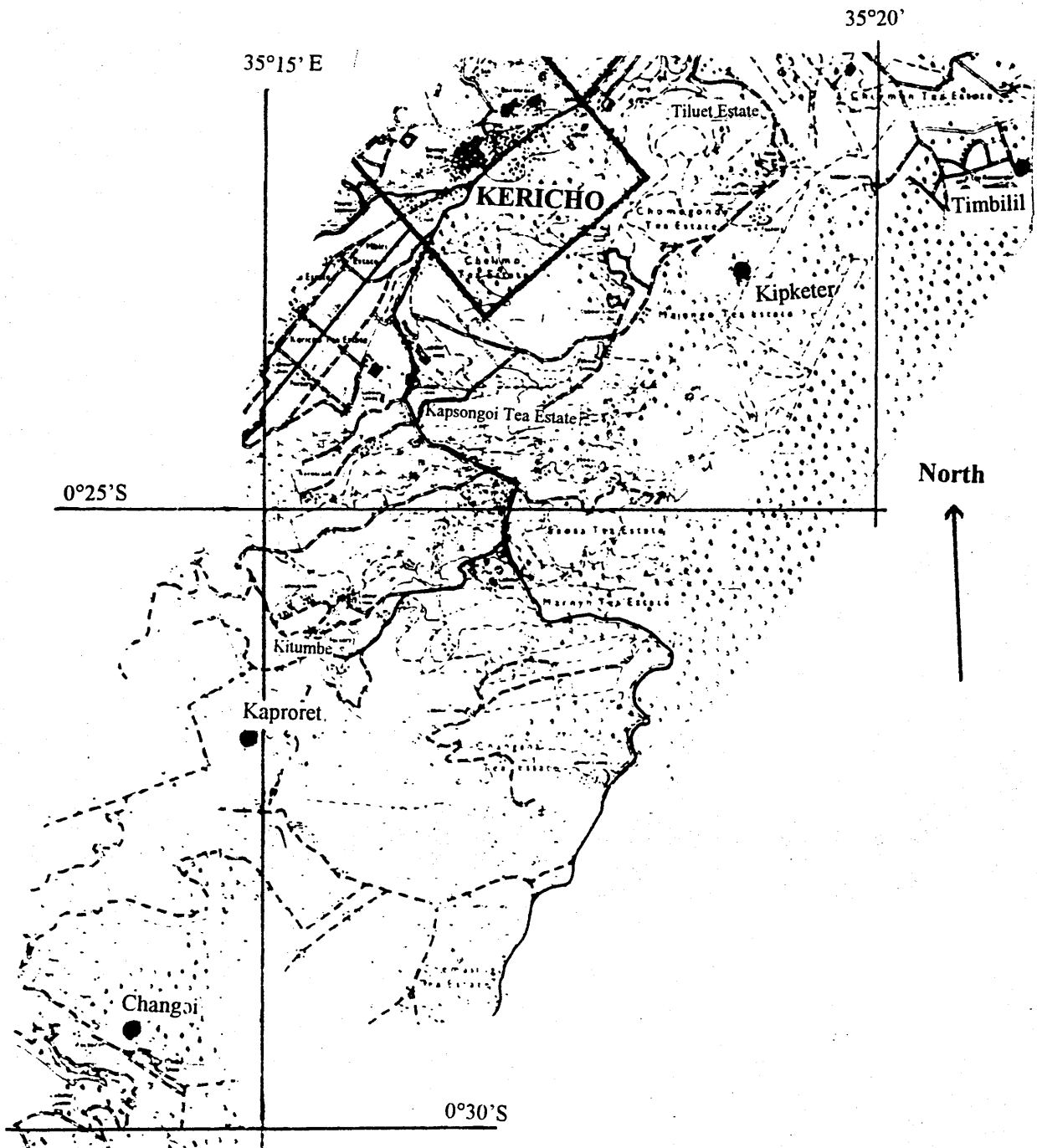


Figure 2.2. Map of part of tea growing region, Kericho, showing the location of the experimental sites.

Soil sampling

At each site, disturbed and undisturbed soil samples were taken at 0.10, 0.15, 0.20, 0.30 m and thereafter at 0.3 m intervals to a depth of 3 m (Cooper, 1979; Eeles, 1979) using a Jarret auger and a core sampler with $5.3 \times 10^{-5} \text{ m}^3$ cores. Three samples were taken at each depth. For disturbed samples, the field weight was about 0.1 kg.

The soil profiles at three sites (Timbilil, Kaproret and Changoi) showed no obvious horizons up to 3 m depth. This is similar to observations by Cooper (1979) of soil near the Timbilil. The Kipketer site, however had a murram layer starting at 2.4 m deep, but up to this depth, no horizons could easily be distinguished.

The soils were all of dark red colour (2.5YR 3/6) except for the top 0 to 0.1 m, which were either dusky red, 10R 3/2 (Timbilil and Kipketer) or dark reddish brown, 2.5YR 3/4 (Kaproret and Changoi). All the soils were deep (beyond 2 m), free draining, friable clays, volcanic derived, which are classed as nitisols (FAO/UNESCO classification).

Soil physical analysis

Particle size analysis

Particle size analysis was carried out by the pipette method (Gee and Bauder, 1986) on the disturbed soil samples, taking $63\mu\text{m}$ as the sand/silt boundary. To increase replication, each sample was divided into two sub-samples, giving six samples per depth. Table 2.3 gives a summary of the soil physical analysis.

Moisture retention analysis

The undisturbed core samples were weighed fresh, saturated in a water tray with constant depth of 10 mm for 12 hours after which saturation mass was determined (Klute, 1986). They were then transferred to a moisture extractor (Soilmoisture Equipment Corp., USA) for moisture retention determination at -5, -10, -20, -40, -100, -200, -400, -1000 and -1500 kPa (Klute, 1986). The range for soil water potentials were chosen so as to be comparable to work done elsewhere and to be able to determine available water contents, easily available water, field capacity and permanent wilting point.

Volumetric water contents at soil water potential of -10 kPa ranged from 58% to 60% for top soil and for sub-soils, with saturated moisture contents ranging from 65 to 70%.

Fig. 2.3 shows the water retention curve for the four soils (mean 0 - 0.3 m depth).

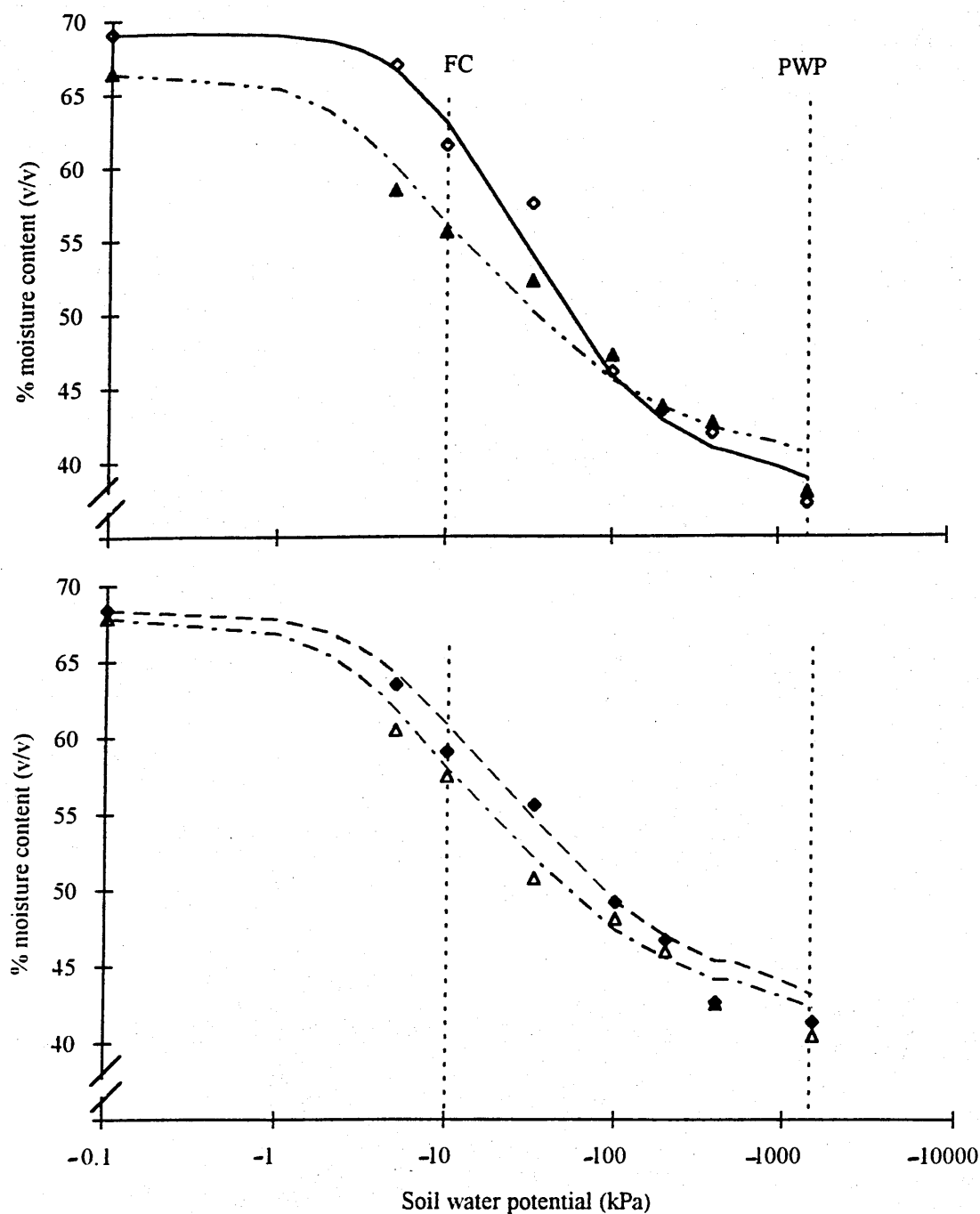


Fig. 2.3. Mean soil water retention as a function of log soil water potential at Timbilil ($\diamond$), Kipketer ($\blacktriangle$), Kaproret ($\triangle$) and Changoi ($\blacklozenge$) in the top 0 to 0.3 m soil. The curves are fitted values using the method described by Van Genuchten (1980).

TABLE 2.3 *Summary of soil physical analysis*

Depth (m)	%Sand	%Silt	%Clay	Texture	Bulk density (g cm ⁻³)	Mean available water mm m ⁻¹ (10 to 1500 kPa)
Timbilil						
0 - 0.3	26	20	64	Clay	0.8	200
0.6 - 1.8	10	17	73	Clay	1.0	180
2.1 - 3.0	8	9	83	Clay	1.0	160
Kipketer						
0 - 0.3	6	20	74	Clay	1.0	180
0.6 - 1.8	12	15	73	Clay	1.0	170
2.1 - 3.0	33	11	56	Clay	1.3	160
Kaproret						
0 - 0.3	26	15	59	Clay	1.2	170
0.6 - 1.8	13	5	82	Clay	1.4	150
2.1 - 3.0	15	3	82	Clay	1.3	150
Changoi						
0 - 0.3	30	11	59	Clay	1.0	180
0.6 - 1.8	18	8	74	Clay	1.1	160
2.1 - 3.0	15	5	80	Clay	1.2	160

Soil chemical analysis

A sub-sample from disturbed soil samples (thoroughly mixed after grinding to pass 2 mm round holed sieve) was taken for each depth and analysed for major nutrients (K, P, Ca, Mg, Mn, Na) by standard methods (Owuor *et al.*, 1990a; Wanyoko *et al.*, 1990) and soil pH in distilled water.

Soil nutrient analysis showed variations between sites. Kaproret had high base contents, hence the high pH (Table 2.4). Kipketer had low magnesium levels, which

were corrected by addition of MgSO_4 at the rate of 250 kg ha^{-1} (Wild, 1988; Wanyoko, personal communication) in the form of granules.

Table 2.4. *Summary of some soil chemical characteristics.*

Site & Depth (m)	Element or parameter (mg kg^{-1})						
	pH	P	K	Ca	Mg	Mn	Na
Timbilil							
0-0.3	5.1	19	521	1162	241	217	25
0.6-1.8	4.2	36	232	88	40	57	24
2.1-3.0	4.5	45	200	49	34	34	27
Kipketer							
0-0.3	3.8	11	111	282	25	65	18
0.6-1.8	4.9	22	106	29	10	53	22
2.1-3.0	5.1	32	93	21	8	29	22
Kaporet							
0-0.3	5.6	27	331	1220	257	67	31
0.6-1.8	5.5	47	276	45	36	34	32
2.1-3.0	5.7	55	206	66	27	18	33
Changoi							
0-0.3	5.0	31	342	1208	220	81	30
0.6-1.8	5.3	49	80	111	86	42	31
2.1-3.0	5.4	52	74	51	54	31	35

Access tube installation

To be able to quantify the water use at the four sites, neutron probe access tubes were installed. Three aluminum access tubes were installed mid-way between two rows during May and June 1992 at each site, diagonally across the experimental plots, using a hand auger.

During July and August 1993, the access tubes were moved to one plot (of clone 6/8) at each site midway between the plants within rows of tea. This was to enable uniform comparisons of water use between the sites

METEOROLOGICAL OBSERVATIONS

To describe the weather and climate at the sites, measurement of meteorological parameters were carried out at these sites. At Timbilil, Kipketer and Kaproret, daily recordings were made at the standard times for synoptic observations (09.00 and 15.00 h local time). At Changoi an automatic weather station was used to take hourly measurements. The methodology and results of these observations are covered in detail in Chapter 3.

CLONAL DESCRIPTION

Tea is heterogeneous, with many overlapping morphological, biochemical and physiological attributes. Two main categories can be distinguished, called China and Assam types, depending on their origin and growth habits. Despite their heterogeneity, leaf pose angles and leaf macro-physiological features, including leaf colour are used in identifying varieties (sub) and/or hybrids. Leaf and floral morphology and growth habits can be used to distinguish between types.

i) China (*Camellia sinensis* var. *sinensis*).

This is typically a slow growing, dwarf plant, with shrub like appearances. It has small, erect and narrow, serrate, dark green leaves. It is thought to have originated from China.

ii) Assam (*Camellia sinensis* var. *assamica*)

This is a tall, fast growing plant, with the features of a full tree. It has large horizontal and broad, mostly non-serrated, light green leaves. It originated from North-East India. (Banerjee, 1992)

The tea genotypes planted in most parts of the world today are hybrids between these two main varieties.

Four clones were chosen for this study with characteristics which fall in-between 'China' and 'Assam'. Table 2.5 summarises some of the known attributes of these clones.

TABLE 2.5 *Summary of some known clonal characteristics*

	S15/10	BB35	6/8	TN14/3
Origin	Kericho	Kericho	Nandi	Nandi
Maximum yield (kg ha ⁻¹)	11,000 ⁽¹⁾	6,000 ⁽²⁾	6,000 ⁽²⁾	5,000
Quality	Plain ⁽³⁾	Plain/high	High ^(2,3)	Plain
Drought tolerance	Susceptible ⁽²⁾	Mildly susceptible	Susceptible ^(2, 4)	Unknown
Texture of stem	Soft	Soft	Soft	Fibrous
Ease in harvesting	easy	easy	easy	hard
Base temperature for extension	9 ⁽²⁾ 7.6 ⁽⁵⁾	11.4 ⁽²⁾ 14.8 ⁽⁷⁾	10 ^(2,6) 14.9 ⁽⁷⁾	7 ⁽⁸⁾

¹Oyamo, 1992; ²Burgess, 1992; ³Owuor *et al.*, 1990; ⁴Othieno, 1978; ⁵Squire *et al.*, 1993; ⁶Stephens and Carr, 1993; ⁷Smith *et al.*, 1990; ⁸Obaga *et al.*, 1988

Clone S15/10

This is an 'Assam' type clone with broad and hairy, planophile leaves. It is currently the highest yielding clone in Kenya, and possibly the world (Oyamo, 1992). It was selected by African Highlands Produce Co. Ltd, Kenya specially for its pubescent young leaves which were considered desirable for a particular manufacturing process.

Clone BB35

BB35 is also an 'Assam' type clone, its leaves, however, are large, smooth, dark green and shiny. One of the high yielding clones, with a high base temperature (Smith *et al.*, 1990, Burgess, 1992), it was selected by Brooke Bond Kenya Ltd.

Clone 6/8

This clone has been used as a quality standard for a long time in Kenya, where it is an average to high yielding clone, with distinctive yellow coloured young 'flushing' shoots. It has small dark green maintenance leaves, which are semi-erect (suggesting a hybrid). It has been found to be susceptible to drought stress (Othieno, 1978; Burgess, 1992). It originated from Nandi tea growing area in Kenya.

Clone TN14/3

TN14/3 has small to medium, light green, semi-erect leaves, with characteristics between 'Assam' and 'China'. It has been used for planting in areas or plots with high pH (Wanyoko, 1987). It originated in the Nandi tea growing area where there are often widespread 'pockets' of high pH within tea plantations. It is an average to high yielding clone, but it is unpopular with pluckers, since it is difficult to harvest shoots with more than two leaves and bud, as the stems become fibrous and hard. It has a fast growth rate and a low base temperature (Obaga *et al.*, 1988; Squire *et al.*, 1993).

CROP MANAGEMENT

Cuttings of the four clones were grown in the TRFK nursery following standard recommendations (TRFK, 1986). To ensure uniformity in initial growth, similar sized plants were selected for transplanting. Seedlings were transplanted when they were 18 months old from the TRFK nursery to the experimental sites. They were planted at a 1.21 m x 0.76 m rectangular spacing giving a population of 10766 ha⁻¹. A row of plants around each plot was used as a guard row, giving a net plot size of 33 m², with 36 plants.

Kipketer was planted on 27th June, Timbilil on 29th, Changoi on 1st July and Kaproret on 26th July, 1991.

After planting the plots were kept weed free by manual weeding and on one occasion, selective herbicide was applied at Timbilil, using standard estate practice to ensure there was no harm to the plants.

Fertilizer

Fertilizer application followed TRFK recommendations (TRFK, 1986). Triple superphosphate fertilizer was used during planting at the rate of 15 g per hole. During the first year a total of 100 kg N ha⁻¹ was applied in six evenly spaced intervals (every two months). In the second year, 160 kg N ha⁻¹ was applied in quarterly applications. This was increased to 200 kg N ha⁻¹ in the third year. Fertilizer was applied as NPKS in the ratio 5:1:1:1.

Tipping

The young tea plants were manipulated to form a flat canopy (plucking table) by continuously removing (by cutting or breaking) any shoots which were longer than a set height. This process of removing these shoots until the tea is mature for regular harvesting is known as tipping. The first tipping was done at 0.25 m above the ground, when the seedlings were at least 0.3 m tall. The next tipping heights were 0.3, 0.4 and 0.45 m. Tipping at 0.45 m was done twice before regular plucking was started.

Harvesting

Harvesting was based on the average estate plucking interval at each site due to the almost constant crop throughout the year. Timbilil and Kipketer were on a 13 to 15 day interval, while Kaproret and Changoi were on 11 to 13 day plucking interval. Details on harvesting and yield measurement are covered in Chapter 7.

CHAPTER 3

WEATHER, CLIMATE ANALYSIS AND SOIL WATER DEFICITS

INTRODUCTION

Weather variability and yield

The climate of Kericho is strongly influenced by the lake breezes from Lake Victoria, some 80 km to the west, which tend to give the area rainfall throughout the year. Unlike much of Kenya, Kericho has a unimodal rainfall distribution, with a peak during April to June. Prolonged dry periods with potential soil water deficits exceeding 400 mm are rare and only occur in two years out of ten (Stephens *et al.*, 1992; Cooper, 1979).

Unlike most tea growing areas of the world, hail storms are a common occurrence in the lake basin region where the largest tea growing zone in Kenya is. The highest incidences occur between May and August (Mwakha, 1983; Stephens *et al.*, 1992), during the rainy season when they can cause heavy yield losses and damage to plants. Earlier work done by Tea Research Institute of East Africa, TRIEA (the predecessor to the Tea Research Foundation of Kenya, TRFK) on hail suppression was inconclusive.

Stephens *et al.* (1992) have described the climate and weather of the Tea Research Foundation of Kenya, but there are few meteorological data available for sites elsewhere in Kericho. The yield of tea is influenced by air and soil temperatures, air saturation deficits, soil water deficits, rainfall and evaporation (e.g. Carr, 1972; Squire and Callander, 1981; Stephens and Carr, 1991; Stephens *et al.*, 1992). In order to explain the variations in the growth and yield of tea at the four experimental sites in this study, it was therefore necessary to monitor these weather variables.

In addition to directly measured variables, responses to environmental stress can also be evaluated using derived variables such as soil water deficit stress time (SWD-time) and saturation deficit stress time (SD-time). SWD-time is defined as the daily integral of soil water deficit above a critical deficit for shoot extension (Stephens and Carr, 1989). SD-time is defined as the daily integral of SD above a critical value of 2.3 kPa (Stephens *et al.*, 1992).

This chapter describes the weather during the experimental period at the four sites described in Chapter 2. The results from this chapter will be used to determine the

effects of environmental variables on genotypic variability within the environments studied.

METHODOLOGY

Meteorological measurements

Installation of Agro-met stations.

Meteorological stations were installed after the start of the experiment; in June 1992 at Changoi, August 1992 at Kaproret and March 1993 at Kipketer. The station at Timbilil has been operational since the inception of TRIEA in the 1950s.

At Kipketer, the station was next to the experimental site, but elsewhere this was not possible for security reasons and they were 0.8, 1 and 1.5 km away from the sites at Timbilil, Changoi and Kaproret respectively.

Though some differences might exist between the measurement site (especially in highly variable parameters such as rainfall) and even within experimental plots, these were beyond the scope of the study.

Meteorological observations

The methods of measurements were similar for Timbilil, Kipketer and Kaproret where daily recording at 09.00 h and 15.00 h local time was done.

At Timbilil, maximum, minimum, wet and dry bulb temperatures, grass minimum, soil temperatures at 0.3 m were recorded daily at 09.00 h using mercury in glass or alcohol in glass thermometers as appropriate (Casella (London) Ltd., UK). Solar radiation was measured with a Gunn-Bellani radiometer (Cassella (London) Ltd., UK) and hours of sunshine using a Campbell Stokes sunshine recorder (Cassella (London) Ltd., UK). Wind speed was recorded on a cup counter anemometer Casella MkII (Cassella (London) Ltd., UK). Wet and dry bulb temperatures and wind speed were also recorded at 15.00 h.

At Kipketer and Kaproret, maximum and minimum temperatures, dry and wet bulb temperatures and daily total rainfall from a standard rain-gauge were observed at 09.00 h. Wet and dry bulb temperatures were also measured at 15.00 h local time. In addition, continuous measurements of air temperature and RH% (relative humidity) at

these two sites were recorded with sensors connected to data loggers. Soil temperature was also monitored at Kipketer using thermistor buried 0.3 m deep under short grass from August 1993, connected to a Squirrel data logger (Grant Instruments, UK). Between March and July the thermistor was at a depth of 0.1 m on bare soil. The soil temperature at 0.3 m depth for this period were simulated using the damping depth earlier determined for Kericho soils (Stigter *et al.*, 1984). An integrated relative humidity and air temperature sensor and logger (Skye instruments, model SDL 2500, UK) was used at Kaproret.

At the fourth site, Changoi, an automatic weather station was set up and used to collect weather data. Two anemometers and a wind vane (Vector Instruments, UK), a pyranometer (LiCor, USA), a tipping bucket raingauge (Campbell Scientific, UK) and three copper-constantan thermocouples were connected to 21X micro-logger (Campbell Scientific, UK). The three thermocouples were used for measurements of wet and dry bulb, and soil temperatures. The wet thermocouple was un-aspirated and was kept wet with a standard wick. The soil temperature was recorded at 0.3 m beneath the grass. The logger was programmed to sample data every minute and store hourly averages. Data was off-loaded using PC208 software (Campbell Scientific, UK) on to a portable computer and stored for later analysis. In addition to the automatic weather station, a Campbell Stokes sunshine recorder was installed in August 1993, to record sunshine hours.

Calibration of instruments

Relative humidity

The RH% sensors used at Kipketer and Kaproret sites, were calibrated in December 1993 at 0% RH using molecular sieve and 75% RH using saturated salt (analar grade) solution at 20°C (Skye Instruments, 1992). Both calibration processes were carried out in a growth cabinet where temperature was maintained at 20°C.

Wind speed

A comparison of wind speed data between Changoi and Timbilil sites showed consistently lower values for the former site. Investigation revealed that the anemometer

at Changoi was lower than 2 m above the soil surface. One anemometer was therefore put at 2 m height above the highest grass surface and compared to an existing one. Comparisons were run for one month (mid-December 1993 to mid-January 1994). The wind speed data for Changoi were adjusted with the calibration factor determined from the comparisons described.

Solar radiation

Due to consistent differences in the recorded incident solar radiation at Timbilil and Changoi sites, comparisons were made at Changoi between the LiCor pyranometer and a Kipp solarimeter for three weeks in August 1993, one week in December 1993 and two weeks in January 1994. The Kipp solarimeter was later re-calibrated at Silsoe Research Institute, UK. The calibration equation derived was used to correct values from the LiCor pyranometer.

Neutron probe

A Wallingford probe (Didcot Instruments, UK) was used for repeated non-destructive soil water content measurements. Water standard counts were taken in an aluminium access tube installed down the centre of a 200 l drum filled with water. Ten readings (16 s) at the centre of the drum were taken, the mean of these readings being taken as the water constant, R_w .

Field calibration during undisturbed core sampling was done at depths of 0.1, 0.15, 0.2, 0.3, and thereafter at 0.3 m intervals to 3 m, one 64 s reading being taken at each depth in the three access tubes. The undisturbed soil samples (three samples at each depth) core volume $5.3 \times 10^{-5} \text{ m}^3$, were weighed when fresh and oven dried at 100-110°C for 48 hours to determine their water contents. These volumetric water contents were used to calibrate the neutron probe. This calibration process was done twice: during a wet season (August 1992) and a dry season (January 1994). The depths were chosen to correspond to those made by Cooper (1979) given that no obvious horizons were found in these soils.

The volumetric water contents determined from core sampling were regressed against the R/R_w data taken during the undisturbed soil sampling.

Calibration equations for each site were:

$$\theta_{\text{Timbilit}} = R/R_w \times 1.013 (\pm 0.034) - 0.02 (\pm 0.006) \quad r^2 = 85\%, n=51 \quad 3.1$$

$$\theta_{\text{Kipketer}} = R/R_w \times 1.011 (\pm 0.083) - 0.003 (\pm 0.0024) \quad r^2 = 76\%, n=51 \quad 3.2$$

$$\theta_{\text{Kaporet}} = R/R_w \times 0.9 (\pm 0.0406) + 0.01 (\pm 0.0009) \quad r^2 = 81\%, n=48 \quad 3.3$$

$$\theta_{\text{Changoi}} = R/R_w \times 0.97 (\pm 0.051) - 0.02 (\pm 0.00187) \quad r^2 = 78\%, n=42 \quad 3.4$$

$$\theta_{\text{Cooper(1979)}} = R/R_w \times 1 - 0.03 \quad 3.5$$

There were minor differences between the calibration done during this study and that done earlier (Cooper, 1979), in the same area. The differences between the regression lines determined in this study were however not significant and the data were combined and a single regression equation calculated:

$$\theta_{\text{combined}} = R/R_w \times 0.997 (\pm 0.0241) - 0.02 (\pm 0.0061) \quad r^2 = 96\% \quad 3.6$$

Soil water measurements

The neutron probe was used to determine the soil moisture contents at each site at two weeks intervals. Three 16s readings were taken at depths of 0.2, 0.3, 0.6 and thereafter at 0.3 m interval to a depth of 3 m, in each of the installed access tubes.

Soil water balance

Model description

A soil water balance model, BALANCE (Hess, 1994), was used to model the actual soil water deficits at the four sites. The inputs for the model are rainfall, R , and reference evapotranspiration, ET_o . To run the model, initial crop and soil parameters need to be set. The crop parameters required are the dates of planting, emergence, 20% and maximum ground cover are some of the parameters of crop data. Crop coefficients, K_c and K_y , are also required to relate potential crop transpiration to ET_o .

For soil data, top-soil depth, volumetric water contents at saturation, field capacity and permanent wilting point both in top- and sub-soil and easily available water as a fraction of total available water are some of the initial parameters. Other soil parameters include bare soil evaporation factors for a two stage drying process, and a drainage

factor, which is defined as the amount of water drained in the first day as a fraction of the total water.

The reference evapotranspiration (ET_o) in the model was computed using the Penman-Monteith combination equation as described by Smith (1991).

The model partitions ET_o into bare soil evaporation (E_s) and crop transpiration (ET_c). E_s proceeds at a maximum rate when the soil is wet and declines as a function of the square root of time after the initial drying of the topsoil (Ritchie, 1972). ET_c is also assumed to proceed at potential rate while the root zone soil water deficit is less than the easily available water capacity, after which it reduces linearly to zero when the deficit reaches the total available water capacity (Hess, 1994). The actual evapotranspiration, ET_a, can be represented as:

$$ET_a = ET_c + E_s \quad 3.7$$

The model then computes the water content, θ , and drainage, D, in the root zone. The soil water deficit on each day is then:

$$SWD_i = SWD_{i-1} + (\theta_{fc} - \theta_{rz_i}) * d_i \quad 3.8$$

where SWD_{i-1} is the SWD on day i-1, θ_{fc} is the field capacity (taken as the water content at -10 kPa), θ_{rz_i} is the root zone water content, R_i is the rainfall, d_i is the root depth, and D_i is the drainage of soil water below the root zone, all on day i. The water content θ is calculated as a sum of the volume water fractions of two layers:

$$\theta_i = \theta_{i-1} + R_i + (d_i - d_{i-1}) * VF_{i-1} * 1000 - ET_{a_i} - D_i \quad 3.9$$

where VF is water volume fraction.

Actual soil water deficits are strongly dependent on soil type and depth so the potential soil water deficits, or evapotranspiration deficit was also calculated for comparison with other tea growing areas.

$$SWD_{pot_i} = SWD_{pot_{i-1}} + ET_{o_i} - R_i + D_{pot_i} \quad 3.10$$

where SWD_{pot} is the potential soil water deficit, ET_o is the potential transpiration and D_{pot} is the potential drainage which was assumed to occur at maximum rate once the soil was at saturation and stop at field capacity.

RESULTS

Table 3.1. *Summary of some measured weather data from the experimental sites. The standard deviations over the different periods of measurements are given in brackets.*

Period	Timbilil (Jun91-Jun94)	Kipketer (Mar93-Jun94)	Kaproret (Aug92-Jun94)	Changoi (Jun92-Jun94)
Temperature (°C)				
Mean daily max.	23.3 (1.49)	23.6 (2.15)	24.8 (2.10)	26.6 (1.67)
Mean daily min.	8.8 (0.98)	9.1 (1.97)	10.6 (1.57)	11.8 (1.16)
Mean 15.00 h				
SD (kPa)	1.0 (0.51)	0.9 (0.42)	1.2 (0.59)	1.5 (0.49)
Mean daily soil temperature(°C)	18.1 (0.54)	19.0 (0.71)		21.1 (0.47)
Mean annual rainfall (mm)	2060 (128.9)	1460	1310	1730(487.9)
Mean wind run (km d ⁻¹)	181 (29.1)			189 (21.9)
Mean solar radiation (MJ m ⁻² d ⁻¹)	19.0 (3.49)			21.6 (3.08)
Mean ETo(mm d ⁻¹)	3.8 (1.15)			4.7 (1.01)

Table 3.1 presents the summary of mean meteorological data for the four sites during the period June 1991 to June 1994. The duration of measurements at each site varied with the installation of weather stations. The long-term mean annual (41 years) rainfall for Timbilil is 2150 mm. The mean differences between the sites are summarised below.

The difference between Timbilil and Changoi in maximum and minimum air temperature and soil temperature at 0.3 m was 3°C, while that of the mean afternoon SD was 0.5 kPa. The variations in air and soil temperatures and mean afternoon SD appeared to be linearly related to altitude. However the differences in rainfall of 700 mm

showed no linear relationship with altitude. Differences in wind speeds were small, but mean daily solar radiation differed by $2.4 \text{ MJ m}^{-2} \text{ d}^{-1}$ and the mean daily potential evapotranspiration by 1 mm d^{-1} , between Timbilil and Changoi.

Solar radiation

The pattern of extra-terrestrial radiation is bimodal, with peaks during October and March and troughs during December and July. This pattern of peaks and troughs is a characteristic of the variations in the tropics. The mean weekly solar radiation incident at Timbilil varied from a maximum of $25 \text{ MJ m}^{-2} \text{ d}^{-1}$ during March to a minimum of about $12 \text{ MJ m}^{-2} \text{ d}^{-1}$ in June and July. Despite the observed daily variations the overall pattern was similar to extra-terrestrial radiation, but with a pronounced peak occurring in March, and a lesser one during October.

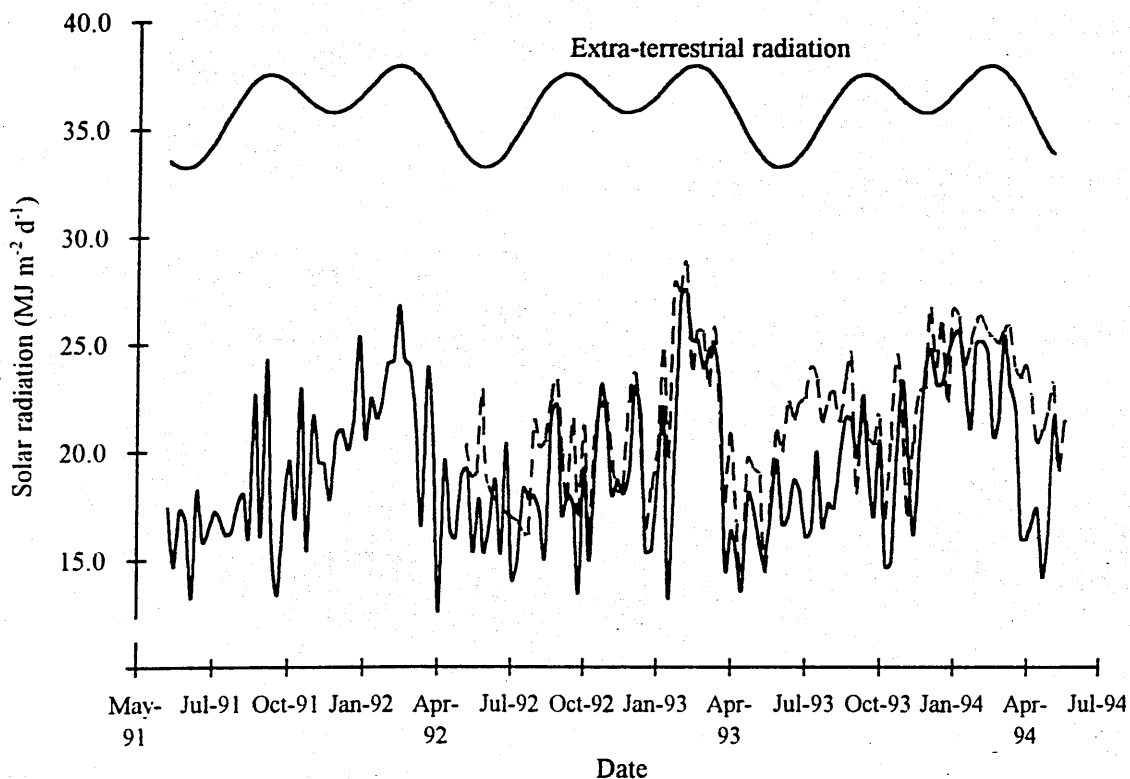


Fig.3.1. Mean weekly values of extra-terrestrial and daily incident solar radiation ($\text{MJ m}^{-2} \text{ d}^{-1}$) at Timbilil (—) and Changoi (---) from June 1991 to June 1994. Measurement at Changoi was started in June 1992.

At Changoi, the maximum incident solar radiation ($28 \text{ MJ m}^{-2} \text{ d}^{-1}$) occurred during March, falling to a minimum of $15 \text{ MJ m}^{-2} \text{ d}^{-1}$ during June and July, a similar pattern to observations at Timbilil (Figure 3.1).

Differences in incident solar radiation between the two extreme sites were noted especially during the wet periods, when more radiation occurred at Changoi than at Timbilil. The annual difference between the two sites was 820 MJ m^{-2} during 1993. Changoi therefore received 12.4% more solar radiation than Timbilil.

Air and soil temperature

The mean air temperature at Timbilil followed the same seasonal pattern described by Stephens *et al.* (1992), with a peak of 17°C occurring in February 1992, though this was not evident in 1993 due to the rains in January, hence the maximum temp was about 16.5°C . The lowest mean air temperature (ca. 15°C) occurred during July in 1991 to 1993. At Timbilil, the mean weekly maximum temperature varied from a peak of 25°C (February 1992 and March 1993) and February 1994 (26°C) to 20°C (June and July in 1991 to 1993 and June 1994). Minimum temperature variations were small in comparison to maximum temperatures, staying mostly between 8 and 10°C (Figure 3.2).

At Kipketer, variations in maximum air temperatures were as observed at Timbilil, from a maximum value of 26°C in March falling to 21°C in June and July rising again towards the end of August and stabilising at 23°C during the short warm wet season (September to early November). Again as with Timbilil, variations in minimum temperatures were between 8 and 10°C during the year. Mean air temperature variations showed the same seasonal pattern as Timbilil with a maximum of 17.5°C in March falling to 15.5°C in June and July rising again by end of August.

At Kaproret, maximum temperatures ranged from 27°C in March, falling to 23°C during June and July, rising again at the end of August at the start of the short warm wet season. Maximum temperatures reached 30°C during January and February 1994. Minimum temperatures ranged from 9°C , to 12°C , however for most part of the year, a mean of 10°C was maintained. The seasonal changes in temperature were as in the other two sites. The mean air temperatures ranged from a maximum of 19°C during the

months of January and February to a minimum of 16°C in the cool months of June and July.

At Changoi, variations in maximum temperatures were similar to those at Kaproret, with peaks during the period February and March 1993 and 1994, falling to a low maximum value of 23°C during June to August 1993. Minimum temperatures ranged from 9°C in March to 13°C in May 1993. Mean air temperatures varied from a maximum in February and March periods with values reaching 20°C falling to a minimum in August. Temperatures rose again in September.

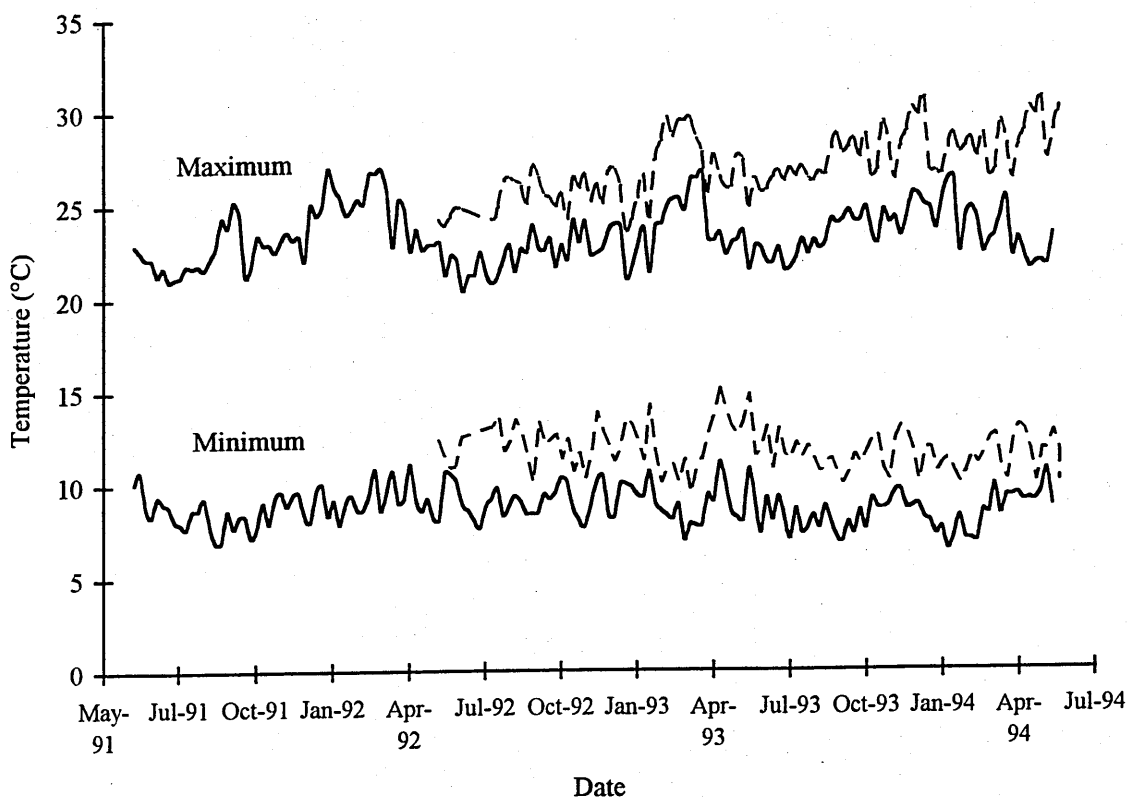


Fig. 3.2 Weekly mean maximum and minimum air temperatures ($^{\circ}\text{C}$) at Timbilil (—) and Changoi (---) during the period June 1991 to June 1994.

Variations in soil temperature were minimal when compared to those of the air, ranging between weekly means of 18 and 19°C throughout the year. There were two peaks in a year, one occurring during March and the other in October, in a similar pattern to both air temperature and incident solar radiation.

The mean-soil temperature at Changoi (0.3 m depth) 21 °C varied in the same way as air temperatures and ranged from between 20 to 22 °C (Fig. 3.3).

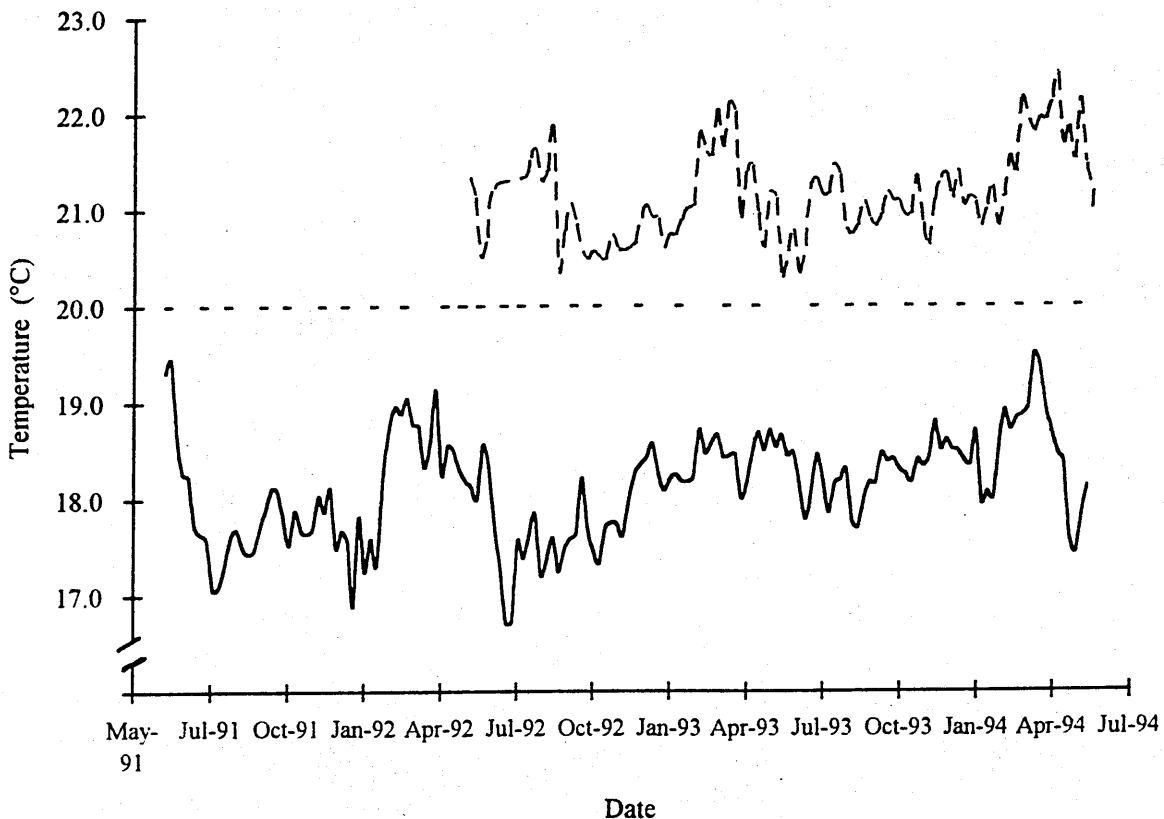


Fig 3.3 Weekly mean soil temperature at 0.3 m depth at Timbilil (—) and Changoi (---). The dotted line at 20°C represent an assumed critical value in tea (Othieno, 1982; Carr and Stephens, 1992).

Thermal time

A base temperature of 10°C was chosen for thermal time calculations as being close to base temperatures for some of the clones used in this study (Burgess, 1992; Stephens and Carr, 1993; Squire *et al.*, 1993). The daily thermal time at Timbilil followed a seasonal pattern, with a peak of 6.7 °C d in 1992 and 6.4 °C d in 1993, falling to a minimum of 3.9 °C d during 1991 to 1994. At Kipketer, the thermal time variations ranged from a maximum in March and October of 6.4°C d to values as low as 2.3°C d in March to August. At Kaproret maximum thermal time occurred in March and December 1993 (7.7°C d) falling to 3.7°C d during the cold period of June and July 1993. The pattern was similar to the other sites.

At Changoi the thermal times were larger than at the other sites due to its higher air temperature, ranging from daily values of 4.6°C d to 9.7°C d (Fig. 3.4).

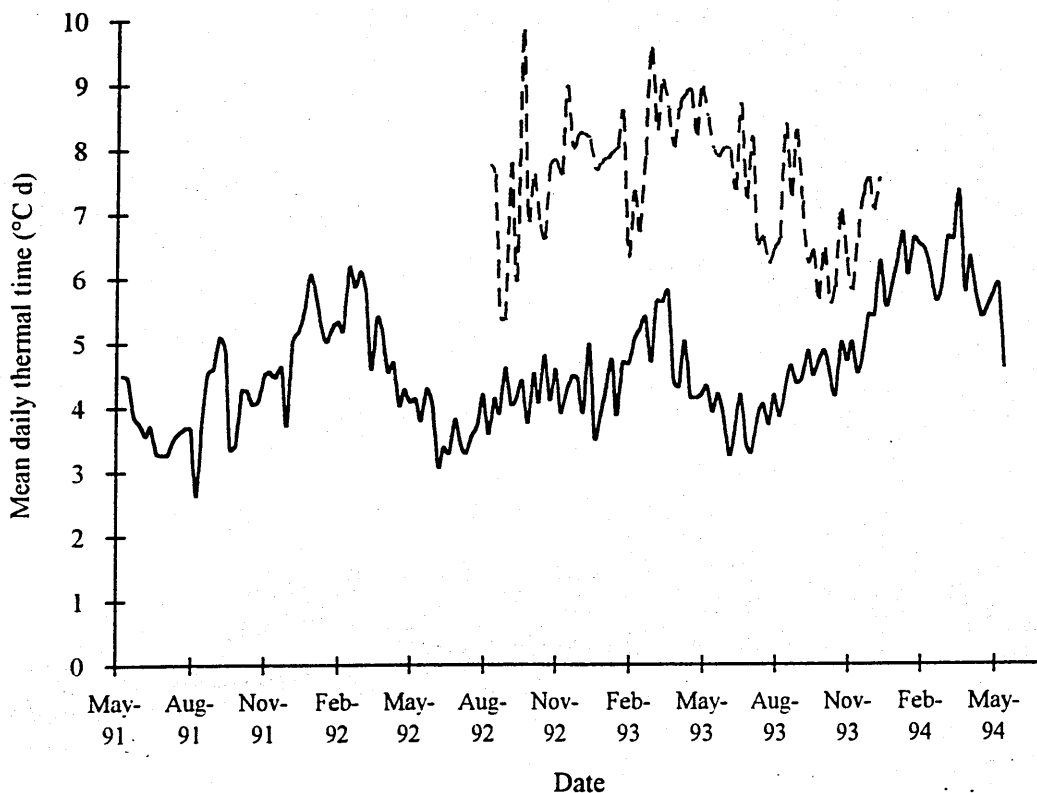


Fig. 3.4. Weekly means of daily thermal time above a base temperature of 10 °C at Timbilil (—) and Changoi (---) during the period June 1991 to June 1994.

Saturation deficits (SD)

At Timbilil, maximum afternoon air saturation deficits (at 15.00 h) occurred during the dry periods in January and February 1992, March 1993 and February 1994. The SD rarely exceeded the critical value of 2.3 kPa. Weekly mean SD's were even lower than daily values (Fig. 3.5).

The annual saturation deficit time, SD-time (the daily integral of SD above 2.3 kPa), for Timbilil was 0.5 kPa d for 1991 (June to December), 3.6 kPa d 1992 and 3.2 kPa d in 1993. At Kipketer, maximum afternoon SDs occurred in March 1993 and February 1994, and minimum during June and July. As at Timbilil, values rarely exceed 2.3 kPa even during the dry periods. At Kaproret as in the other two sites, the maximum SD occurred in March 1993 and February 1994. Maximum values at this site exceeded the critical value of 2.3 kPa during dry periods, with minimum occurring during May and June (0.5 kPa). The annual SD-time in 1993 was 20 kPa d.

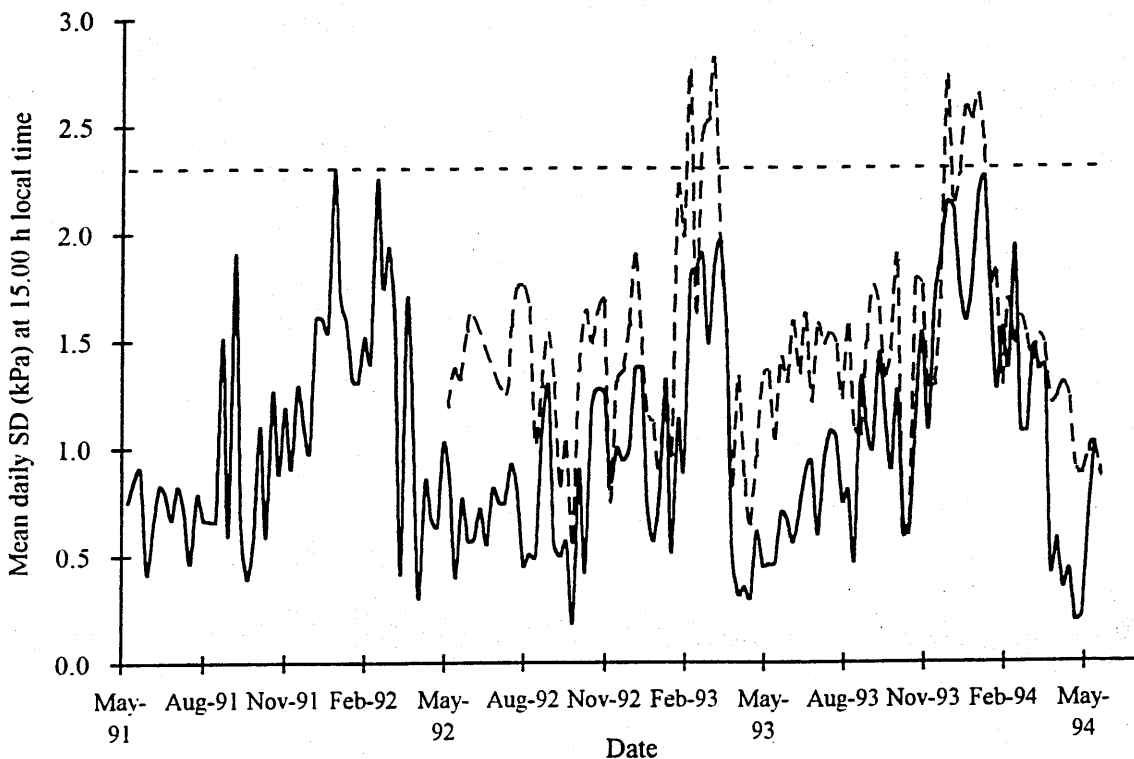


Fig. 3.5. Weekly mean afternoon saturation deficits at Timbilil (—) and Changoi (---) during June 1991 to June 1994. The dotted line represents an assumed critical saturation deficit (Tanton, 1982).

At Changoi, the afternoon SDs were higher than Timbilil and Kipketer but closer to those of Kaproret. Peak daily values of 4 kPa were measured during February, March and December, 1993 falling to a minimum of 0.5 kPa during October and May 1992, and November 1993. The annual SD-time was higher than in the other sites reaching 25 kPa d in 1993.

Wind

At Timbilil, the maximum wind run occurred during February and March, reaching 240 km d^{-1} . Peak hourly wind speeds during these periods reach maxima of 3.6 m s^{-1} . Minimum wind speeds occurred mainly during the cool rainy season (June to August) with mean values of 130 km d^{-1} .

At Changoi, maximum wind run occurred during the dry periods of February and March 1993 and low values occurring during rain periods. There were however periods during rainy season when peak hourly wind speeds could reach 3.4 m s^{-1} (Figure 3.6).

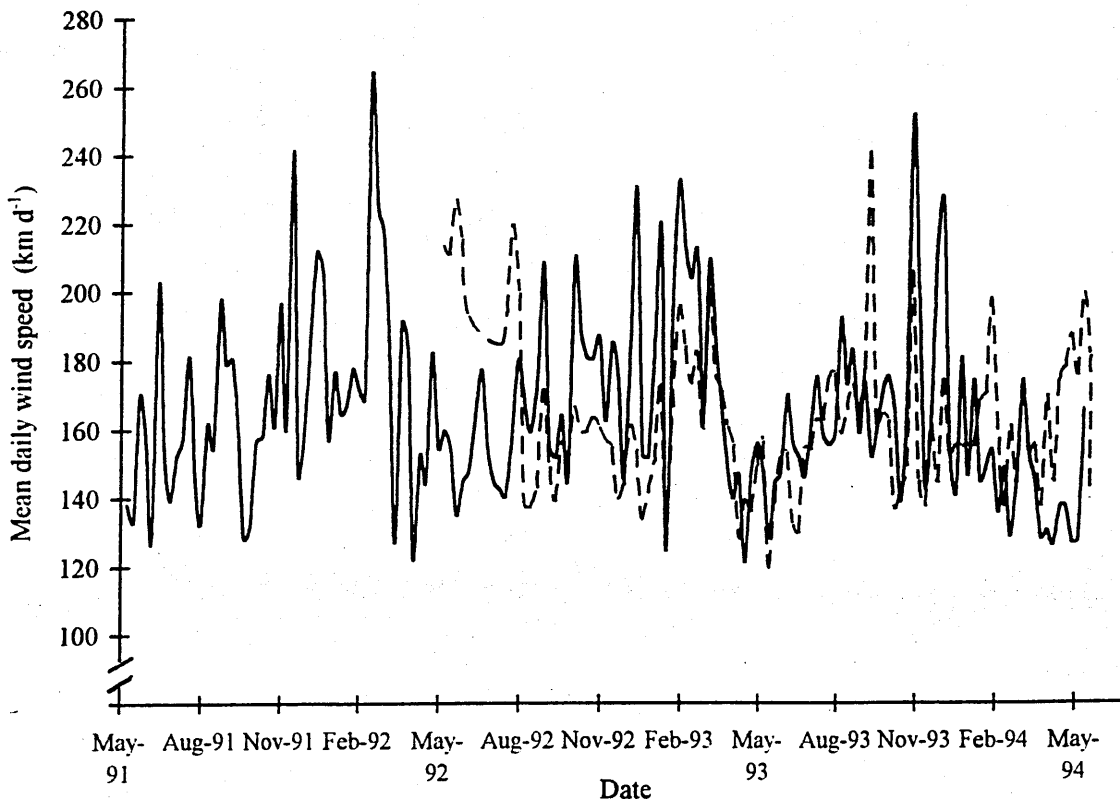


Fig. 3.6. Weekly mean daily wind speeds at Timbilil (—) and Changoi (---) during the period June 1991 to June 1994.

Evapotranspiration

At Timbilil, ETo (Penman-Monteith) showed a seasonal variation similar to the air saturation deficits, with low values during the rainy or wet periods (about 2 to 3 mm d⁻¹) rising to 4.5 mm d⁻¹ during the warm dry season. The ETo during the warm dry season reached 6 mm d⁻¹ which occurred during January and February in the three years studied (1992 to 1994).

At Changoi, ETo varied in a similar pattern to that of Timbilil, but with slightly higher values. Maximum values occurred during March 1993 reaching values of 5 mm d⁻¹ dropping to low values during the months of June to August (Fig. 3.7). Peak ETo values reached 8 mm d⁻¹. The comparison for 1991 and early 1992 was not possible since there was no reliable data on solar radiation, wind speed and air saturation deficits, before the installation of the automatic weather station.

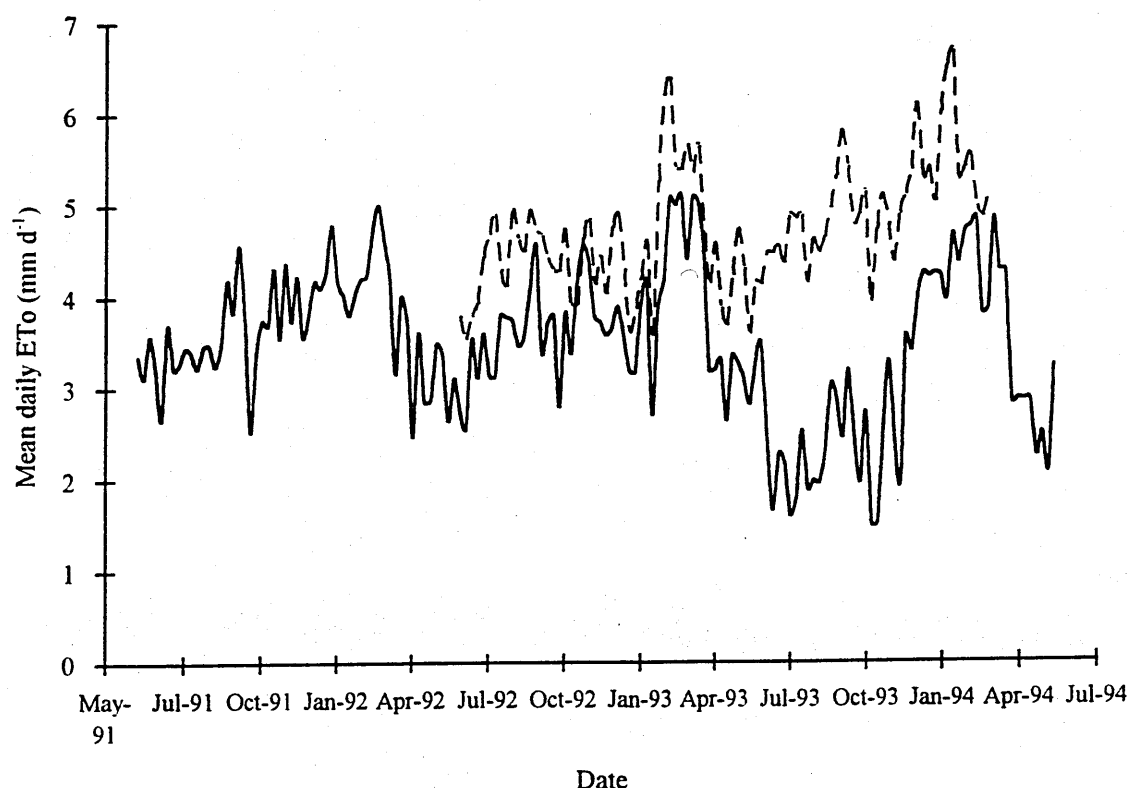


Fig. 3.7. Comparison of weekly means of daily reference crop evapotranspiration, ETo (Penman- Monteith) for Timbilil (—) and Changoi (---) during the period June 1991 to April 1994.

Rainfall

At Timbilil the main rainy season occurs from April to August with a dry season from November to March. The period from September to October is a short warm wet season, which in 1991 and 1992, received mean weekly rainfall between 35 and 40 mm. In 1993, September was drier than the previous two years, though the short warm wet period started towards the end of September. The months of January and February 1993 received rainfall totals of 140 and 169 mm which were higher than the long term mean of 88 and 95 mm respectively (Fig. 3.8a). Mean annual rainfall for three years (1991 to 1993) was 1970 mm, lower than a long term average (41 years) of 2105 mm.

At Kipketer the main wet season in 1993 started in the last week of March and continued until June. The period starting at the end of August to October was warm and wet. Mean annual rainfall was lower than for Timbilil at 1400 mm.

At Kaproret, the main wet season for this site occurred from April to July in 1992. The month of January 1993, as at Timbilil, was wet with a total of 131 mm of rain. In 1992 and 1993 the short warm wet seasons occurred during October and November. The mean annual rainfall for this site was the lowest of the four sites at 1310 mm.

At Changoi, the main wet season lasted from April to end of August, and was followed by a short warm wet season from mid August to October. The dry season started at the end of November and lasted until the beginning of March, though in 1993, January and February was wetter than usual, receiving a total of 172 and 117 mm respectively (Fig. 3.8b).

Soil water deficits

The potential soil water deficit reached maximum of 270 mm and 450 mm at Timbilil and Changoi respectively. Thus the evapotranspirational demand was almost twice as large at Changoi (Fig. 3.7). However actual SWDs were less different because of the restricted root zones of the young tea and therefore the small available water capacity. At Timbilil, actual soil water deficits were estimated using the model BALANCE described in methodology section of this chapter. The model was also used to calculate the actual soil water deficits in 1991 and early 1992 when no neutron probe measurements were available.

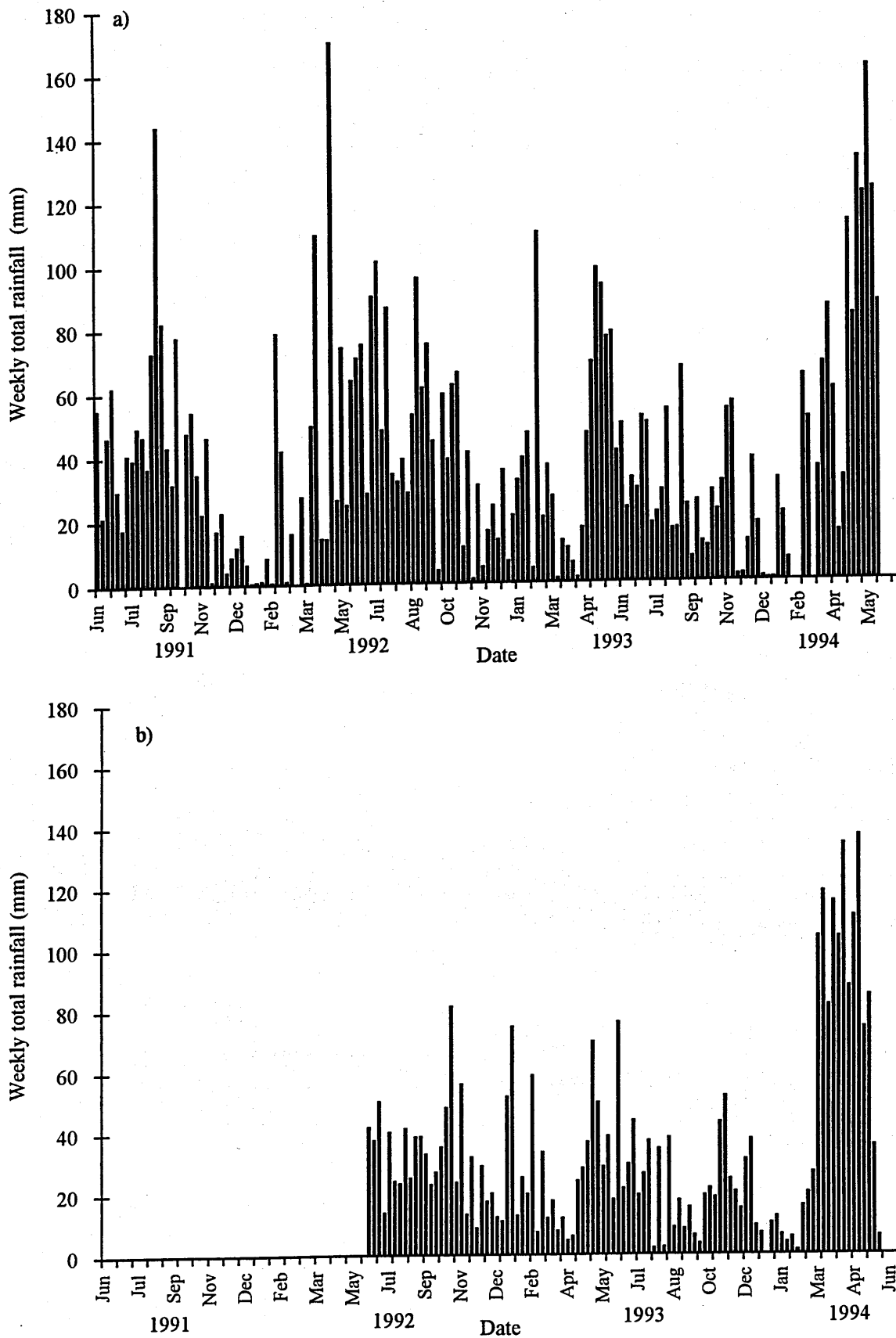


Fig 3.8. Weekly total rainfall at a) Timbilil and b) Changoi during the period June 1991 to June 1994. Measurement at Changoi started in June 1992.

Fig. 3.9 show the simulated deficits at the site from the start of the experiment. In 1993, the maximum soil water deficits occurred in April (62 mm), while the periods January to February and June to September the SWD did not exceed 20 mm. During the period January to March 1994, the soil water deficits reached a maximum of 95 mm in February. However this was reduced to field capacity in April.

At Changoi the variations in simulated soil water deficits were similar to those of Timbilil, but larger deficits during October and November 1993 (55 mm at Changoi compared to 38 mm at Timbilil, Fig. 3.9). In 1994, the maximum soil water deficit was 134 mm in February.

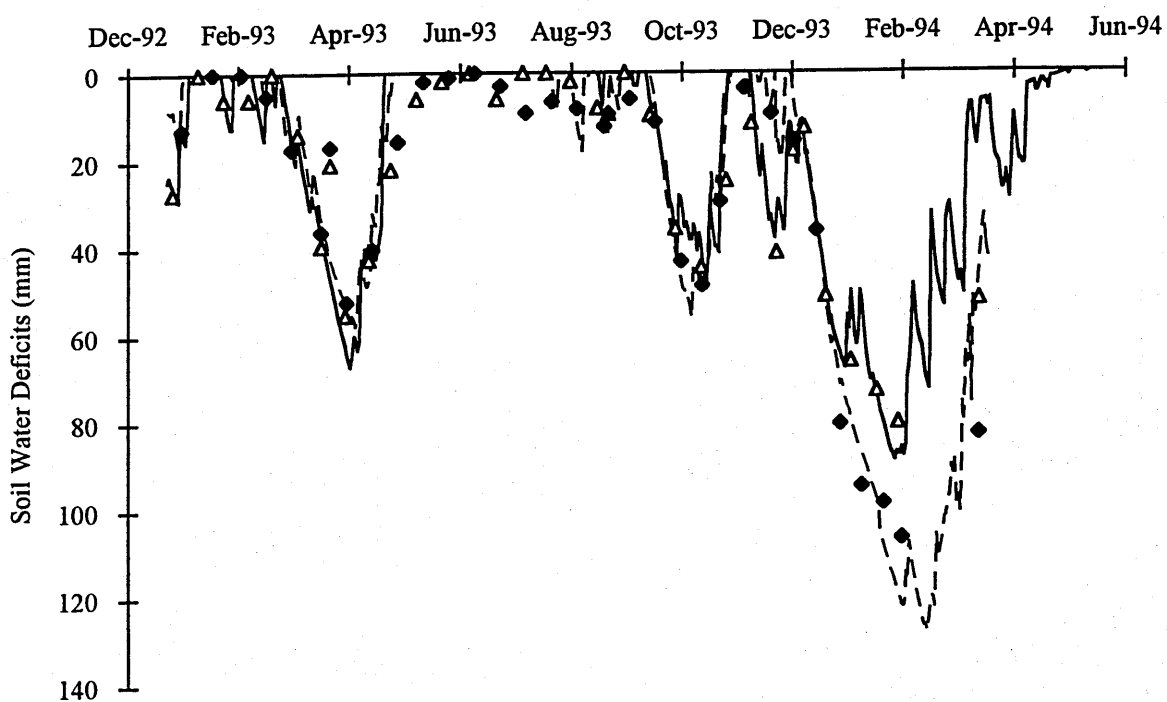


Fig. 3.9. Actual soil water deficits calculated from neutron probe measurements (Δ , $\blacklozenge$) and output of BALANCE model (—, ---) at Timbilil and Changoi respectively from January 1993 to April 1994.

Comparison of model and neutron probe

The model provided a good fit with measured neutron probe data at Tmbilil and Changoi. To test the fit, a regression analysis of model output and SWD as measured by neutron probe was carried out ($r^2=87\%$). Only during periods of recovery from drought did the model underestimate SWD ($r^2 = 56\%$). In most cases, the dates of return to field capacity were different but the start of dry spells were similar. The relationships between the model and neutron probe during dry or wetting of the soil were as follows;

$$\theta_{\text{probe}} = 1.13(\pm 0.074)\theta_{\text{model}} + 0.2 \quad r^2 = 99\% \text{ Drying} \quad 3.11$$

$$\theta_{\text{probe}} = 1.4(\pm 0.162)\theta_{\text{model}} - 5.4 \quad r^2 = 56\% \text{ Wetting} \quad 3.12$$

Hail

The largest number of incidences were recorded at Timbilil site. Of a total of eight storms, five were moderate and three were moderate to severe (with significant yield losses). Six hail storms were recorded at the Kipketer site, one being severe. The Kaproret site had the least occurrences, recording only three on the experimental site, all being moderate. At the Changoi site, a total of seven hail storms were recorded, two being severe, in October 1992 and April 1994.

At Timbilil during the period May 1992 to June 1994, a total of twelve negligible hail incidences occurred. These however tended to be localised and did not affect the whole estate or the experimental plot. The number of such incidences at the other sites is difficult to quantify, but could be in the same proportions to those of Timbilil. Hail storms causing significant yield losses seemed to occur mostly after a drought. At Kipketer and Changoi, the hail storms in early April 1994 was just after the December 1993 to March 1994 drought.

A hail storm was described as moderate if less than two harvests were lost and severe if more than two. A negligible hail storm was described as causing very little or no yield loss (as compared to a mean of the two previous harvests).

DISCUSSION

At Timbilil, the weather during the experimental period was similar to the 20 year mean for the site (Stephens *et al.*, 1992). The mean annual incident solar radiation was 69 TJ ha^{-1} , which is 2 TJ ha^{-1} more than the 20 year mean reported by Stephens *et al.* (1992). The solar radiation during the periods June 1991 to May 1992 and June 1993 to May 1994 was higher than the long term mean for these months, and it exceeded the 80% probability during February and March 1992. Though the period June 1992 to May 1993 was similar to the long term annual mean, it was more than the 80% probability exceedence during February 1993. The differences between the long term mean and the mean during the experimental period could have been due to the solar radiation incident during the months of February and March.

The air temperatures recorded during this study are similar to those reported by Stephens *et al.* (1992) for Timbilil. The mean maximum temperatures were close to the long term annual and monthly mean except for February 1994 when the maximum temperature was, on average, 1°C above the long term mean. On the other hand, minimum temperatures recorded in this study showed little difference from the 20 year mean reported by Stephens *et al.* (1992), implying that minimum temperatures are more conservative than maximum. The variations in mean air temperatures were also similar to those reported by Stephens *et al.* (1992), when minimum and maximum temperatures were used.

Soil temperature variations were similar to those reported by Stephens *et al.* (1992), but are below the critical 20°C level, which is known to restrict shoot extension rates and hence yield (Carr and Stephens, 1992). This has implications on choice of clone for planting at high altitudes if economic yields are to be sustained.

The thermal time values are higher than those reported by Stephens *et al.* (1992), because a different base temperature was used. If the same base temperature of 12.5°C is used, the values for the Timbilil site are similar to those reported by Stephens *et al.* (1992), reflecting the small year to year variations in air temperature at this site.

Rainfall data for the 3 year period June 1991 to May 1994 were close to the long term (41 years) annual mean at TRFK, though there were differences in monthly rainfall

data. This suggests that there are differences in rainfall distribution between years though this was difficult to quantify in this study.

The annual total saturation deficit time found in this study for Timbilil was similar to those reported by Stephens *et al.* (1992) for the moderately dry years (with maximum potential soil water deficits below 280 mm).

The number of hail storms recorded in this study at Timbilil was lower than the 20 year average reported by Stephens *et al.* (1992). There were a total of eight hail storms at Timbilil five of which did not cause any damage, and two were negligible. Only one hail storm was moderate to severe. This contrasts sharply with that Stephens *et al.* who reported between 18 to 30 incidences in 6 out of 10 years. However a number of hail incidences occurred which did not affect the experimental plots.

The experimental period was therefore representative of the mean weather experienced at Timbilil, although the soil water deficits in 1994 were greater than the 80% exceedence limit.

Comparisons between experimental sites

Solar radiation

There were differences in the incident solar radiation at Changoi and Timbilil sites ranging from 0.5 to 1 MJ m⁻² d⁻¹ during the dry season to 3 MJ m⁻² d⁻¹ during the wet season. The higher incident solar radiation recorded at Changoi may be due to the lack of as much cloud cover as Timbilil. These differences raise questions on the direct use of solar radiation data recorded at Timbilil for other sites. However such differences may not be a hindrance when long term data are being considered since annual variations are small (Stephens *et al.*, 1992).

Lapse rate

The lapse rate (the reduction in temperature per unit increase in altitude) was stable at 6°C km⁻¹ for air temperature measured hourly, but increased when maximum and minimum air temperatures were used. The constant lapse rate for air temperature in this study is similar to those reported by Barry and Chorley (1976). This makes it possible to

extrapolate or interpolate air temperature at other altitudes where no measurements are available.

Soil temperature showed a higher lapse rate of $7^{\circ}\text{C km}^{-1}$ than air temperature. Only three sites (Timbilil, Kipketer and Changoi) were used for regression which could have led to errors in the estimation of the lapse rate. The differences in the thickness of the grass layer at the respective weather stations could also be a major factor, since the thicker grass at Timbilil could have resulted in lower temperatures.

Thermal time, air and soil temperature

Variations in thermal time showed similar seasonal trends between the sites, with differences only in the amplitude of the variations. The close similarity in variations at Changoi and Kaproret and at Kipketer and Timbilil could have been due to relative nearness of these pairs of sites as compared to the distance between the extreme sites.

The differences between the mean soil temperature at Timbilil, Kipketer and Changoi were larger than the seasonal variation within each site. These differences in soil temperatures could be a major factor contributing to the differences in yield reported at nearby sites by Carr and Stephens (1992). Othieno and Ahn (1982) also reported that increasing soil temperature by use of mulch in young tea improved growth at Timbilil.

Air saturation deficits

Changoi and Kaproret had larger mean annual SD values than both Kipketer and Timbilil. The fact that air saturation deficits exceeded 2.3 kPa less often at high altitudes (Timbilil and Kipketer) imply that restrictions on growth and yield caused by low humidity are greatest at low altitudes.

Rainfall and SWD

Though there appeared to be an increase in annual rainfall with altitude, this was not linear (Table 3.1). The least rainfall fell at Kaproret, in the same area which has reported probably the largest yield in the world (Oyamo, 1992). While it is not clear that the rainfall data were similar to previous years, localised variations in rainfall within an estate are not uncommon, implying uneven yield potential in one estate. The largest

amount of rainfall fell at Timbilil. Low yields have also been recorded from this site as compared to other sites (Othieno *et al.*, 1992).

The differences in actual root zone SWD between Timbilil and Changoi was due to the differences in root depths. The root depths at Changoi were 45% deeper than those at Timbilil (Chapter 6), though the maximum available water depletion differed by only 8% (45% at Timbilil and 53% at Changoi). The higher evapotranspirational demand at Changoi may be a limitation to the realisation of yield potentials.

Hail storms

Hail occurred most frequently at the higher altitude sites of Timbilil and Kipketer. The least affected was the Kaproret experimental site, though there were more hail storms recorded at other parts of the estate. A severe hail storm occurred at Changoi during the early stages of the tea growth. A single incident of severe hail damage was recorded at Kipketer and Changoi in April 1994. There does not seem to be a clear reason as to the prevalence of hail incidences at both Timbilil and Kipketer, though the amount rainfall and number of rain days could be a factor. The tendency of severe hail storms to occur after drought seem to support the view that the formation of hail is enhanced by litter, or dust particles in the atmosphere (Schnell and Tan-Schnell, 1978) since these tend to increase during dry weather conditions.

The unpredictability of hail incidence and damage in Kericho means that any experimental results should be treated cautiously if estimate of yield losses due to hail are not made.

Comparisons with other areas of east Africa.

Solar radiation

The annual incident solar radiation at Timbilil was 8% less than the mean value for Mulanje, Malawi (74 TJ ha⁻¹; Carr and Stephens, 1992) whereas Changoi received 5% more. Annual solar radiation at Mufindi, however is 6% lower than that of Timbilil. These differences are most probably due to the presence of more cloud cover at Timbilil (and indeed at Kericho as a whole) compared to that of Malawi. Since solar radiation is

the main driving force in dry matter production, the yield potential at Changoi is higher than that recorded elsewhere in eastern Africa.

Air temperature

The seasonal variations in air temperature at Kericho are much less than those for Mufindi (Burgess, 1992; Stephens and Carr, 1991) and Malawi (Carr and Stephens, 1992). The mean air temperatures at Mufindi range from 13 to 18 °C, while those at Mulanje are between 17 and 24 °C (Carr *et al.*, 1987). These amplitudes are larger than those experienced at Kericho (14 to 17 °C at Timbilil and 17 to 20 °C at Changoi). These differences occur because Kericho is closer to the equator than either Mufindi or Malawi. The higher altitude, especially of Timbilil is also a factor since air temperature decrease with a rise in altitude. Mean air temperatures are therefore more stable at Kericho.

Saturation deficits

The SD-time for Changoi, despite being higher than the other sites in this study, was slightly more than half the 40 kPa d reported by Carr *et al.* (1987) for Mulanje (Malawi). Air saturation deficits exceed 2.3 kPa less frequently and hence restrictions on growth and yield imposed by these deficits, are much less than in Malawi. This is similar to Mufindi where air saturation deficits rarely exceed 1.8 kPa (Stephens and Carr, 1991).

Rainfall and soil water deficits

The rainfall recorded in this study was much greater than in tea growing areas in Tanzania (Burgess, 1992, Stephens and Carr, 1991) where it ranges from 980 at Ngwazi in Mufindi to 1520 mm at Mulanje in Malawi (Carr *et al.*, 1987). The main tea growing areas in Mufindi have a rainfall of 1200 to 1600 mm (Stephens, 1992). These are equivalent to 48% and 74% of the annual rainfall at Timbilil, and 57% and 88% of that at Changoi.

The maximum potential soil water deficits which occurred during the 1994 drought were 270 mm at Timbilil and 450 mm at Changoi. These values are lower than those

reported for Ngwazi Mufindi (Stephens and Carr, 1991; Burgess, 1992) where potential deficits (in the absence of irrigation) can reach 700 mm at the end of the six-month dry season. This implies that the potential crop production for Kericho should be higher than at Ngwazi if there are no other limiting factors such as hail, soil and air temperatures.

CONCLUSIONS

The differences in the measured environmental parameters between the sites were relatively small, except for rainfall with a difference of 700 mm between Timbilil and Kaproret. The differences in actual SWDs were small because of the restricted root depth of the young plants. A 3°C difference in both air and soil temperatures between extreme sites was recorded. This difference in temperature is significant in Kericho, since temperatures are low (near base temperatures). The mean daily air temperatures from continuous hourly records of air temperature indicated a lapse rate of 6.1°C km⁻¹. The mean difference in the incident solar radiation between Changoi and Timbilil was 2.4 MJ m⁻²d⁻¹. The air saturation deficits were below critical values except for short periods at both Kaproret and Changoi. These differences can be used to explain variations in the measured plant parameters between the sites.

The differences between the experimental sites at Kericho and other eastern Africa tea growing areas were large, especially in potential soil water deficits, which imply higher yield potentials at Kericho. The reasons for lower yields than potential at Kericho will be considered in Chapter 7.

The climate in Kericho is favourable for tea growth and yield except for:

- a) the low temperatures at higher altitudes (above 2000 m),
- b) the irregular and unpredictable hail damage,
- c) the relatively large soil water deficits that occur for 2 to 3 months in areas with less than 1500 mm rainfall (normally lower altitudes),
- d) the occurrence of large afternoon saturation deficits (above 2.3 kPa) during certain seasons at lower altitudes.

CHAPTER 4

GENOTYPE - ENVIRONMENT INTERACTIONS: A SUMMARY OF RESULTS

INTRODUCTION

In Kenya, there are large differences in elevations, climate and soils between and within the two main tea growing regions to the east and west of the Rift Valley. These differences are reflected in the variations in the yield of tea in these regions. And an understanding of the causes of this variation would be useful in determining the potential maximum yields and in selecting suitable clones for particular areas.

The response of a crop to different environments is usually expressed by Genotype x Environment (GxE) interactions. In multilocation trials, GxE interactions have been found to be useful in, a) yield estimation and prediction based on limited experimental data, b) determining yield stability and the pattern of response of genotypes or agronomic treatments across environments and c) in providing reliable guidance for selecting the best genotypes or agronomic treatments for planting in future trials at new sites (Cossa, 1990).

If the GxE interaction is subject to genetic control, then the level of interaction may also be used as a selection criterion (Wickramaratne, 1981). Indeed effective plant improvement depends on an understanding of GxE interactions (Ivory *et al.*, 1991). Genotypic performance across environments (genotypic stability) is expressed in three empirical parameters: a) the mean performance (given by the genotypic mean yield or attribute in all the test environments), b) the slope of regression line of clonal performance against mean performance in each environment (environmental index) and c) the sum of squares from regression (Eberhart and Russell, 1966).

In tea, GxE interactions have been noted in a study of drought resistance (Carr, 1977) and in yield (Wickramaratne, 1981; Rono *et al.*, 1991). Wachira *et al.*, (1990) working with three clones in Kenya showed that there were significant shoot population density and shoot mass by environment interactions. GxE interactions in total dry matter production and partitioning, and the harvest index of tea have not been reported in literature.

In this chapter, the analysis of total plant dry mass and yields are reported and the Clone x Environment interactions discussed. From the analysis of interactions, questions are posed which form the basis for analysis and interpretation of results in the chapters to follow.

METHODOLOGY

The experiment was conducted at four sites ranging from 1800 m to 2200 m a.m.s.l. Full details of the experimental layout, clones, sites and weather are provided in Chapters 2 and 3. The climate of the sites could be categorised into three seasons: a cool and wet season starting in April and ending in August; a warm and wet and sometimes dry season from September to mid November; and a warm and dry season from mid November to March.

The data were subjected to analysis of variance using Genstat (Lawes Agricultural Trust, 1993). Significant interactions were further analysed by joint linear regression using procedure RJOINT in Genstat's Procedure Library (Lane and Ryder, 1994). The response of each clone at the four sites was assessed by computing a linear regression of individual attribute (yield or dry matter) on the mean of all the clones in each environment, which is termed the environmental index (Eberhart and Russell, 1966; Wickramaratne, 1981). This only allows for comparisons of relative responses between the clones tested.

Seasonal variations in clonal response to measured or derived environmental factors are covered in detail in Chapters 5 (dry matter) and 7 (yield).

RESULTS

Dry matter production.

Over the 34 month period of the experiment, clone TN14/3 produced the highest dry matter in all the sites, and clone S15/10 the lowest. There were significant clone x site interactions, which were further analysed using linear regression (Fig. 4.1). The regression coefficients of clones 6/8, BB35 and S15/10 were below unity and the mean total dry matter of BB35 and S15/10 were below the grand mean (Fig. 4.2). These clones can be described as having below average adaptability and take less advantage of

favourable environments for dry matter production than clone TN14/3. This clone had a regression coefficient considerably greater than unity (1.9), and mean total dry matter greater than the grand mean. It therefore has wide adaptation, and a large response to environmental change.

Table 4.1. *Analysis of variance and regression analysis for four clones (genotypes) in four sites (environments) in total dry matter production.*

Source of variation	df	Sum of squares	Mean square	F
Genotypes	3	5706947	1902316	109.46***
Environments	3	2869766	956589	55.04***
Interactions	9	1319744	146638	8.44***
Regressions	3	885583	295195NS	16.99***
Deviations	6	434161	72360	4.16**
Error	48	834207	17379	

*** indicates significance at $P \leq 0.001$

** indicates significance at $P \leq 0.01$

NS indicates differences are not significant [see text for explanation]

The analysis of variance for the regression is given in Table 4.1. Though the regressions were heterogeneous (i.e. each variety had its own characteristic response line to the environment), there were significant deviations from these regressions. When the mean sum of squares of regressions was re-tested against the deviation, it was found to be not significant different ($P \leq 0.05$). This meant that the response lines were no significantly different from each other. Further investigation on clonal differences in slope and intercepts of the regression lines showed that the significant deviations from expected performance was due to clones BB35, 6/8 and S15/10. The slopes and intercepts of these clones were not significantly different. Though the regression line of clone TN14/3 was significant ($r^2 = 88\%$, $P < 0.05$), the intercepts of all the clones were similar ($P < 0.05$).

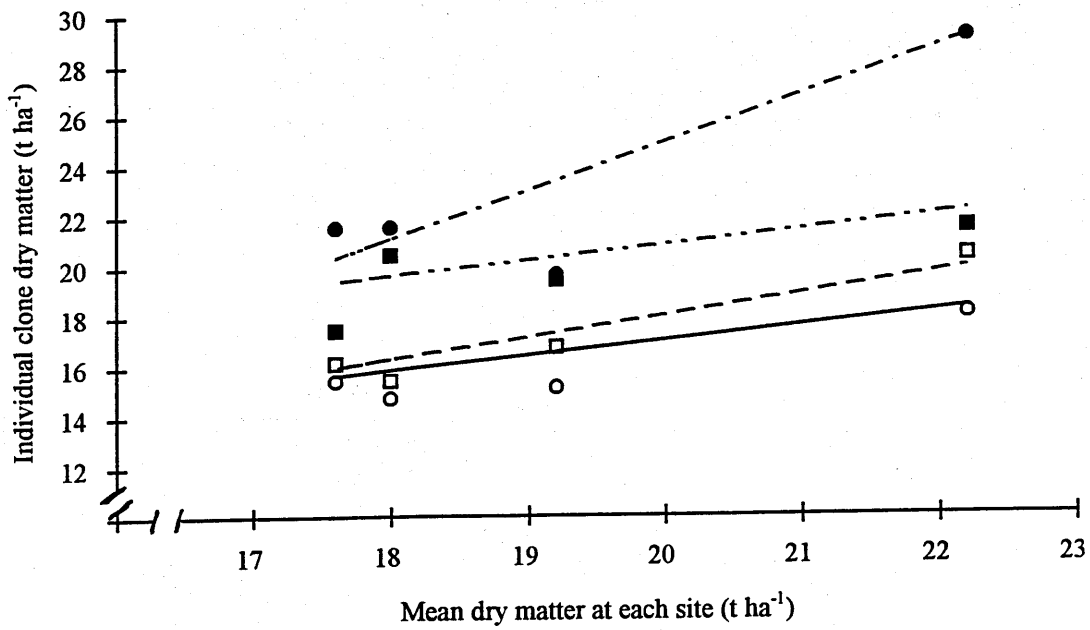


Fig. 4.1. Relationship between total dry matter production (TDM) for clones S15/10 (○), BB35 (□), 6/8 (■) and TN14/3 (●) with TDM at each site over the period June 1991 to April 1994.

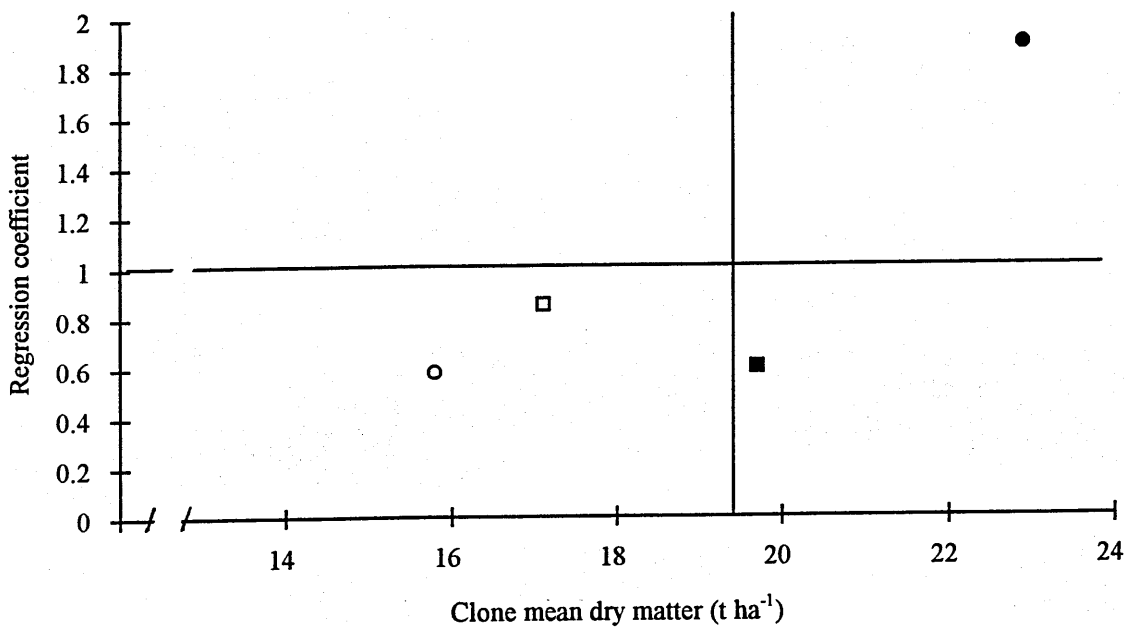


Fig. 4.2 Relationship between response to environmental change (regression coefficients) and clonal mean dry matter production of clones S15/10 (○), BB35 (□), 6/8 (■) and TN14/3 (●).

Total yields

The annual total yields during July 1993 to June 1994 period varied between the sites, the lower altitudes producing larger yields.

GxE interactions were found to be significant and were further analysed by linear regression. Though the heterogeneity of regressions were significant, as in the dry matter analysis, the deviations were also significant. Re-testing of the regression mean sum of squares against the deviations, showed that the regressions did not account for a significant ($P < 0.05$) proportion of the variance (Table 4.2). Further analysis showed that the significant deviations were due to the response of clone 6/8. The slopes of the response were however not significantly different for clones BB35, 6/8 and TN14/3, while there were no significant differences in the intercepts of all the clones.

Table 4.2. *Analysis of variance and regression analysis for four clones (genotypes) in four sites (environments) in yield.*

Source of variation	df	Sum of squares	Mean square	F
Genotypes	3	4287204	1429068	40.19***
Environments	3	11893973	3964657	111.5***
Interactions	9	1332086	148010	4.16***
Regressions	3	761595	253865NS	7.14***
Deviations	6	570491	95082	2.67*
Error	48	1706832	35559	

*** indicates significance at $P \leq 0.001$

* indicates significance at $P \leq 0.05$

NS indicates differences are not significant.

Regression analysis showed clone 6/8 as having a low response to environmental change with a regression coefficient of 0.78 ($r^2=82\%$, $P=0.062$) and hence can be described as stable (Fig. 4.4). The regression coefficient of clone TN14/3 was 0.88 ($r^2=99.6\%$) with a mean yield lower than the overall mean (grand mean).

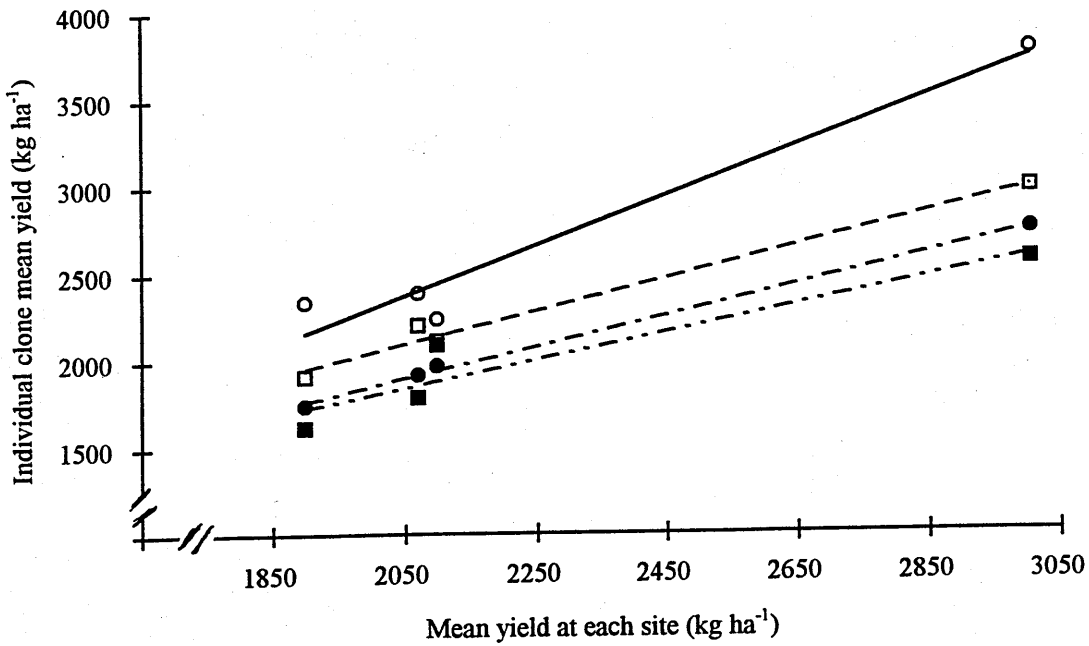


Fig. 4.3. Relationship between yield for clones S15/10 (—○—), BB35 (—□—), 6/8 (—■—) and TN14/3 (—●—) with yield at each site over the period June 1991 to April 1994.

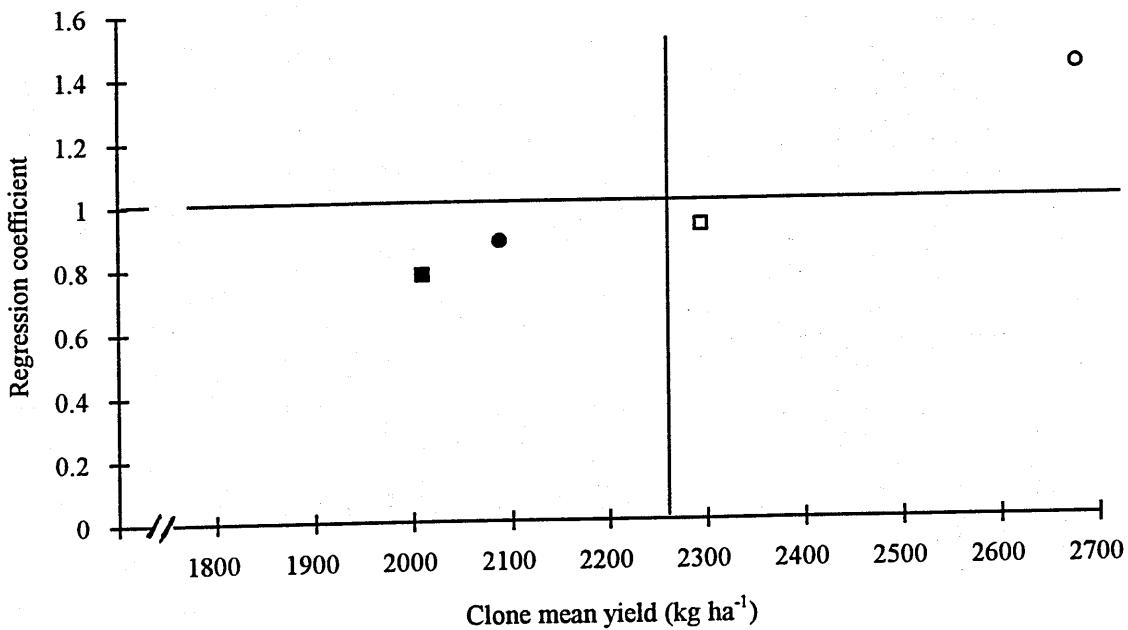


Fig. 4.4 Relationship between response to environmental change (regression coefficients) and clonal mean yield of clones S15/10 (○), BB35 (□), 6/8 (■) and TN14/3 (●).

It therefore has below average performance and like clone 6/8, is stable. On the other hand, clone S15/10 had a regression coefficient greater than unity (1.48) with a mean yield larger than the grand mean. This shows an above average performance, with greater sensitivity to environmental change and therefore a wide adaptation.

Clone BB35 has a regression coefficient close to unity (0.93; $r^2=98\%$), implying an average performance, however its mean yield was larger than the grand mean, showing that the clone has more a general adaptation than clones TN14/3 and 6/8.

DISCUSSION

The changes in clonal responses to environment in dry matter production and yield raise questions as to their genetic control. At Changoi, Clone TN14/3 produced 35% more dry matter than at Timbilil compared with 22 to 32% for the other clones. However, clones 6/8, BB35 and TN14/3 all showed similar (56-58%) differences in yield between extreme sites. By comparison clone S15/10 produced 61% more yield at Changoi than at Timbilil.

There were no significant correlations between regression coefficients and clonal mean dry matter produced, suggesting that this trait could be under different genetic control. However, there were significant correlation between regression coefficients and clonal mean yield ($r = 0.97$). Wickramaratne (1981) using 31 clones also reported significant correlation of regression coefficients with genotype mean yield. Due to the small number of genotypes used, it was not possible to arrive at a conclusion as to genetic control of yield. The significant deviations in the joint linear regressions (Tables 4.1 and 4.2) may also be due to the small number of genotypes as well as the lower than expected values from Kaproret.

Though clone TN14/3 showed a wide adaptation in total dry matter, its suitability to high yielding environments in dry matter (and indeed its interactions with environment) is in contrast to other reports on this clone (Obaga *et al.*, 1988; Wachira *et al.*, 1990; Squire *et al.*, 1993).

Though the analyses of variance showed significant GxE interactions, they only accounted for a small part of the total sum of squares (12.3%, 6.5%) in total dry matter

and yield respectively. That the sum of squares due deviations were significant in both yield and total dry matter could be due to a number of factors least of which is the number of genotypes used.

These contrasting responses raise questions and form the basis of the analysis of following chapters, to determine what causes these variations.

- 1) Why does clone TN14/3 produce more dry matter than the other clones and have a greater response to environment than the other clones?.
- 2) Why does clone S15/10 produce a larger yield than the other clones and respond more favourably to better environments?.
- 3) What features of the environment contribute to the between site differences?.

The differences in dry matter production will be discussed in detail in Chapter 5 on light interception and dry matter production. Chapter 6, on dry matter partitioning, continues to explore possible reasons for differences in dry matter response and also looks at other factors (harvest index) responsible for differences in yield.

The differences in yield will be discussed in detail in Chapter 7 on yield. Chapters 8 and 9 then look at components of yield in order to explain the seasonal variability in yield.

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CHAPTER 5

LIGHT INTERCEPTION AND DRY MATTER PRODUCTION

INTRODUCTION

The rate of dry matter production depends on the incident solar energy, the canopy area available to intercept radiation, the availability of water and nutrients and the conversion efficiency (Squire, 1985). Accumulation of dry matter by shoots depends on the rate of export of photosynthates (or assimilates) from the leaves and imports by the shoots (Manivel and Hussain, 1986). In total, the rates of photosynthesis and translocation account for the productivity (annual and seasonal changes in growth) of the bushes. Although the photosynthetic rate is the main factor determining the rate of dry matter accumulation, other factors such as maintenance respiration, carbon allocation, nutrient uptake and translocation may respond to environmental changes associated with temperature and water stress arising from soil or atmosphere.

Magambo and Cannell (1981) reported that harvested tea bushes of clone 6/8 produced 16.9 t ha^{-1} of dry matter per annum, but 26.3 t ha^{-1} when left to grow freely (un-harvested). This compares with 22 to 23 t ha^{-1} for harvested bushes of the same clone grown under irrigation in southern Tanzania (Burgess, 1994).

The mean daily total solar radiation at Timbilil ($0^{\circ}22'S$ $35^{\circ}21'E$) is about $18.4 \text{ MJ m}^{-2} \text{ d}^{-1}$ (Stephens *et al.*, 1992). Of the total incident radiation about 20% is reflected back by a crop surface (canopy) into the atmosphere and a similar percentage is re-emitted as long wave radiation (Cannell, 1988). While the light saturation point for single leaves is about 300 W m^{-2} , it is about 600 W m^{-2} for whole canopies (Squire, 1977; Sakai, 1975; Callander and Woodhead, 1981). However, solar radiation in the tropics may not be limiting, and therefore other limiting processes to utilisation of incident light energy need to be examined.

The relationship between dry matter and solar radiation can be expressed as:

$$\text{DM} = S_o \cdot f_s \cdot \epsilon_s \quad 5.1$$

where DM is the total dry matter (g m^{-2}), S_o is the incident solar radiation (MJ m^{-2}), f_s is the fractional radiation interception and ϵ_s is the conversion efficiency for solar radiation (g MJ^{-1}), which is also termed Radiation Use Efficiency (RUE).

Most of the incident short-wave radiation on tea bushes with full ground cover is intercepted by leaves in the top 0.3 m of the canopy (Hadfield, 1974), with only 5% reaching the ground. The proportion of radiation intercepted depends on factors such as canopy expansion and canopy architecture (in terms of leaf area and ground cover). The fractional light interception f_s for continuous canopies can be expressed as:

$$f_s = (1 - e^{-kLAI}) \quad 5.3$$

where k is the light extinction coefficient and LAI is the leaf area index (m^2).

However for young tea, equation 5.3 has to be modified to account for the crop cover due to the substantial bare soil between the rows. A number of authors (Jackson and Palmer, 1979; Burgess, 1992) have described f_s using crop ground cover, which can be represented as:

$$f_s = GC.(1 - e^{-kLAI^*}) \quad 5.4$$

Where GC is the crop cover and LAI* is the canopy or green leaf area index.

Little information exists on the determination of k in tea but can be estimated by measuring intercepted radiation or by calculation with a knowledge of canopy structure Campbell (1986).

Estimated values of k for tea have been reported (Corley, 1983; Burgess, 1992) as 0.6. This is a value which is midway between erectophile leafed canopies ($k \approx 0.3$) and planophile ones ($k \approx 0.9$).

The RUE, ϵ_s , is defined as the ratio of dry matter produced per unit intercepted solar radiation.

$$\epsilon_s = DM / S_i \quad 5.2$$

where S_i is the intercepted radiation ($MJ m^{-2}$). The RUE is determined by the relationship between leaf photosynthesis and light intensity. It also depends on the photosynthetic pathways, whether C3 or C4 plant species. Plants with C4 photosynthetic pathways are known to have higher ϵ_s than C3 plant species such as tea. In addition, Cannell *et al.*, (1987) suggested that woody plants may have smaller RUEs than field crops because of the respiration of the woody parts.

Several workers have reported values of ϵ_s for different crops under a variety of environments. Willow, (*Salix* sp.) has ϵ_s values ranging from 0.99 to 1.38 g MJ⁻¹ (Cannell *et al.*, 1987). Tea however has lower RUEs ranging from 0.25 g MJ⁻¹ to 0.55 g MJ⁻¹ (Magambo and Cannell, 1981; Squire, 1985; Carr and Stephens, 1992; Burgess, 1992).

Table 5.1. *Comparison of conversion efficiencies (total solar radiation) of some perennial crops with tea.*

Crop	Location	ϵ_s (g MJ ⁻¹)	Source
Tea plucked	Kenya	0.25	Magambo and Cannell (1981).
unplucked	„	0.39	
plucked	Tanzania	0.33 -0.55	Burgess, 1992.
Field crops	UK	1.4	Monteith, 1977
Willow	UK	1.58	Cannell <i>et al.</i> , 1987
Oil palm		0.9	Squire, 1990

High temperatures and SDs may also decrease ϵ_s . For example, Stockle and Kiniry (1990) reported that increased vapour pressure differences between sub-stomatal air and the air surrounding the leaves may lead to reductions in leaf conductances and photosynthetic capacity of well-watered plants and hence a reduction in RUE. Other factors like plant respiration may also be associated with the reduction in RUEs. In India, Barua (1990) reported that the respiration of the tea plant increased linearly between 20 - 40°C, the rate being faster in young, growing organs like shoots and roots than in older ones.

The limited information available on light interception, RUE and dry matter production in tea highlights the importance of further research on factors affecting the rate of canopy development and the radiation use efficiency. This chapter presents an

analysis of the clonal differences observed and discusses the effects of environment on light interception and dry matter production at four sites in Kericho.

METHODOLOGY

Ground cover

Ground cover was measured at 14 day intervals on plants selected at the start of measurements in June 1992. Plants with ground cover close to the plot mean were selected. One plant per clone was selected in each replicate and in the observation plot, giving a total of 20 plants. A grid measuring 1.2 x 0.8 m, with squares of 0.0036 m² was placed just above the canopy surface and the cover in each square was examined by looking down directly on to it. If 75% or more of a square was covered by leaves, it was recorded as fully covered. Those squares with less than 25% coverage were ignored (Burgess, 1992). The total number of squares counted was expressed as a fraction of the projected final area to be covered (i.e. 1.21 x 0.76 m).

During plant harvests, the ground cover of the harvested plants was also measured.

Leaf Area Index (LAI)

During the first two harvests, in May and August 1992, the area of all leaves was measured using a leaf area meter (LiCor model LI2005). Thereafter, a leaf area card (Pethiyagoda and Ragendram, 1965; Ng'etich and Wachira, 1992) was used due to the number of leaves to be measured. The total leaf area was divided by the measured ground cover to determine the LAI. During the harvests done in August and December 1993 and April 1994, the leaf area of 200 randomly selected leaves was determined from each sampled plant. The total leaf area was estimated from the total leaf dry mass and the leaf specific mass (kg m⁻²). An analysis of variance of specific leaf areas showed no significant differences between clones or seasons.

Ceptometer measurements

A Degacon ceptometer (Delta-T Devices) was used to measure radiation interception of the four clones used in the study. Incident photosynthetically active radiation (PAR) at the canopy and that falling through the canopy to the ground were measured using the

ceptometer. One set of measurements was made during overcast skies and the other during sunny conditions. To allow for direct comparison by other methods, the same plants were also used for ground cover measurements. The diffuse PAR was measured by switching the ceptometer to single sensor mode and taking the reading with the sensor shaded by a circular piece of cardboard of 0.1 m diameter held 1 m high in full sunlight. The intercepted radiation was then calculated from the difference of the two measurements. The canopy extinction coefficient was also calculated by using an inversion of the leaf area indices and the intercepted radiation (Campbell, 1986).

For general use, Campbell (1986) proposed an ellipsoid model for determination of k in randomly distributed leafed canopies. The model assumes that the shape of canopies can be represented as an ellipsoid. The shape factor of an ellipsoid is characterised by the ratio of the horizontal to vertical projected areas, x . The relationship between x and k is expressed as:

$$k = \sqrt{[x^2 + \tan^2 \phi] / \{x + 1.744(x + 1.182)^{-0.733}\}} \quad 5.5$$

where ϕ is the sun's zenith angle.

The fraction of transmitted PAR, τ , below a canopy with a leaf area index LAI is described by the relationship:

$$\tau = \exp[A(1-0.47)f_b \text{LAI} / \{(1-1/2k)f_b - 1\}] \quad 5.6$$

where f_b is the fraction of PAR that is beam and A is a function of leaf absorptivity a , which is typically equal to 0.9 in the PAR band:

$$A = 0.283 + 0.785 a - 0.159 a^2 \quad 5.7$$

Equation 5.6 is often inverted to determine LAI

$$\text{LAI} = \{[(1-1/2k)f_b - 1] \ln \tau\} / \{A(1-0.47f_b)\} \quad 5.8$$

Whole plant harvests

Plants to be harvested were selected from the observation block of 80 plants of each clone situated to one side of the experimental area as described in Chapter 2. Ground cover and stem diameters were used to select plants to be representative of the plot mean as much as possible. Between May 1992 and April 1993, three plants were

harvested from each clone at the four sites. From August 1993, the number of harvested plants was increased to four per clone. Each plant was treated as a replicate.

To study the effect of seasons on dry matter production, whole plant harvests were done in May and August 1992, January, April, August and December 1993 and April 1994 to coincide with the major seasons in Kericho (Stephens *et al.*, 1992). The selected plants were cut at the base of the stem. All the leaves were stripped off and the total leaf area was determined.

Excavation of the roots was carried out on a rectangular area of 1.21 x 0.76 m centred on the stump of the cut plant. The area of excavation on the soil surface was equivalent to the plant spacing.

From August 1993, root excavation was carried out in 0.2 m depth increments. During the harvests in December 1993 and April 1994, root excavation was also carried out in 0.2 m x 0.2 m areas along the horizontal and depth increments to enable determination of root mass per unit soil volume.

RESULTS

Ground cover

At Timbilil and Changoi, the ground cover increased from a mean of 5% at the start of the measurements in July 1992, to 15% and 22%, respectively by early September 1992 (Fig. 5.1). By April 1994, the mean ground cover had risen to 75% and 90% at Timbilil and Changoi respectively. Clone TN14/3 had the largest ground cover at three sites, while clones 6/8 and S15/10 had the least. In October 1992, the ground cover at Changoi was reduced by severe hail damage and took three months to recover. At Kipketer, there were wide variations between the clones, with clone TN14/3 having greater ground cover ($P \leq 0.05$) than clones 6/8 and BB35 during most of the study period, a similar pattern to the other sites.

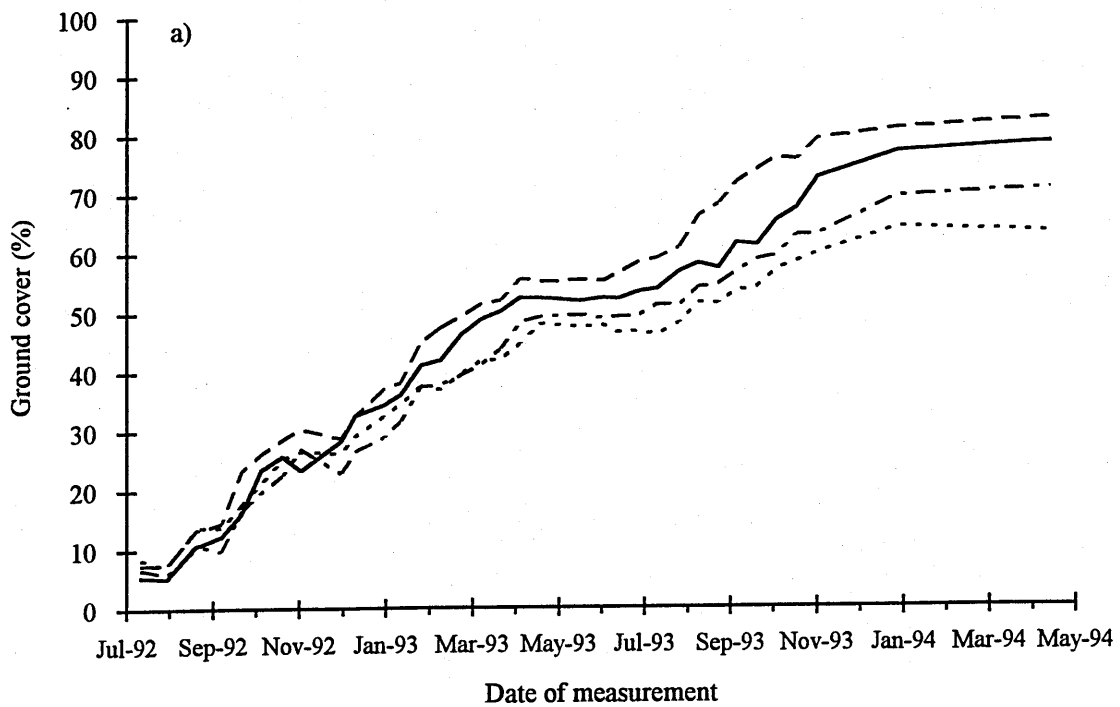
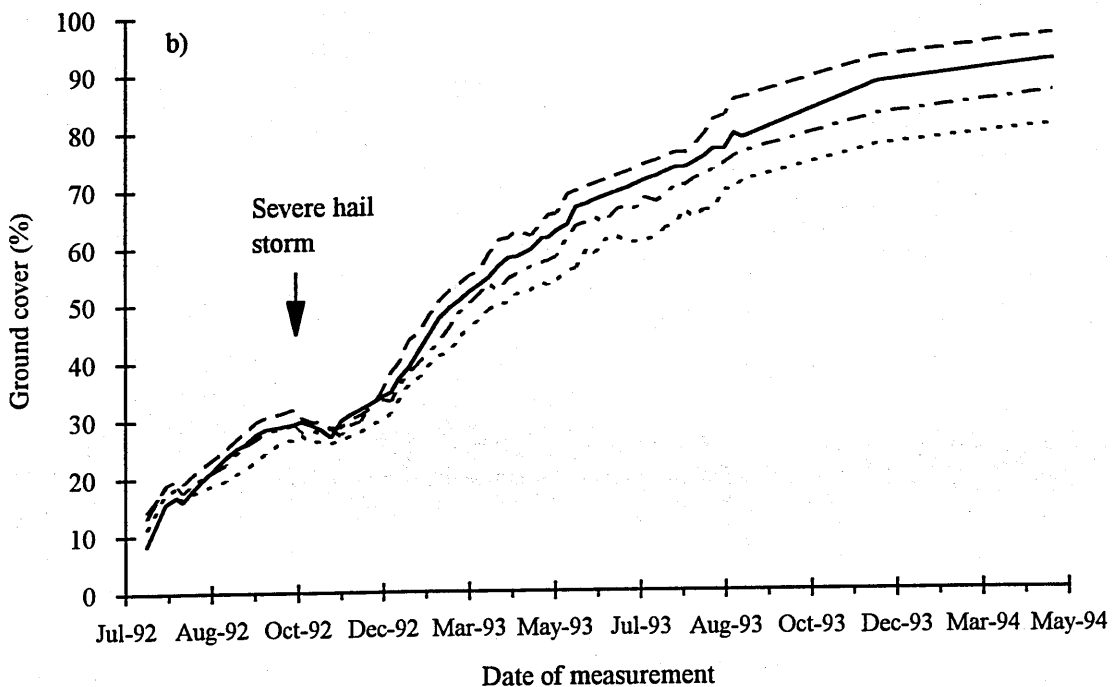


Fig. 5.1. Mean ground cover of four clones S15/10(—) , BB35(— —) , 6/8 (· · ·) and TN14/3 (— · —) at a) Timbilil and b) Changoi from July 1992 to April 1994.

The mean ground cover over the period May 1992 to December 1993 showed linear relationship with mean air temperature at each site. Excluding the Kaproret site improved the regression fit ($r^2=99.9\%$), with a mean rate of change in ground cover of $3\%^\circ\text{C}^{-1}$. Clone BB35 had the largest slope of $4.03\%^\circ\text{C}^{-1}$ ($r^2=98.5\%$, $P=0.055$), though not significant (Fig. 5.2).

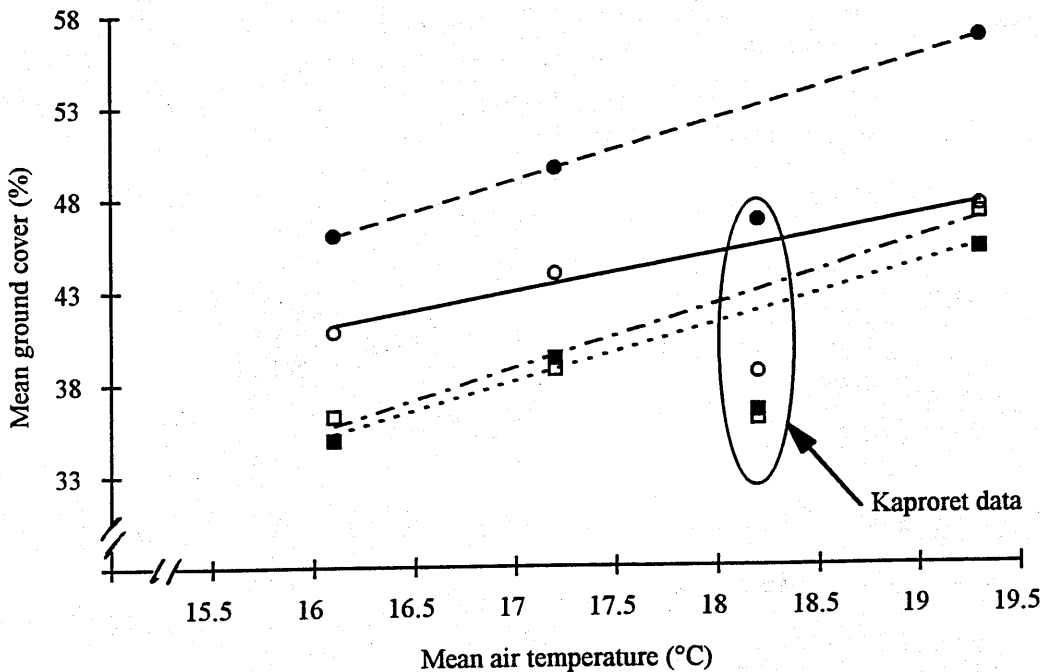


Fig. 5.2 Relationships between mean ground cover and air temperature at the four sites for clones S15/10 (—○—) BB35 (-□-) 6/8 (-■-) and TN14/3 (-●-) during the period May 1992 to April 1994.

The effects of temperature and water stress on canopy development with time were further investigated by looking at the relationships with air temperature and ratio of actual to potential crop (or canopy) transpiration. Though no significant relationships were found (r^2 varied between 15% and 75%), the trends showed a possible reduction in canopy development at higher temperatures due to the higher water stress experienced at this period.

Leaf area indices, LAI*, were calculated from individual leaf area values and the ground cover measured during whole plant harvests. Differences between clones were not significant. Clone S15/10 and BB35 however, had lower LAI* than both clones 6/8 and TN14/3 (Table 5.2).

Table 5.2. *Mean Leaf Area Indices (LAI) of clones S15/10 and TN14/3 at Timbilil and Changoi, during dry matter harvests.*

Harvest date	Clone S15/10		Clone TN14/3	
	Timbilil	Changoi	Timbilil	Changoi
May '92	2.2	2.5	2.4	2.5
Aug. '92	2.6	2.8	3.1	3.4
Jan '93	3.0	3.1	3.8	4.3
Apr. '93	3.8	4.0	4.5	5.0
Aug. '93	4.5	4.3	5.2	5.4
Dec. '93	4.7	5.0	6.3	5.8
Apr. '94	5.2	5.4	6.1	5.8

Extinction coefficients

There were clonal variations in extinction coefficients measured in December 1993, but these were not significant (Table 5.3). There were no differences due to sites though clones at Kaproret tended to have slightly smaller values.

Leaf Area Index values (LAI) determined from ceptometer measurements and those from measurements using inclined point quadrant were in close agreement. However values of k derived from plant structure were much higher than those derived from the LAI using the other two methods. The difference could have been due to the structures of the harvested tea bush where the semi-major axis is shorter due to the flat canopy top. This overestimates values of x , the ratio of horizontal to vertical projected area, which is a function of structure. While there are indications that this ratio is affected by drought,

since there is a reduction in tea bush canopy depths and not in the circumference of the plucking surface, it could not be confirmed in this study.

Table 5.3. *Mean extinction coefficients from two methods of measurements made during December 1993.*

Method				
Ceptometer		Plant structure		
Projected area (m ²)				
Clone	k	Horizontal	Vertical	k
S15/10	0.56	0.2865	0.0791	0.87
BB35	0.59	0.26786	0.0835	0.85
6/8	0.63	0.25518	0.0946	0.81
TN14/3	0.61	0.31371	0.1097	0.83
Mean	0.60			0.84
%cv	18.2			22.5

Light interception

Using measurements of GC and LAI*, the clonal light interception at each site was calculated for all the whole plant harvests. Since only two sets of radiation measurements were available at Timbilil and Changoi, light interception for Kipketer and Kaproret were calculated using incident solar radiation at Timbilil and Changoi respectively. Timbilil and Kipketer, and Changoi and Kaproret are only about 5 km apart and solar radiation was assumed to vary little over these distances. Though there could have been linear dependence of incident solar radiation with altitude (due to the cloud cover changes between sites) this could not be determined in this study.

The increases in f_s were similar to those of ground cover. The largest increment was shown by clone TN14/3, intercepting about 90% of incident solar radiation by April 1994 at Changoi (Fig. 5.3). The amount of intercepted radiation rose from less than 1 MJ m⁻² d⁻¹ in May 1992 to more than 17 MJ m⁻² d⁻¹ in April 1994.

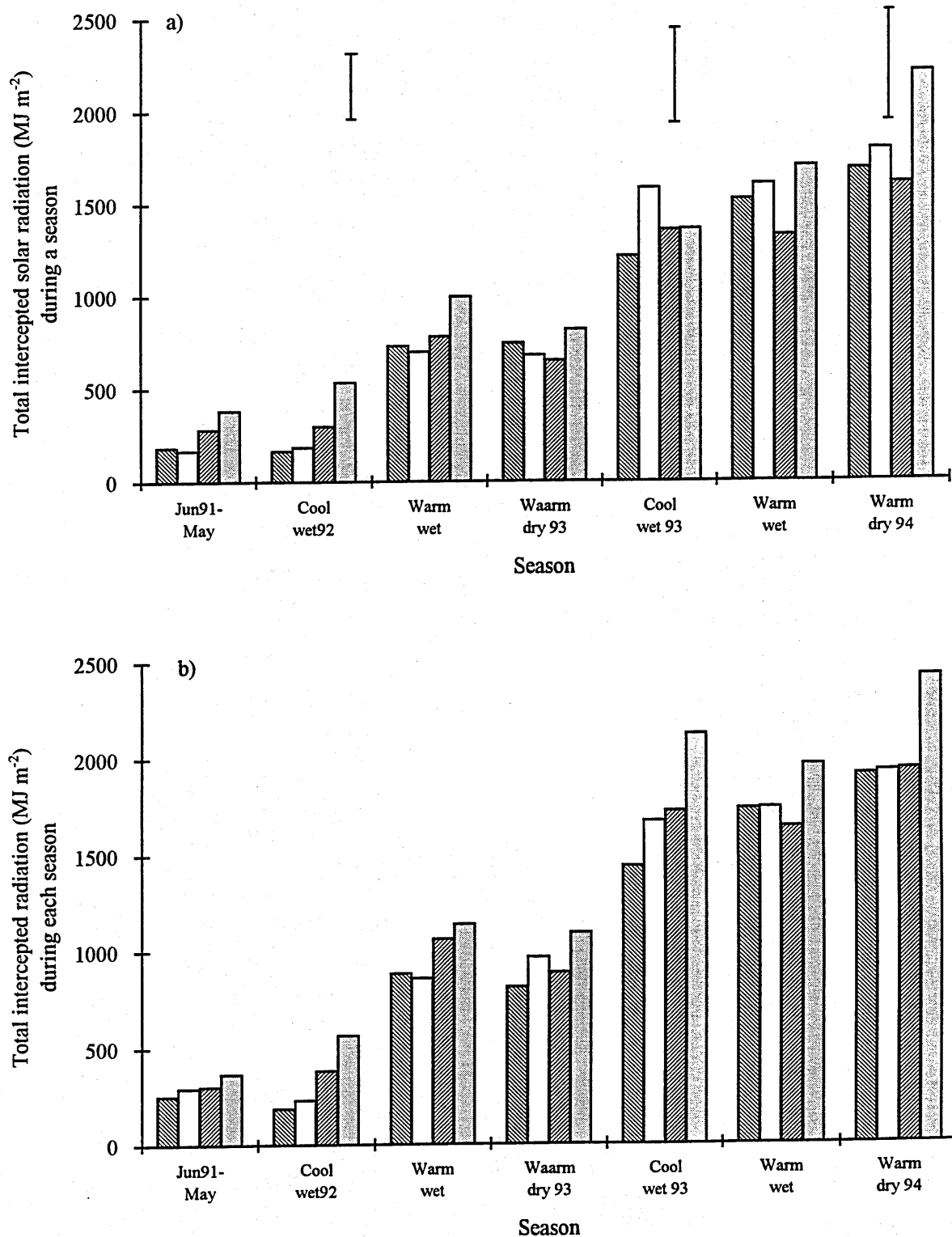


Fig 5.3. Seasonal changes in intercepted solar radiation for a) clone S15/10 and b) clone TN14/3 at Timbilil (▨) Kipketer (□) Kaproret (▩) and Changoi (▤). The LSD bars are for difference between clones and sites at $P=0.05$.

Total dry matter production

In the 34 months to April 1994, clone TN14/3 produced the most dry matter at each site ($P \leq 0.001$) (Table 5.4). At Changoi all clones produced more ($P \leq 0.01$) dry matter than at the other sites. Clone S15/10 produced the least ($P \leq 0.05$) dry matter at all the sites. At Changoi there were differences between all the clones, while at Kaproret, clones 6/8 and TN14/3 were similar ($P \leq 0.05$). At both Kipketer and Timbilil, clones S15/10 and BB35 were not significantly different ($P \leq 0.05$).

Table 5.4 *Total dry matter ($t\ ha^{-1}$) for 34 month old plants; April 1994*

	S15/10	BB35	6/8	TN14/3	Mean
Timbilil	14.7	15.4	20.4	21.5	18.0
Kipketer	15.4	16.1	17.4	21.5	17.6
Kaproret	15.1	16.7	19.4	19.6	19.2
Changoi	18.0	20.3	21.4	29.0	22.2
Mean	15.8	17.1	19.7	22.9	
LSD ($P=0.05$)					
Sites	1.15				
Clones	0.87				
Interactions	1.88				

The total dry matter increased from mean of 4 g per plant ($0.0435\ t\ ha^{-1}$) at planting to a mean of $0.48\ t\ ha^{-1}$ in May 1992. By April 1994, the total plant dry matter had reached $18\ t\ ha^{-1}$ at Timbilil site and $22\ t\ ha^{-1}$ at Changoi site.

Responses of total dry matter (TDM) to mean air temperature during the period of growth were linear.

$$TDM = 0.485T + 8.24, r^2 = 78\%$$

While there were no differences between the response of clones TN14/3 and 6/8, clones S15/10 and BB35 were highly responsive to temperature, with slopes of 1.06 and $1.59\ t\ ha^{-1} ^\circ C^{-1}$ respectively. Removal of Kaproret from the analysis did not improve the linearity of the regression of clones TN14/3 and 6/8.

Rate of dry matter production

In clone S15/10, the rate of dry matter production rose, from $0.5 \text{ g m}^{-2} \text{ d}^{-1}$ in May 1992 during the cool and wet season to reach a maximum of $3.5 \text{ g m}^{-2} \text{ d}^{-1}$ during the period August to December 1993 (Fig. 5.4), as the plants grew and intercepted more radiation. By comparison, the rate in clone TN14/3 rose from $0.6 \text{ g m}^{-2} \text{ d}^{-1}$ to $5.5 \text{ g m}^{-2} \text{ d}^{-1}$ during the same period.

The initial advantage of clone 6/8 in rate of dry matter production was lost during the period April to August 1993. The growth rate of all clones was greater at Changoi than at the other sites. The rate of dry matter production was generally lower during periods of drought, the largest such effects were during the period December 1993 to April 1994, when the drop in rate of dry matter production was 58% at Changoi, but interestingly there was an increase of 4% at Timbilil over the previous period.

During the period January to April 1994, the rate of dry matter production at Timbilil was the largest ($3.8 \text{ g m}^{-2} \text{ d}^{-1}$), while the lowest rate ($2.3 \text{ g m}^{-2} \text{ d}^{-1}$) was at Kipketer. The mean rate during this period ($3.0 \text{ g m}^{-2} \text{ d}^{-1}$) was lower than the period August to December 1993 ($4.8 \text{ g m}^{-2} \text{ d}^{-1}$).

The response to mean air temperature prevailing during the period between harvests were influenced by other factors. The largest slope of response was shown by harvests immediately after a cool wet period (August 1992 and 1993), while the least was after the warm dry and warm wet seasons. There were clonal differences in these responses, clone BB35 having the largest, while 6/8 the least. During periods of drought, the response of clones TN14/3 and 6/8 to temperature were not significant. Inclusion of SD and SWD in a stepwise regression did not improve the significance of the response. When the whole duration of growth was considered and age was included in the regression analysis, the significance was greatly improved (Table 5.5).

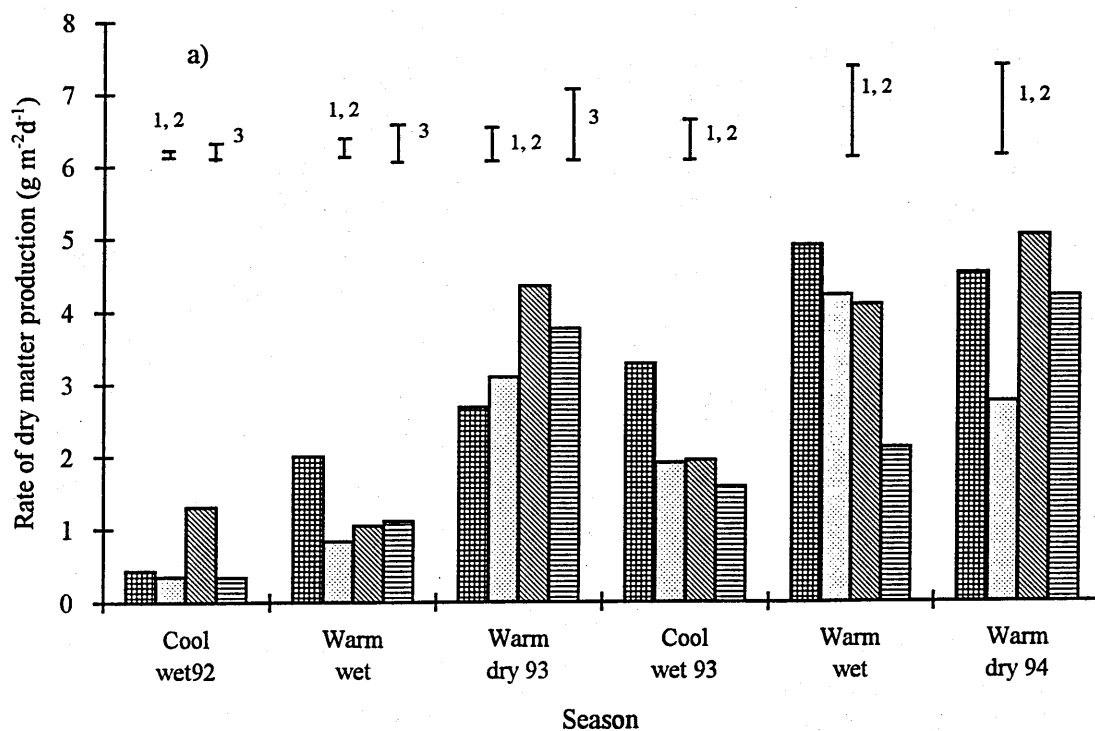
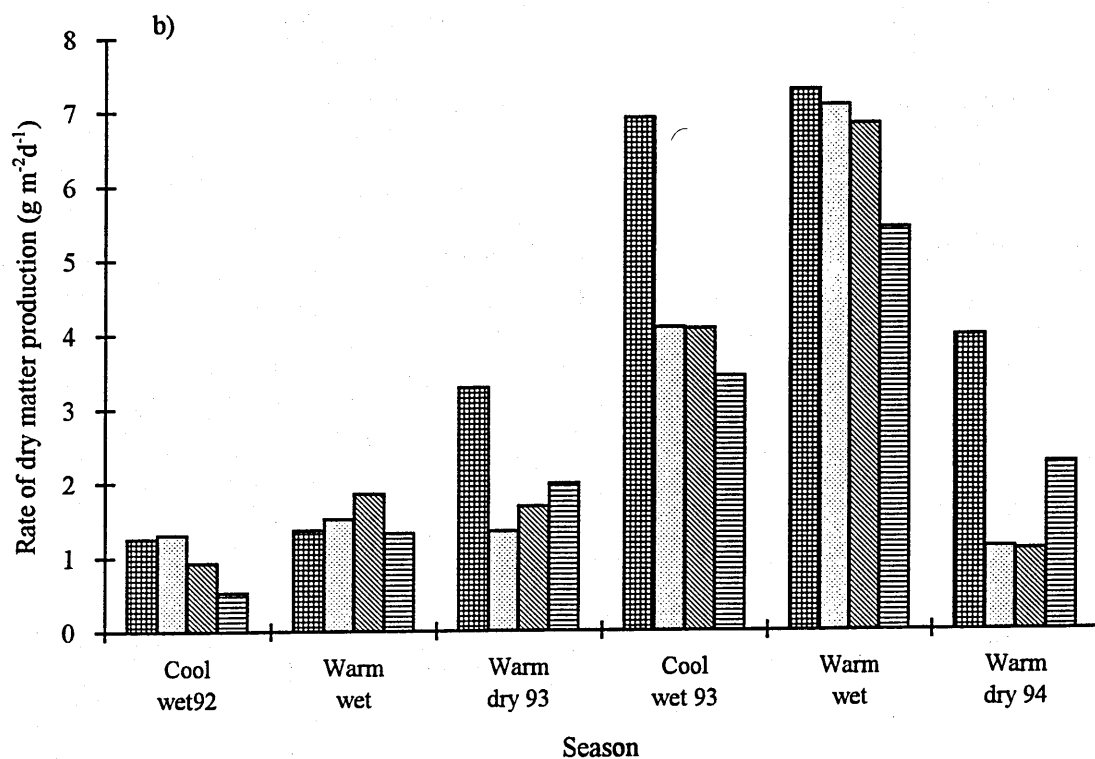


Fig 5.4. Changes in rates of dry matter production of clones TN14/3 (■), BB35 (□), 6/8 (▨) and S15/10 (▤) at a) Timbilil and b) Changoi from May 1992 to April 1994. The LSD bars are for differences between 1=sites, 2= clones and 3=interactions at $P=0.05$.

Table 5.5. *Differences in partial slopes of relationships between mean air temperature, time since planting and rate of dry matter production at four sites (n=24).*

	Temperature (g m ⁻² d ⁻¹ °C ⁻¹)	Time (g m ⁻² d ⁻¹ y ⁻¹)	Intercept (g m ⁻² d ⁻¹)	r ²	P
S15/10	-0.014(±0.224)	2.044(±0.438)	-1.35(±3.71)	43.5	0.001
BB35	0.138(±0.202)	1.606(±0.402)	-3.25(±3.35)	45.4	0.001
6/8	0.063(±0.213)	2.008(±0.402)	-2.35(±3.54)	52.4	0.001
TN14/3	-0.140(±0.324)	2.446(±0.402)	0.33(±5.38)	38.7	0.003

Radiation use efficiency

The seasonal changes in RUEs are shown in Fig. 5.5. These varied from a minimum of 0.1 to a maximum of 0.56 g MJ⁻¹ during the period May 1992 to April 1994. The lowest recorded RUEs occurred during January to April period in 1993 and 1994. During these periods, ϵ_s were lower at Changoi than at Timbilil (Fig. 5.5). There were clonal differences in the values of ϵ_s though most of these were not significant. Clone TN14/3 and 6/8 nearly always had greater RUEs than BB35. These rankings appeared to change at Changoi, where the RUE for clone BB35 was higher than the other clones when available water depletion was below 45% (Fig. 5.5).

On the other hand, ϵ_s was not always greatest at the warmer sites particularly during the dry seasons (Fig 5.6). Clonal differences were at their minimum during the cool wet or warm wet seasons and maximum during the warm dry season, though linear relationships with mean air temperature were not significant. The drop in ϵ_s during dry periods was more pronounced during the December 1993 to April 1994 period when the soil water deficits were greatest. The mean values at Timbilil dropped by 32%, those at Changoi by 69% while Kipketer and Kaproret were similar (56% and 53% respectively). Though the effects of soil water deficits on ϵ_s were not linear, there appeared to be a reduction in ϵ_s when the soil water deficit were larger than 60 mm. The rate of change of ϵ_s with SWD beyond 60 mm appeared to be greater at Timbilil than at Changoi.

These relationships were further investigated by looking at the effect of transpiration and mean air temperature on RUE. Reduction in ϵ_s with decreases in transpiration were apparent though not significant when each site was considered separately.

The mean values of ϵ_s during the period May 1992 to April 1994 were not significantly different between the clones or sites, though it was lowest at Kaproret (0.31 g MJ^{-1}). The largest value was 0.45 g MJ^{-1} for clone BB35 at Kipketer. The mean RUEs at each site excluding Kaproret were similar (0.39, 0.41 and 0.4 at Timbilil, Kikpeter and Changoi respectively).

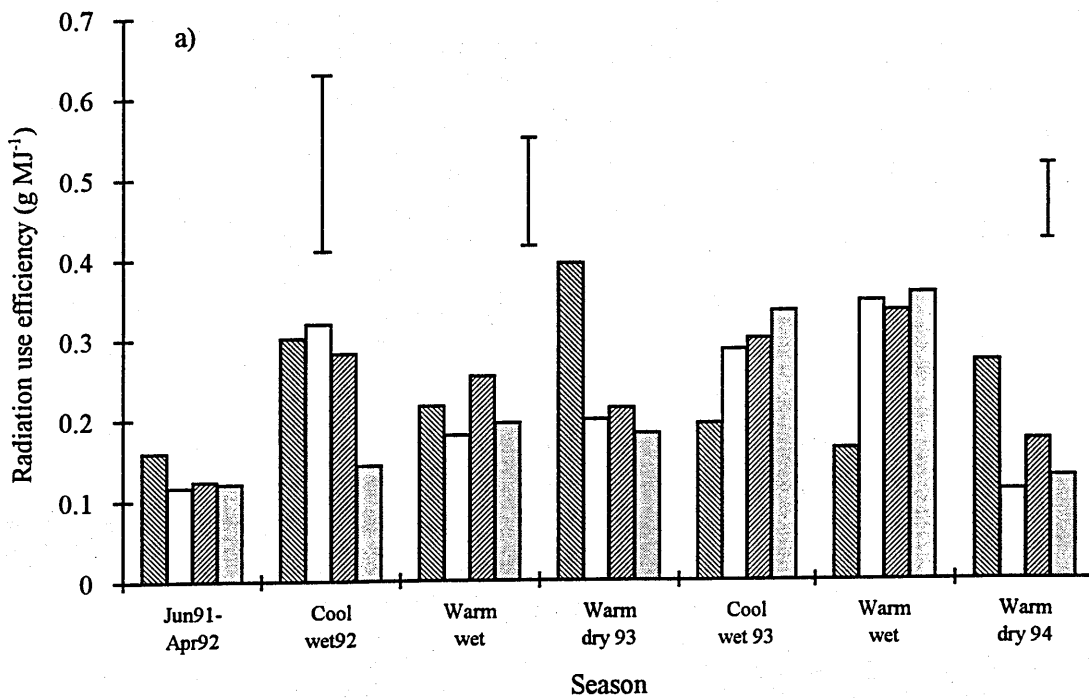
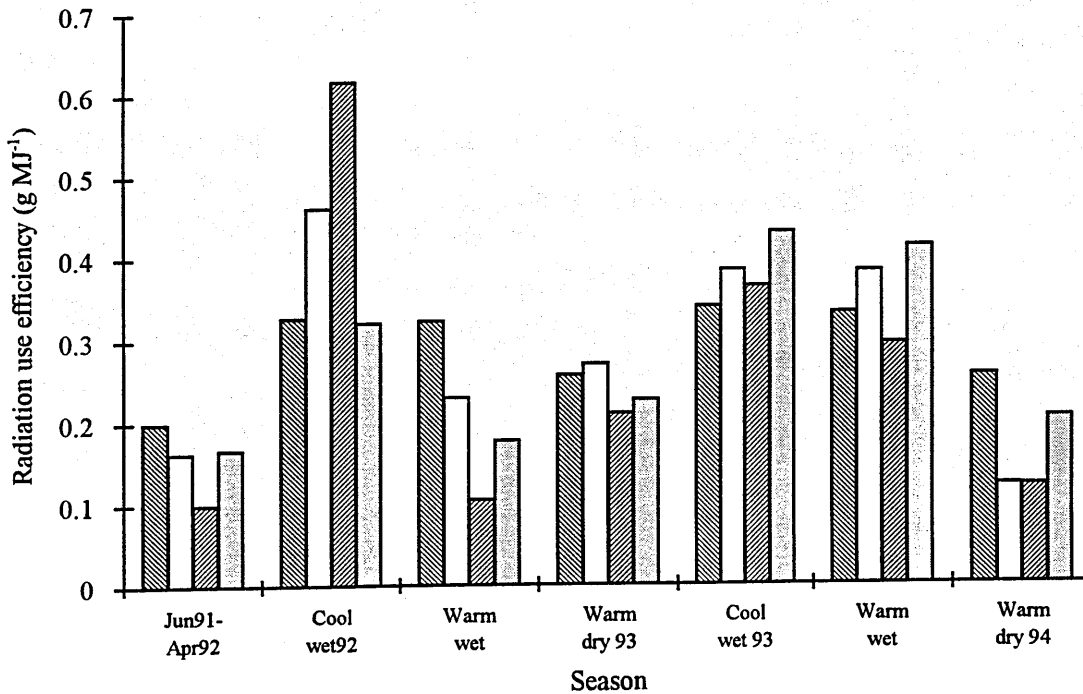


Fig 5.5. Changes in radiation use efficiency of clone a) S15/10 and b) TN14/3 with season at Timbilil (▨), Kipketer (□), Kaproret (▩) and Changoi (▤). The LSD bars are for differences between sites at $P=0.05$.

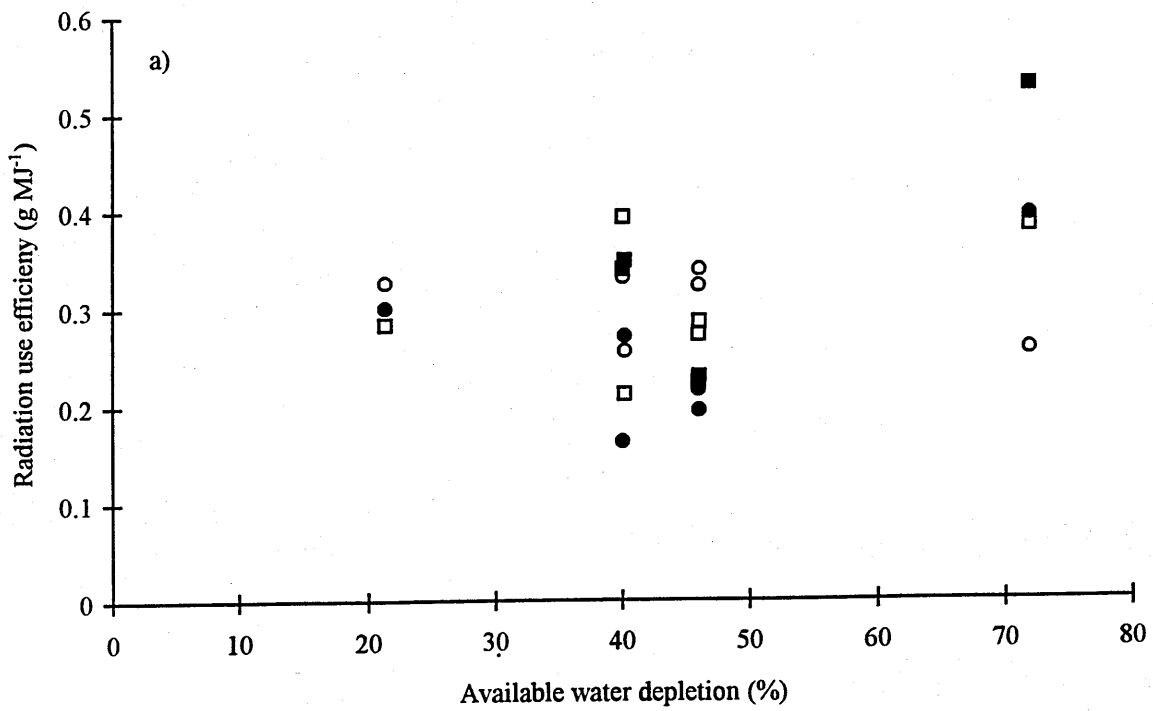
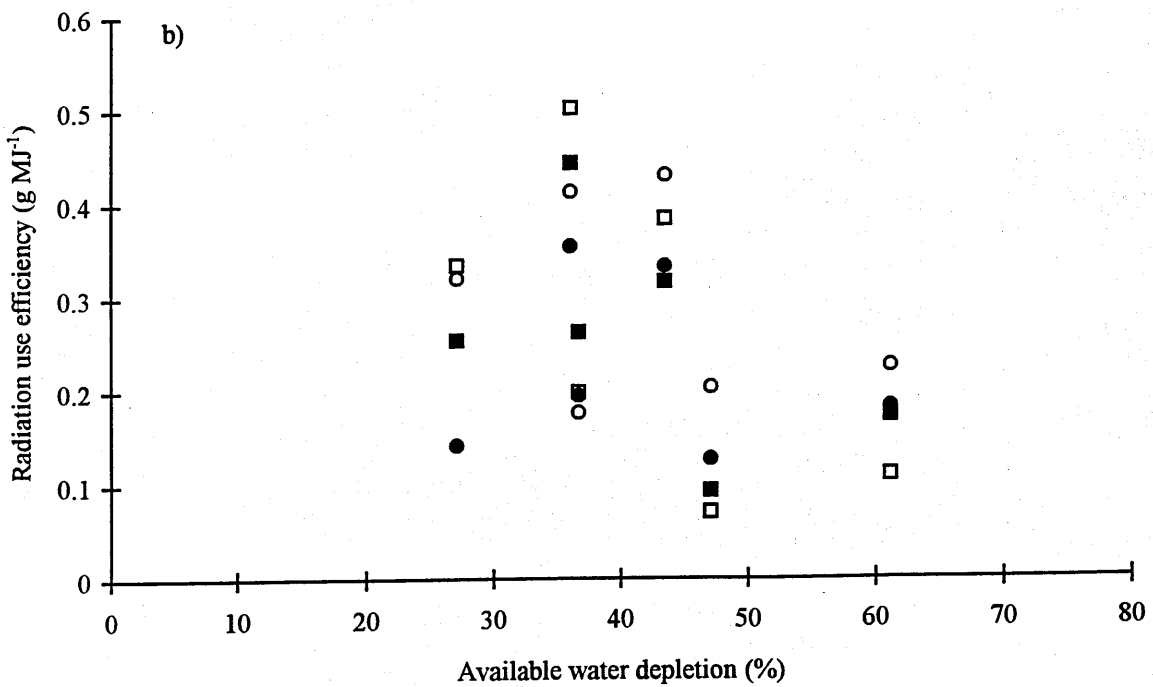


Fig. 5.6 Relationships between RUE and available water depletion of clones S15/10(○), BB35 (□), 6/8 (■) and TN14/3 (●) at a) Timbilil and b) Changoi.

DISCUSSION

Responses to temperature

Rate of canopy development

The mean ground cover was greater at lower altitudes due to the higher temperatures during the cool wet season May to August 1992 and warm wet season September to November 1992. The slow increase in ground cover at higher altitudes (Timbilil and Kipketer) was strongly correlated to effects of the lower temperatures experienced at these sites. Burgess (1992) reported slow development of GC during the cool season in Tanzania, when temperatures are known to restrict shoot extension (Stephens and Carr, 1990).

The relationship between mean ground cover and mean air temperature at each site was linear. This suggests that the rate of increase in ground cover could be influenced more by long term effects of air temperature than short term ones experienced during seasonal changes.

Intercepted solar radiation

The greater intercepted radiation in Kericho than in southern Tanzania (Burgess, 1992) must have been due to the difference in incident solar radiation at these two experimental areas. The clonal differences in intercepted radiation are attributed to ground cover and incident solar radiation, since extinction coefficients were similar.

The slow development of ground cover at Timbilil meant lower interception values, and hence lower dry matter production, though temperature (both soil and air) may have been more limiting than solar radiation.

The values of extinction coefficients determined in this study were similar to the estimated value used by Burgess (1992). That it was highly variable (large %cv) is probably a problem with technique in measurement. The difficulty in determining values of extinction coefficients using the ellipsoid model (Campbell, 1986) in this study was probably due to the shape of a tea canopy, which is more of a "wine glass" type shape than ellipsoidal.

Rate of dry matter production

The increases in rate of dry matter production with time were similar to those reported for clones S15/10, BB35 and 6/8 in Tanzania (Burgess, 1992), an increasing trend as the plants grew. The seasonal changes in rates of dry matter production may have been due environmental factors during these seasons. When the preceeding period was a cool wet or warm wet season, the relationships between rate of dry matter production and mean air temperature were positive and linear. The rate of increase in dry matter production with temperature however varied with season and was greatest during the warm wet season. Inclusion of the age of the plants in the stepwise regression improved the fit considerable. This implies that though water stress reduced rate of dry matter production (January to April 1994), these effects were masked by the increase in plant dry matter with time.

Radiation use efficiency

The values of ϵ_s found in this study are similar to those reported by Burgess (1992) in Tanzania but higher than those reported by Magambo and Cannell (1981) in the same location as this study. The differences may be due to the younger plants used in this study, as compared to 7 year old plants used Magambo and Cannell (1981) since older plants are known to have higher rates of respiration (Charles-Edwards, 1982). Though no effect of temperature could be determined in this study, the negative correlation with mean air temperatures during dry seasons imply greater control by water stress. Marshall *et al.* (1992) also reported that ϵ_s was not strongly affected by temperature in a stand of groundnut. On the other hand, since ϵ_s was calculated from DM and S_i , the lower values of ϵ_s at Changoi during warm dry seasons may have been due to the larger intercepted solar radiation that may not have been useful for photosynthesis if the canopies were already light saturated.

Total dry matter production.

The total dry matter production at Changoi was comparable to that of similarly aged plants of clones S15/10, BB35 and 6/8 in Tanzania (Burgess, 1992) where mean annual values are similar. The relationship between mean air temperature during the period June 1991 and April 1994 and total dry matter production at each site were linear (though not

significant, $r^2 = 77\%$). The lack of a significant relationship with air temperature could have been due to effects of soil water stress during the dry season. The low soil temperatures recorded at Timbilil (Chapter 3) could have been a limitation to total plant dry matter mass, while the larger values of dry matter recorded at Changoi may have due to more intercepted radiation causing a positive feedback.

Response to water stress

Rate of canopy development

The influence of water deficits on canopy development was not explicitly studied in this experiment. The rate of increase in ground cover at Timbilil was reduced during the period January to May 1993. Such effects were not evident on the development of ground cover at Changoi, though those of Kipketer and Kaproret were affected in a similar manner to Timbilil.

Though the ground cover of clone S15/10 was large, its total leaf area was less than that of clone 6/8, which had a smaller ground cover. This might explain why the greater quantity of abscised leaf found under clones 6/8 and BB35 during the dry season (Chapter 6) did not result in a decrease in ground cover during the drought of January to April 1994. This seems to confirm the fact that influence of soil water stress on ground cover was less than on total dry matter production. This hypothesis is further explored in Chapter 6 on dry matter partitioning.

Rates of dry matter production

The changes in relative positions of Changoi and Timbilil in rates of dry matter production during the warm dry periods (January to April 93 and December to April 94) may have been due to limiting soil moisture. Due to the fact that drought was not a treatment, direct relationships between rate of dry matter production from whole plant harvests and soil water deficits could not be attempted in this study. However the reduction in rates of dry matter production during the 1994 dry season reported in this experiment are similar to those reported by Burgess (1992) for clones S15/10, BB35 and 6/8.

Radiation use efficiencies

The low ϵ_s determined for the period December 1993 to April 1994 may have been due to a decrease in soil moisture that restricted growth, even though solar radiation was not limiting. On the other hand total incident solar radiation during this period was higher than the previous period, which may have influenced lower values of ϵ_s calculated if the tea bush canopies were already light saturated. The variations in RUEs during periods of water stress could be related to changes in available soil water capacity as the depth increased. Such apparent relationships are shown in Fig. 5.5, where the decline in ϵ_s appeared to be in two groups.

Responses to other factors

Hail

Hail reduced canopy development at Changoi during the period October and November 1992. While the loss in dry matter production may have been substantial, the effects on recovery were difficult to assess. The other hail incidences when the plants were past this stage at all the sites did not seem to have any appreciable effect on the canopy development.

Bringing into bearing

The initial ground cover development was very similar to plants from the same clones grown in Tanzania that were pegged (Burgess, 1992). Clonal differences were, however lower probably implying that bringing to bearing by continuous tipping process produces more uniform canopies. The effects of temperature are shown by the spread in clonal response at both Timbilil and Changoi (Fig. 5.1 a, b & 5.2).

While the effects of harvesting on canopy development may not be readily apparent in this study, Magambo and Cannell (1981) suggested that the low dry matter they recorded was due to harvesting of shoots.

Proportional contribution to total dry matter

While the changes in mean dry matter produced between extreme sites was only 23%, clones TN14/3 and BB35 produced 35% and 32% more dry matter respectively at

Changoi than at Timbilil. Clone S15/10 produced 22% more dry matter at Changoi than at Timbilil, while it was only a 5% increase in clone 6/8. In contrast, Ground cover increased by 20% between Timbilil and Changoi. There was 13% more radiation incident at Changoi than Timbilil, which led to differences in total intercepted solar radiation ranging from 28% (S15/10) to 54% (BB35), while clones TN14/3 and 6/8 were similar (34% and 33% respectively).

Of the parameters which contribute to the total dry matter (equation 5.1), incident solar radiation accounted for 60% of the differences between Timbilil and Changoi. Ground cover accounted for 32% while RUE only accounted for 8%. However clones behaved differently (Table 5.6)

Table 5.6. *Proportional contribution (%) of ground cover, incident solar radiation and RUE to total dry matter during the period April 1993 to April 1994.*

	Ground cover	Solar radiation	RUE
S15/10	12	64	24
BB35	72	45	-17
6/8	11	96	-7
TN14/3	54	43	3

CONCLUSION

The differences in total dry matter production found in this study were due to both genotype and environment. The differences in intercepted solar radiation between extreme sites (over 30%) was the major contributor to the observed differences in dry matter, and RUE contributed the least. This points to the importance of ground cover and hence methods of rapid canopy development like pegging are important.

Effects of drought on ground cover development were not apparent in this study, though rate of dry matter production was reduced during the dry season. The difference

in responses between sites points to the importance of temperature in GxE interactions for dry matter production and hence in clonal selection.

Values of extinction coefficient determined in this study are similar to values estimated for tea in Tanzania. The values of radiation use efficiency determined in this study ranging from 0.3 to 0.45 g MJ⁻¹ are similar to those reported for irrigated tea in Tanzania.

The importance of hail damage on young tea plants is highlighted by reduced ground cover and three months it took to recover at Changoi.

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CHAPTER 6

DRY MATTER PARTITIONING

INTRODUCTION

Dry matter partitioning is the apportioning of the assimilates to the various plant organs and is influenced by all the main environmental and cultural factors (Squire, 1990) and by genotype (Burgess, 1992; Othieno, 1982b).

In tea, the harvest index (HI), defined as the fraction of the total dry matter partitioned to harvestable shoots, ranges from 7 to 24% (Murty and Sharma, 1986; Magambo and Cannell, 1981; Burgess, 1992, 1994). These values are small compared to forest trees with harvest indices ranging from 40 to 85% (Cannell, 1985) and 42% for oil palm (Corley, 1983). Magambo and Waithaka (1983) reported that the harvest index of harvested tea decreased 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. Corley (1983) suggested that the decline in yield per tree in oil palm was due to the increased leaf area indices as the plant ages. Othieno (1979) and Magambo and Waithaka (1983) however, reported a positive correlation between shoot:root ratios and yields of tea.

Genotypic variations in total dry matter production and partitioning in tea have been found to be influenced by the above ground dry matter (Magambo and Waithaka, 1983) and Burgess (1992) reported clonal differences in dry matter partition in young tea. In his experiments, clones with high yield partitioned a smaller proportion of the total dry matter to the roots.

Dry matter partitioning is affected by the physical environment by influencing the partition factors and the periods in which plant parts increase in mass (Squire, 1990). The environmental variables found to have influence on partition of assimilate are temperature, photoperiod, water stress and nutrition. Seasonal changes in partitioning in Coffee (*Coffea arabica*) was ascribed to changes in air temperature and water stress between seasons (Cannell, 1985). These seasonal changes in partitioning may be caused by the changes in direction of movement of photosynthates observed in tea due to changes in season (Manivel and Hussain, 1982). This might also explain the observed

rhythmic changes in shoot growth in tea (Fordham and Palmer-Jones, 1977) known as the 'Fordham effect', identified as the cause of seasonal yield fluctuations.

Changes in partitioning of dry matter are also influenced by soil water deficits. Once a critical soil water deficit has been exceeded, plants partition more to the roots than the shoots. In his review of control of shoot:root ratios, Wilson (1988) noted that water stress increased the partitioning of carbon to the roots, decreasing shoot growth proportionately more than the total growth. Cannell (1985) also reported that water stress decreased the shoot to root ratio in tree crops. He also showed that in a constant environment favouring continuous growth, the ratio of shoot to root relative growth rates tends to be constant.

Cultural practices are also important in partitioning of assimilate. Linder and Rook (1984) reported that improved nitrogen nutrition and reduced soil water stress lead to increases in total dry matter production, reduction in fine root turnover and hence a increase in the shoot:root ratio in trees. Some cultural practices such as pruning in tea, are known to conserve water in the soil (Squire and Callander, 1981).

Tanton (1979) proposed that the tea crop is sink limited and that plucking of immature shoots, essential for manufacture of quality tea, is a major factor limiting yield. This argument was supported by Magambo and Cannell (1981) who showed that groups of tea bushes produced 16.9 t ha^{-1} when harvested and 26.3 t ha^{-1} annually of dry matter when left to grow freely (un-harvested). Othieno (1982b) also suggested that plucked tea has a low dry matter productivity attributed to effect of plucking limiting the development of woody stems.

Dry matter partitioning can be a useful tool in clonal selection, for defining suitable selection criteria (Magambo and Waithaka, 1983; Burgess, 1992). An understanding of clonal differences (and site differences) in partitioning to the useful structures (harvest index) is therefore important to growers and scientist alike.

Chapters 4 and 5 have shown that there were large differences in dry matter production between sites and genotypes in this experiment. Chapter 6 reports on clonal and environmental effects on how this dry matter is partitioned to various plant organs.

METHODOLOGY

Dry matter partitioning was determined from the seven whole plant harvests from the observation plots at each site between May 1992 and April 1994. Three plants from each clone were sampled during the major seasons at Kericho described in Chapter 3. These seasons are: April to August a cool and wet period, September to mid-November, a warm wet and sometimes warm and dry period, and mid-November to March, a warm dry period.

An initial harvest in June 1991 was done before planting out in the field, on representative plants from the nursery. The first harvest after out-planting was during May 1992 when the plants were just over 10 months old.

At each harvest the sampled plants were separated into leaves, tender stems, woody stems, coarse and fine roots. On a tea bush, tender stems (or branches) are usually those parts of branches that are still green, while woody stems are the hard fibrous part of the stem or branches. Fine roots were taken as those with diameter < 1 mm, while coarse roots were those with diameters greater than 1 mm. These definitions of harvested parts closely follow those developed by Magambo and Cannell (1981) and Burgess (1992) in order to allow direct comparisons their results in Kenya and southern Tanzania respectively.

Partitioning to harvested shoots was estimated by counting the number of plucked points (stumps) on the bush and using the average clonal shoot dry mass to calculate the total harvested shoot mass. The harvested shoots are those shoots removed for the manufacture of tea.

Root mass was determine by excavation of an area equivalent to the plant spacing, centred around a cut plant. Due to the variability in sizes of cut plant parts, drying in the oven for 36 to 48 hours at 85 to 90°C was used until constant dry mass was achieved. Abscised leaf was also estimated at the harvests from January 1993 onwards. Fallen leaves were collected from under three selected plants per clone, each on an area of 1.21 x 0.76 m equivalent to the plant spacing, before each hand weeding of the plots. The leaves were washed gently (to remove soil) and dried in an oven for 24 to 36 hours depending on the perceived moisture content of the leaves.

RESULTS

The variations in partitioning to the various plant organs showed differences between clones, sites and seasons. During some of the harvests, there were significant GxE interactions in partitioning to roots and shoots. An underlying time trend was also observed in the partitioning to these two attributes.

Partitioning to harvested shoots, leaves and stems

Harvested shoots

The rate at which dry matter was partitioned to shoots differed significantly between clones ($P \leq 0.05$) and between sites ($P \leq 0.01$), while there were also significant interactions during some of the harvests. The mean values range from $0.03 \text{ g m}^{-2} \text{ d}^{-1}$ for clones TN14/3 and 6/8 to $0.05 \text{ g m}^{-2} \text{ d}^{-1}$ for clone S15/10 during the initial harvest in May 1992. By August 1993, the partition to shoots had increased to $1.18 \text{ g m}^{-2} \text{ d}^{-1}$ for clone S15/10 at Changoi. During August 1993, after a cool wet period, clone S15/10 partitioned more to leaves and shoots at all the sites ($P \leq 0.05$).

During the initial harvest, the plants at Changoi partitioned more to harvested shoots than all the clones at the other sites ($P \leq 0.05$). Partitioning to both leaves and shoots was more at Changoi ($P \leq 0.05$) than any other site.

During the harvest in December 1993 after a period of warm weather, partitioning to shoots increased to 10% (clone TN14/3) and 16% (clone S15/10) of the total dry matter. There were significant GxE interactions in partitioning to shoots during this period. The increase in HI during the period December 1993 to April 1994 was lower than that of the previous period (August to December 1993) at all the sites. This decrease was more marked at Changoi (59%) while it was the least at Kaproret (43%). The drop at Kipketer and Timbilil were similar to that of Kaproret (44 and 45% respectively).

Linear relationships between seasonal changes in harvest indices and mean air temperature were not significant for most of the seasons except for clone BB35 during the warm dry period January to April 1993. During this period, the harvest index of clone BB35 increased by $0.061 (\pm 0.0057) ^\circ\text{C}^{-1}$ ($r^2 = 99.8\%$).

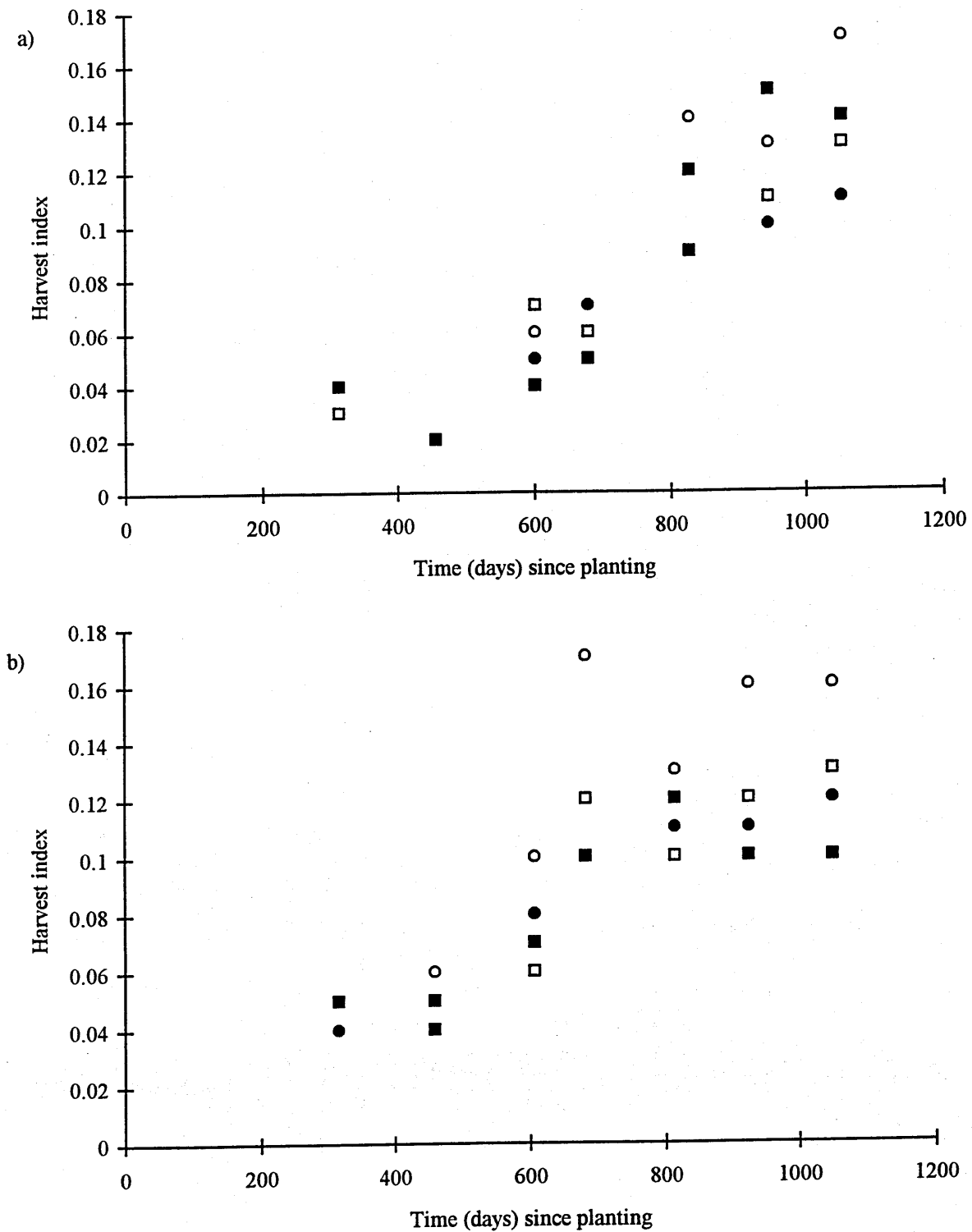


Fig. 6.1. Changes in harvest index with time from May 1992 to April 1994 at a) Timbilil and b) Changoi for clones S15/10 (○), BB35 (□), 6/8 (■) and TN14/3 (●)

During the other seasons, relationships between mean air temperature and HI were either curvilinear (convex or concave) or not significant at all. During relatively dry periods (January to April 1993 and 1994), the HI at Kipketer were larger than at the other sites.

The changes in cumulative HI with time on total dry matter are shown in Fig. 6.1. The increases appear to follow a logistic growth curves. Though the parameters for these curves were not characteristic of site, the time taken to reach the point of maximum increase in HI was smaller at lower altitudes (about 700 days at higher altitudes compared to 500 days at lower altitudes).

Leaves

The proportion of total dry matter partitioned to leaves excluding harvested shoots, was relatively constant for all clones over the experimental period within a range of 25 to 50%, though there appears to have been a gradual decrease with time. At the initial harvest in 1991, leaves accounted for a mean of 40% of the total plant dry mass, and there were no significant difference between the clones. By April 1994, the proportion partitioned to leaves had dropped slightly to a mean of 37% for leaves still on the plant. In the same period however, the dry matter in abscised leaves rose to more than 10% of the total dry matter (Table 6.1).

From May 1992 onwards, there were clonal differences in partitioning to the leaves. Clone S15/10 partitioned more dry matter to leaves (50%) than the other clones ($P < 0.01$). Clonal differences between sites were also significant, showing a decline in proportion of dry matter partitioned to the leaves with a decrease in mean air temperature, though not significant

Abscised leaf

There were seasonal differences in amount of abscised leaf collected from under the selected bushes. An increase at each site during the warm dry season was observed. Clonal differences were significant, clones 6/8 and BB35 had the highest leaf fall, both occurring at Changoi, while there were no significant differences at Timbilil (Table 6.1).

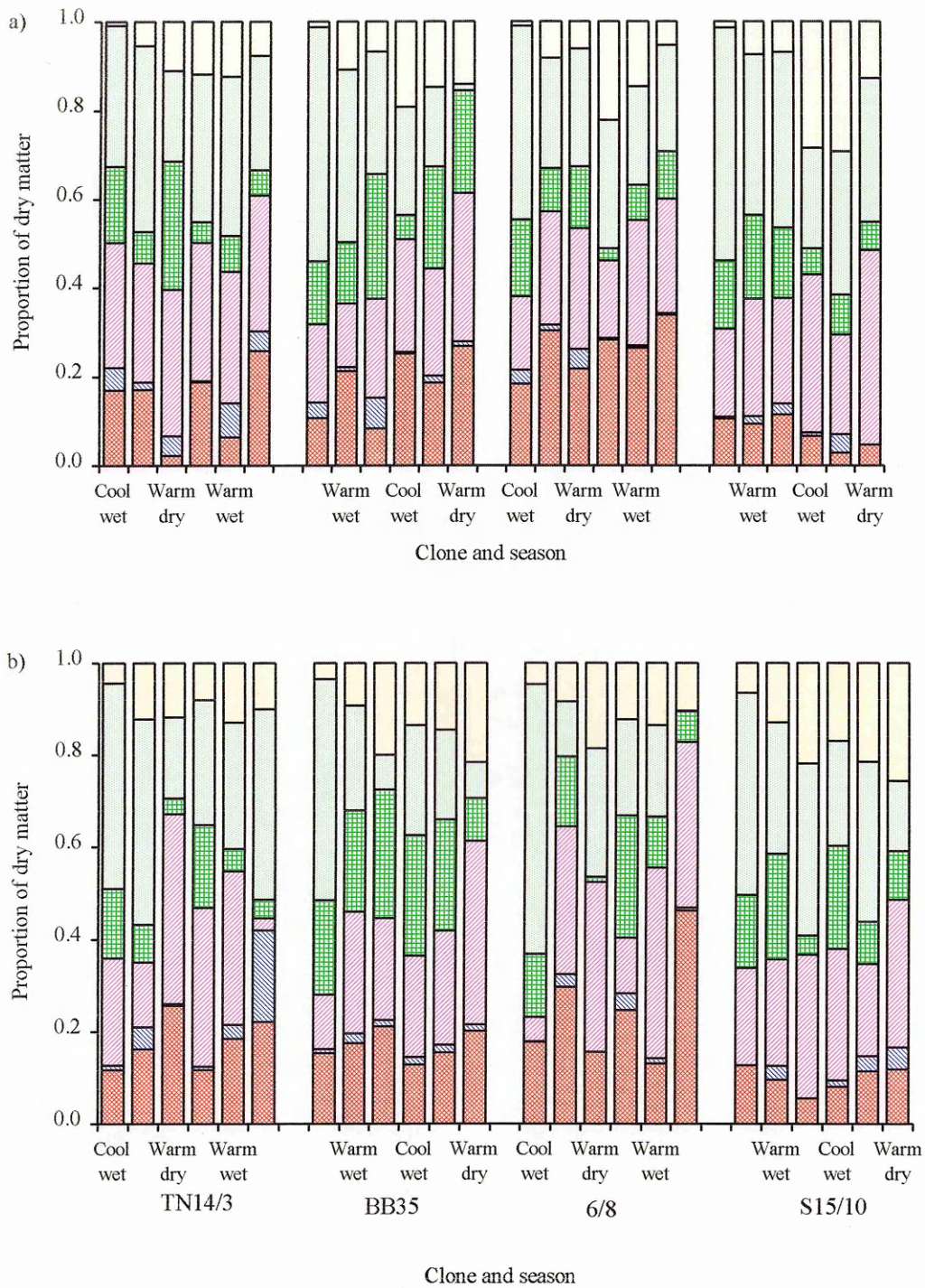


Fig. 6.2. Seasonal changes in partitioning of dry matter increment of four clones at a) Timbilil and b) Changoi, from May 1992 to April 1994. Harvested shoots , Leaves , Tender stems , Woody stems , Fine roots , Coarse roots .

During the cool and wet seasons, there were no site differences in leaf abscission. There seemed to be an increase in leaf abscission with time.

Table 6.1 *Comparison of abscised leaf (g m^{-2}) of four clones at four sites during the cool wet (1993) and warm dry (1994) seasons.*

Apr. - Aug. 1993 (Cool wet)						Dec. 1993 - Apr. 1994 (warm dry)				
Site	TN14/3	BB35	6/8	S15/10	Mean	TN14/3	BB35	6/8	S15/10	Mean
Timbilil	35.8	49.6	51.4	36.8	43.4	66.8	98.3	95.5	51.8	78.1
Kipketer	37.2	44.3	48.9	39.0	42.3	75.9	113.8	107.2	50.3	86.8
Kaprorret	49.6	59.5	57.4	42.7	52.3	67.5	108.1	91.0	59.8	81.6
Changoi	44.6	58.3	56.1	42.0	50.5	74.9	216.9	118.8	54.2	116.2
Mean	41.8	53.0	53.5	40.1		70.5	134.3	103.1	54.0	
CV%		10.4						17.4		
LSD (P=0.05)										
Sites		NS						18.2		
Clones		2.11						11.4		
Interactions		NS						NS		

Tender stems

Partitioning to tender stems accounted for less than 25% of the total biomass of the plant in most clones. There were differences between the sites in partition to tender stems, though the ranking varied with season. After a cool wet season in 1992 (April to August), the proportion of dry matter partitioned to tender stems was largest at Kaprorret $P \leq 0.05$ (22%) and least at Changoi. Clone BB35 had the highest proportion of tender stem while clone 6/8 had the lowest ($P \leq 0.05$). By contrast in the 1993 warm dry season, partitioning to tender stems was largest at Timbilil ($P \leq 0.05$) and least at Kaprorret. In this harvest clone BB35 again had the most ($P \leq 0.05$) dry matter partitioned to tender stems. This however changed during the harvest in April 1994 when partitioning to tender stems was lower than during December 1993 in all the sites. As in

the other harvests, clone S15/10 partitioned more to tender stems, though this was no different from clone BB35, while clone TN14/3 was the least (Fig. 6.2).

Woody stems

Partitioning to wood was at most just significantly different between the sites. There were no significant GxE interactions in partitioning to woody stems throughout the duration of the study. Analysis of variance showed that partition to woody stems was variable even between replicates (c.v. ranging from 12% to 27%).

Partitioning to wood during August 1992, January and August 1993 was significantly higher in clone TN14/3, than in BB35 ($P \leq 0.05$). Partitioning to wood was highest at Changoi ($P \leq 0.05$) during April 1993 and lowest at Kaproret.

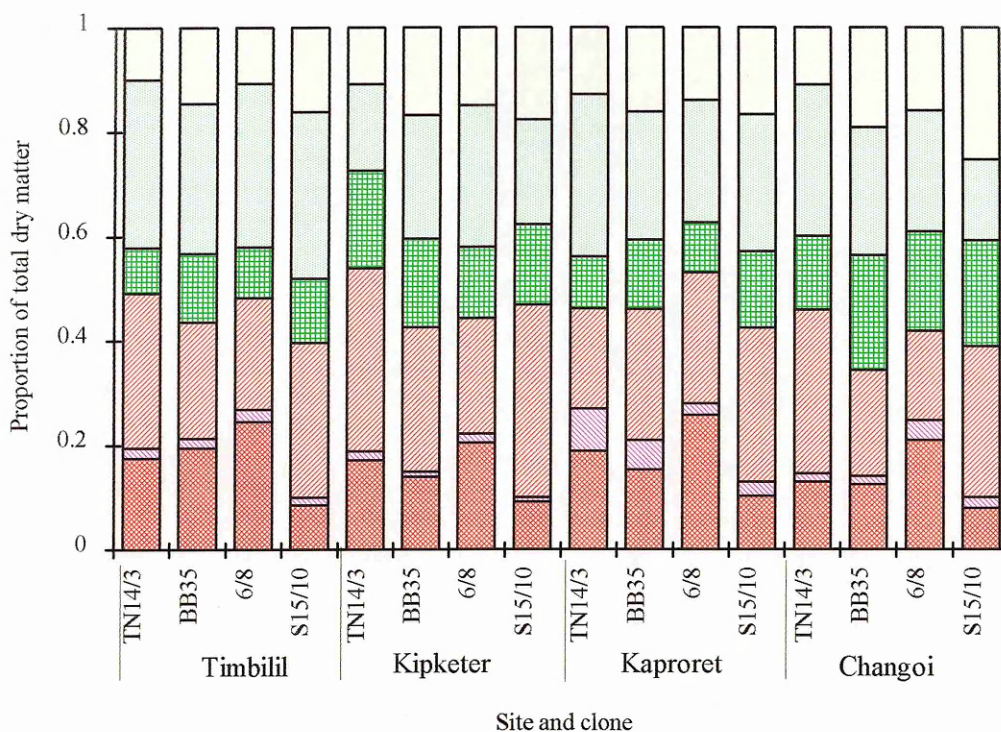


Fig. 6.3. Proportional partitioning of total dry matter of four clones at four sites during the period April 1993 to April 1994. The partitions are to shoots , leaves , tender stems , woody stems , fine roots  and coarse roots .

Partitioning to roots

Partitioning to roots accounted for 10 to 20% of clone S15/10 total dry matter, while it ranged from 15 to 32% for the other clones. There were also differences between the sites, Changoi having the largest proportion of dry matter partitioned to roots (up to 25%) while Timbilil had the lowest (20%) (Fig. 6.2).

Clone 6/8 partitioned most to coarse roots in all the sites ($P \leq 0.05$), while clone S15/10 partitioned the least. Only clone TN14/3 partitioned significantly more to fine roots than the other clones at all sites.

Seasonal changes in partitioning to roots were also evident. During the first field harvest in May 1992, clone 6/8 partitioned more to the roots than clones BB35 and S15/10 ($P \leq 0.05$), but was not significantly different from clone TN14/3. At this harvest partitioning to fine roots was highest at Timbilil (5%) and lowest at Changoi (3%) ($P \leq 0.05$). In the subsequent harvests however, the proportion of dry matter partitioned to fine roots was more at Kaproret than at any other site.

During the warm dry periods (January to April 1993 and 1994) the proportion of dry matter partitioned to roots increased at each site, though clonal increases were not consistent. The largest change was that of clone 6/8 at Changoi (45% increase) during the period January to April 1994, while partitioning to roots was least in clone S15/10 (less than 5% increase) at Timbilil.

Rooting depth

There were clonal variations in final root depth measured during the whole plant harvest in April 1994. Tea plants at Changoi had the deepest roots (1.4 m) $P \leq 0.01$, while those at Kaproret were shallow. There were no significant differences in mean root depths between Kaproret and Timbilil.

Clonal differences in final root depths were also significant. Clone S15/10 had the shallowest roots at each site and both clone 6/8 and TN14/3 had the deepest ($P < 0.05$) except at Kaproret where the roots of clone TN14/3 were shallower than clone 6/8 ($P < 0.05$).

The increase in root depth could be modelled using an exponential of the form:

$$d_t = d_o \cdot e^{k_r t} \quad 6.1$$

where d_t is the root depth at time t (days) since planting, d_o is the initial depth (m) and k_r is the relative root extension rate ($\text{m m}^{-1} \text{d}^{-1}$). This relationship was found to account for more than 90% of the variance in all the sites. The mean relative rate of downward root extension was greater at Changoi ($0.0017 \text{ m m}^{-1} \text{d}^{-1}$) than at all the other sites, while Timbilil had the least. Differences between clones were also significant. Clone TN14/3 at Changoi had the largest relative rate of downward extension ($0.00216 \text{ m m}^{-1} \text{d}^{-1}$), while the least was clone S15/10 at Timbilil ($0.00135 \text{ m m}^{-1} \text{d}^{-1}$).

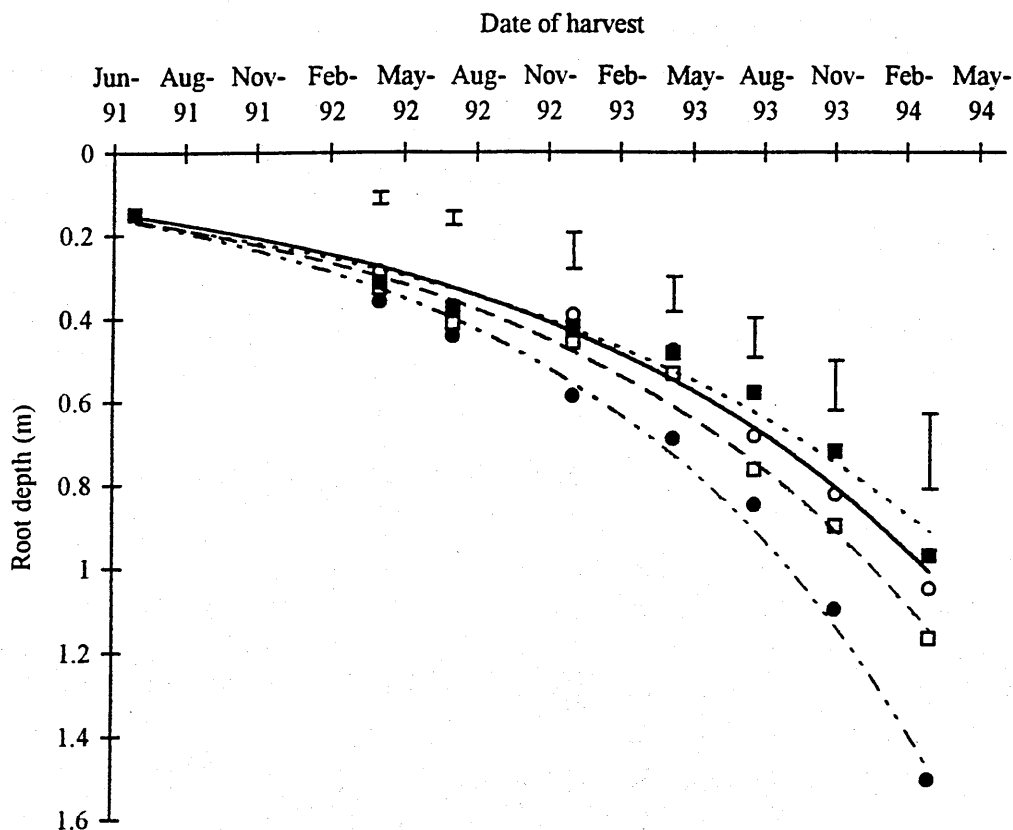


Fig. 6.4 Mean root depth at each plant harvest at Timbilil —○—, Kipketer —□—, Kaproret —■— and Changoi —●—. The curves are fitted with an exponential equation (Eq. 6.1). LSD bars are for differences at $P=0.05$.

Table 6.2 *Changes in the relative root extension rates with mean air temperatures between May 1992 and April 1994.*

Site	Timbilil	Kipketer	Kaprorret	Changoi
Mean air temp (°C)	16.1	17.2	18.1	19.3
Mean k_r ($\text{m m}^{-1}\text{d}^{-1}$)	0.001475	0.001525	0.001334	0.001704
Maximum SWD (mm)	91	95	116	134

There were significant GxE interactions in final root depths. These interactions were analysed in terms of response to mean air temperature (Fig. 6.5) and by excluding Kaprorret due to earlier mentioned soil physical and chemical conditions (Chapters 2, and 5).

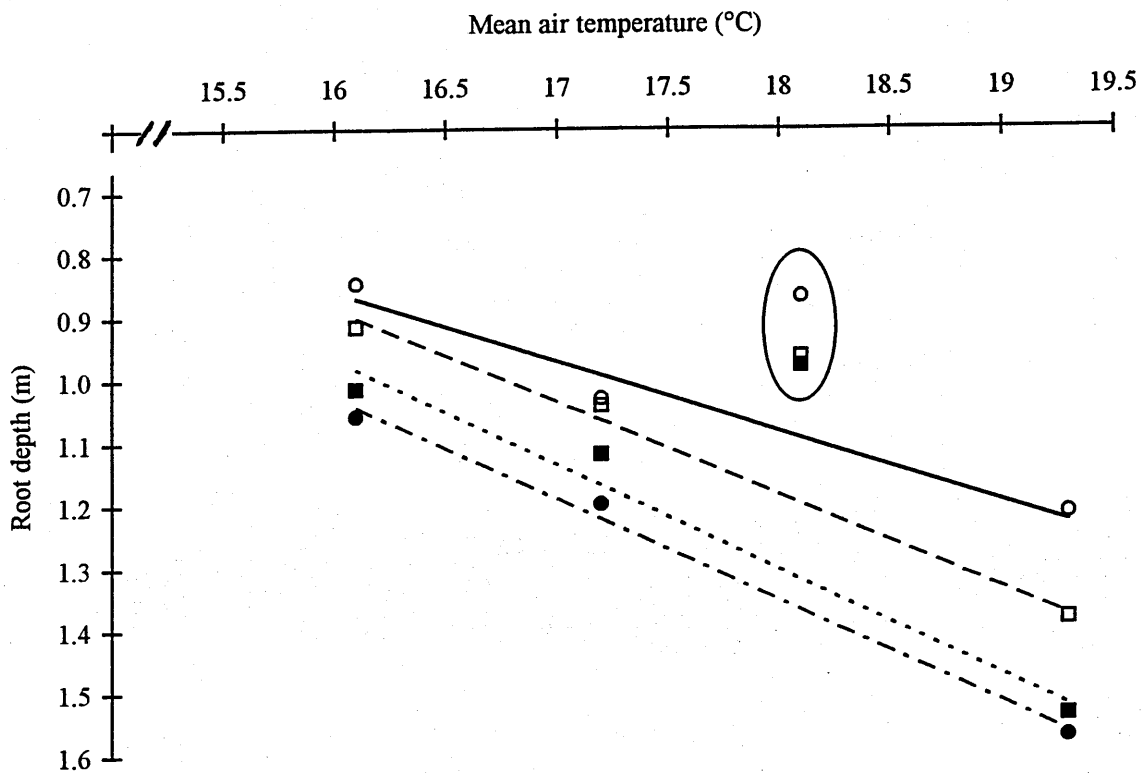


Fig. 6.5. Relationships between mean air temperatures and final root depths at April 1994 for clones S15/10 —○—, BB35 —□—, 6/8 —■— and TN14/3 —●—. The fitted linear regression lines exclude Kaprorret data (circled).

Clones TN14/3 and 6/8 had the greatest response to mean air temperature, though there were no significant differences between their slopes ($0.163(\pm 0.0125)$ and $0.169(\pm 0.02657)$ $\text{m } ^\circ\text{C}^{-1}$, respectively). Clone S15/10 had the least response to temperature with a slope of $0.112(\pm 0.0201)$, ($r^2 = 97\%$), while BB35 had a slope midway between these two extremes. Only the slope of TN14/3 was significant ($P=0.048$), while those of clones BB35, 6/8 and S15/10 were not significant.

Root distribution.

At the last three harvests (August and December 1993 and April 1994), where root mass per unit soil volume could be determined, differences in root distribution between clones and sites were evident. Fig. 6.6 shows a comparison between sites for clone 6/8. Between 50 to 60% of the fine roots were confined to the top 0.4 m. The remaining mass was evenly distributed (or nearly so) down near the final depth. At Kaproret the pattern was different from the other sites, where most roots were in the top 0.7 m depth in all clones (Fig. 6.6(c)). Few roots could penetrate through this depth and in clone TN14/3 55% of the fine roots were confined to the top 0.2 m. Though the maximum root depth at this site was comparable to those at Timbilil in some clones, the root mass per unit volume of soil at depths beyond 0.7 m were lower than at any other site.

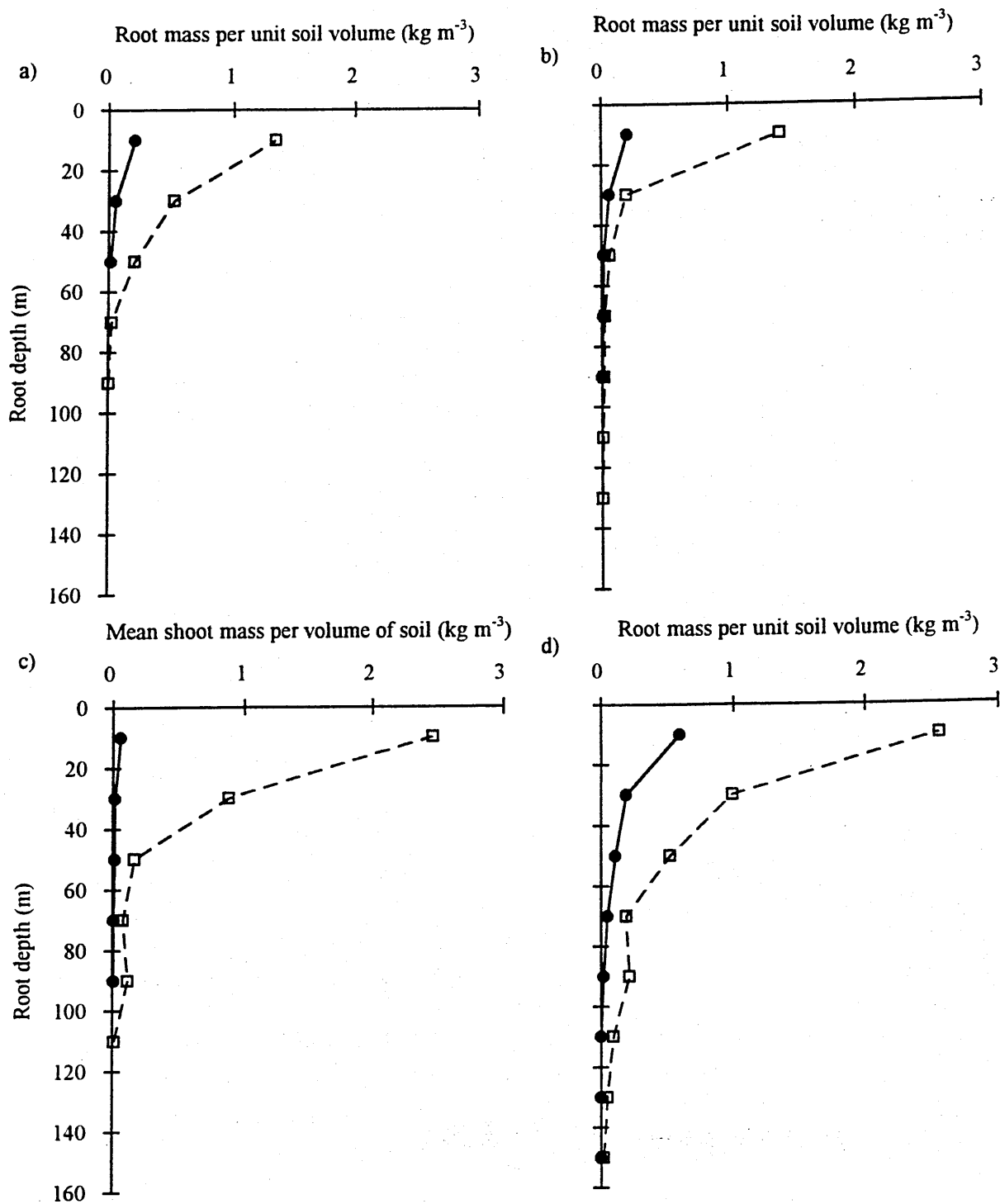


Fig. 6.6. Distribution of fine —●— and coarse —□— roots of clone 6/8 at a) Timbilil, b) Kipketer, c) Kaproret and d) Changoi during the whole plant harvest in April 1994.

Shoot:root ratios

Shoot to root ratios were lowest with clones having higher partitioning to roots i.e. clones TN14/3 and 6/8, and was largest in clone S15/10 ($P < 0.01$). There was a time trend with the mean ratios increasing from 0.19 in May 1992 to 0.78 in December 1993 and dropping to 0.65 in April 1994.

There were seasonal changes in shoot to root ratios, while interactions were only significant during the initial harvests (Table 6.3)

Table 6.3 *Clonal and site differences in shoot to root ratios during the initial (May 1992) and final (April 1994) field harvests.*

Site	May 1992					April 1994				
	S15/10	TN14/3	6/8	BB35	Mean	S15/10	TN14/3	6/8	BB35	Mean
Timbilil	0.24	0.16	0.19	0.14	0.18	1.36	0.58	0.50	0.45	0.72
Kipketer	0.35	0.12	0.09	0.11	0.17	1.20	0.46	0.43	0.67	0.69
Kaprorot	0.29	0.18	0.12	0.21	0.20	0.93	0.37	0.37	0.53	0.55
Changoi	0.23	0.15	0.18	0.28	0.21	1.45	0.63	0.44	0.60	0.78
Mean	0.28	0.15	0.15	0.19	0.19	1.23	0.51	0.44	0.56	0.65
CV%	5.1					11.6				
LSD ($P=0.05$)										
Sites	NS					0.0406				
Clones	0.0109					0.0406				
Interactions	0.0218					0.0811				

DISCUSSION

Responses to temperature

Harvest index

The values of HI reported in this study were found to range from 9 to 19%. Burgess (1992) reported similar results from young tea plants in Tanzania. The findings in this study are in sharp contrast to earlier reports from Timbilil on mature clone 6/8 by Magambo and Cannell (1981) as having a HI of 8%. By contrast, in Tanzania HIs of up to 24% have been reported for irrigated clone 6/8 (Burgess, 1994). These results seem to suggest that the HI of tea will continue to rise as tighter harvesting controls and better cultural practices are implemented. This assertion is confirmed in part by some of the results in this study on the differences in clonal increase in HI with time. Though the maximum point of HI may not have been reached by the close of this study, there are indications that the increase in HI is of a logistic form. Such analyses using logistic functions also indicate that lower altitudes may reach maximum harvest index much earlier than higher altitudes. The yield of 11000 kg ha⁻¹ reported by Oyamo (1992) for 16 year old clone S15/10 tea probably reflects this increasing HI and, assuming more than 95% light interception and a RUE of 0.4 g MJ⁻¹, gives an estimated HI of 37%.

The lack of significant linear relationships between seasonal changes in HI and mean air temperature are similar to those found in yield (Chapter 7). This suggests that the reactions to environmental stress may not always have been immediate, but could be felt after the stress. This suggestion is implied by the observed decline in HI with increase in air temperature (across the sites) during the cool wet season in 1993, where an opposite trend (increase with temperature) was expected. The other probable reason for this observation could be the relatively "late" dry season experienced in 1993, being felt more during March and early April as opposed to January to March (Fig. 3.8, Chapter 3). During the warm wet (1993) and warm dry (1994) seasons, relationships between HI and mean air temperatures were convex suggesting that temperature was not the main limiting factor.

Rooting depths

Variation in final roots depths between sites was mainly due to soil differences in temperature and soil water deficits. These root depths were, however, less than those reported by Burgess (1992) for similarly aged plants in Southern Tanzania. The climatic differences between the two regions could be the main contributor to the increased depths since temperatures in Southern Tanzania are higher than those at Kericho for a good part of the year. The prolonged drought and the differences in soil characteristics are also factors which need to be considered. The low temperature at Timbilil may also have contributed to the differential increase in shoot depth between sites. However the linear response of final root depths to mean air temperature contrasts with previous results of Carr (1971) and Fordham (1972), who reported that root growth was greater in cool seasons. This difference in root growth is contrasted by the greater proportion of dry matter partitioned to roots at higher altitudes shown by clones TN14/3, BB35 and S15/10. The results from this study seem to suggest that seasonal differences do not mean that root growth rates are greater at lower temperatures. This also implies that the long terms effects of temperature are more important in root growth than the short term seasonal fluctuations.

The rooting patterns (distribution) are similar to those reported by Burgess (1994) for clone 6/8. However there were differences between sites, due to both environmental and soil factors at each site.

Abscised leaf

Clonal differences in leaf abscission seem to suggest differences in response to water stress. Burgess (1992) also reported similar clonal differences in clones 6/8, BB35 and S15/10 in southern Tanzania. While there were indications of correlations with mean air temperature, these were however not significant, probably due to the large variability between clones at each site.

Responses to water stress

Harvest index

The fall in the rate of increase in dry matter and in particular partitioning to shoots during the dry season was as a result of the large soil water deficits experienced during these periods. Burgess (1992) and Othieno (1982b) also reported reductions in dry matter partitioned to leaf and tender stems during the dry season.

The changes in partitioning between shoots and roots during the dry season are similar to other reports on tea (Othieno, 1982b, Burgess, 1992) and in other crops (Linder and Rook, 1984). Clones with larger shoot:root ratios have been associated with high yields.

While there may not have been apparent effects of soil water deficits on HI, there were yield reductions during periods of water stress (Chapter 7). The reason for this apparent anomaly might be due to the overall rise in yield as the plants matured.

Rooting depths

There did not appear to be any effects due to water deficits on root depths, since the increases between harvests were more or less in keeping with equation 6.1. While the root depths was deepest at Changoi, which had larger soil water deficits (Chapter 3), this site also had higher temperature, confounding the effects of water stress. However stepwise regression analysis showed that the variance due to soil water deficits was not significant. Burgess (1992) also reported that soil water stress did not affect the maximum rooting depths of clones 6/8, BB35 and S15/10. Therefore partitioning to roots in tea seems less susceptible to water stress than to shoots. This finding agrees with general observations for other plants by Jones (1992).

Abscised leaf

By reducing the leaf area through leaf abscission, the plants reduce their transpirational losses. The larger amount of abscised leaf found in harvests at the end of warm dry seasons seem to suggest that the magnitude could be used as a relative indicator of stress. Clone 6/8 has been reported to be drought susceptible (Othieno, 1978; Burgess, 1992) but abscised less leaf than clone BB35. This loss of dry matter did

not seem to affect the ground cover of the plants (Chapter 5) indicating that it was the lower leaves in the canopy that abscised.

Partitioning to woody stems

Partitioning to woody stems did not appear to be influenced by soil water deficits. This is similar to other reports (Burgess, 1992), though as stated earlier, large variability may have obscured any responses to either temperature or water stress.

Genotype x Environment interactions.

Though there were GxE interactions in harvest indices, differences between sites and clones could not be explained by linear relationships with air temperature alone.

The significant clone x site interactions in temperature response found in maximum root depths is important when the overall control of plant growth and development by temperature is considered. Othieno (1982a) reported that the low soil temperatures experienced at Timbilil may be the cause of the observed lower yields. At three years old, the clones showed different slopes of root depth with temperature. Extrapolating to lower temperatures suggests that the clonal ranking in root depths would change when mean air temperature is close to 15 °C for clones BB35 and S15/10 and 13°C for clones S15/10 and 6/8 and even lower (6 °C) between clones 6/8 and BB35. However it is not known if the relationship between temperature and root depth would be linear over a range greater than that studied here.

Responses to other factors

The results from Kaproret are very different from those obtained at the other sites showing consistently less dry matter partitioned to harvested shoots, stems and coarse roots and more to fine roots. This response is common where plants are nutrient-stressed (Cannell, 1988; Squire, 1990). The high pH could have resulted in some of the micro-nutrients (e.g. manganese) becoming less available (Wild, 1988) though this could not be determined visually as in the case of Kipketer site. However the pH measured at this site was in the upper marginal range normally used for tea growing (Othieno, 1992).

Root depths were also about 30% less than expected indicating that there were severe physical impediment to root penetration. The greater soil bulk density at Kaproret may have been sufficient to result in this restricted root penetration and also in the reduced shoot:root ratio (Goss and Russell, 1977).

CONCLUSIONS

Clonal differences in dry matter partitioning in this study have been attributed to effects of both genotype and environment. Clone S15/10 had the largest harvest index and shoot:root ratio at all the sites, while the lowest were either 6/8 or TN14/3. Seasonal variations in harvest index could not be attributed to temperature or soil water deficits alone. The variation in harvest index with time seem to suggest that the potential yield of a crop could be assessed at an earlier stage (say 2 to 3 years) than is presently done.

The clones partitioned similar proportions to stem at all sites. Differences were observed in partitioning to tender stems. Clones S15/10 and BB35, which were the highest yielding in this study, also had the largest partitions to tender stems.

Differences in root depths between sites were attributed mainly to temperature, but those between clones were due to the different genotypes. The existence of a GxE interaction in root growth may be an important factor in clonal selection for temperature and water stress.

Poor soil conditions were observed to be the cause of the changes in clonal response to temperature in root growth and harvest index at Kaproret. The extent of such soil conditions in tea growing areas needs assessment.

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CHAPTER 7

YIELD AND YIELD DISTRIBUTION

INTRODUCTION

The main climatic variables influencing the yield of tea are temperature, the saturation deficit of the air and, through their influence on plant and soil water deficits, rainfall and evapotranspiration (Carr, 1972; Stephens *et al.*, 1992). In Kenya yield reductions of 200 kg ha⁻¹ annually have been observed in commercial fields for every 100 m rise in altitude, mainly due to associated temperature differences (Othieno *et al.*, 1992). Other climatic variables like wind stress (Carr, 1985) and low soil temperatures (Othieno, 1982) have also been reported to reduce tea yields. Of the known climatic variables in this region, hail is perhaps the least easily quantified and the most variable, causing damage and losses to the tea industry during most of the year (Carr and Stephens, 1992; Othieno *et al.*, 1992). There are most storms between May and October when yield losses can reach 140 kg ha⁻¹ (losses of about 10 to 20% annually) (Mwakha, 1983; Stephens *et al.*, 1992).

Yields from commercial estates in Kenya have risen over the last 40 years from about 1000 kg ha⁻¹ in 1950's to over 3500 kg ha⁻¹ in 1990's. The rise has been due to a combinations of factors including the planting of new (clonal) varieties and increased fertiliser inputs. Yield increases in the past 40 years can also be ascribed to technological changes and better management. Yields of up 11000 kg ha⁻¹ have been reported for clone S15/10 in a commercial field at 1900 m altitude (Oyamo, 1992).

The annual yield distribution in Kenya is relatively uniform (Stephens *et al.*, 1992; Carr and Stephens, 1992), with only short-term fluctuations induced by hail and by changes in temperature or soil moisture. Fluctuations in tea yield are determined by factors which affect the partitioning of the assimilate between the young shoots which make up the yield and the rest of the bush (Squire, 1979).

Tea yields have been related to three major variables: air temperature, soil water deficits and saturation deficits (Carr and Stephens, 1992). Saturation deficits (SD) above 2.3 kPa in Malawi (Tanton, 1982) and soil water deficits exceeding 40 mm in Tanzania (Stephens and Carr, 1989) have been reported to reduce yields. Clonal differences in

yield response to water stress have been observed (Othieno, 1978; Burgess, 1992). This variation is also affected by nutrition (Stephens and Carr, 1991).

Most work on tea yields and weather have been at single sites, Timbilil (Othieno *et al.*, 1992) in Kericho, Mufindi (Stephens and Carr, 1989, 1991; Burgess, 1992) in Tanzania and Mulanje (Carr and Stephens, 1992) in Malawi. There is therefore a need to evaluate tea clones of the same age at different sites.

There are large differences in yield reported for clones in Kericho (Othieno *et al.*, 1992) and from the same clones at different sites (Chapter 4). There is need to look at the reasons for these differences. This chapter reports on genotypic variability in yield and the effects of the main environmental factors at each site.

METHODOLOGY

Yield measurement

The soils and weather at the four sites used in this study have been described fully in Chapters 2 and 3. The design and layout of the experiment is described in Chapter 2.

It is important that yields obtained in the experiment should be comparable to those from similarly aged tea on estates. The harvest interval was therefore based on practise by neighbouring estates so that at Timbilil and Kipketer a 14 day interval was used, while at Kaproret and Changoi a 12 day interval was imposed. These intervals were kept constant throughout the year because annual temperature variations are only slight. Shoots were harvested by hand and pluckers were instructed to select only those with two leaves and a bud protruding above the canopy.

The tea was brought into bearing by continuous tipping as described in Chapter 2. The first tipping was done in January 1992 and this was continued whenever the plants had exceeded set heights (0.2, 0.3, 0.4 and 0.45 m) above the ground (Chapter 2). The first regular harvesting was done in December 1992.

Shoot dry mass:fresh mass ratio.

The Tea Research Foundation of Kenya uses a factor of 0.225 to convert green leaf mass to dry matter. However, this factor has been shown to vary with clone and soil moisture content (Burgess, 1992) and with fertiliser (Cloughley *et al.*, 1983) and

nutrition (Stephens and Carr, 1993). In this study, a sample of harvested shoots were weighed fresh and oven dried for 24 to 36 hours at 85-90°C and thereafter their dry mass was determined at each harvest. The clonal mean ratios between the shoot dry and fresh mass (Table 7.1) at each site were used to convert green leaf tea yields to made tea.

Table 7.1. *Mean clonal shoot dry mass:fresh mass ratios during December 1992 to June 1994.*

S15/10	BB35	6/8	TN14/3	TRF
0.22	0.20	0.19	0.24	0.225

Clone TN14/3 had the highest ratio, and 6/8 the lowest. These values are similar to those found by Burgess (1992). The seasonal changes in dry matter contents are discussed in Chapter 9.

Hail damage assessment

Hail damage to the experimental plots was recorded during the period May 1992 to June 1994. Normal estate practice was used to estimate the loss in crop as the difference between the actual yield and average yield of the previous three weeks harvest (Othieno *et al.*, 1992). The yield was deemed to have recovered when it reached or exceeded the average yield for two harvests preceding the hail event.

RESULTS

Total yields

The effect of clone and site on yield is reported from July 1993 to June 1994, during the third year after planting (Table 7.2). Changoi had a larger annual yield ($P \leq 0.001$) than the other sites, while Timbilil had the lowest. There were significant interactions between the clones and the sites, which are examined in Chapter 4. Clone S15/10

yielded more than the other clones ($P \leq 0.001$) while that of clone 6/8 the least, though this was not significantly different from the yield of clone TN14/3.

Linear relationships between yield and mean air temperature were found. The linear relationship between mean air temperature (July 1993 to June 1994) and mean yield for all clones was not significant ($r^2 = 76\%$) unless Kaproret was excluded ($r^2 = 99.9\%$). The annual increase in yield per unit rise in temperature was $326 \text{ kg ha}^{-1} \text{ y}^{-1} \text{ }^\circ\text{C}^{-1}$. The removal of Kaproret from the regression analysis can be justified since the soil conditions differed from the other sites and were atypical of the area (Chapter 2).

There were significant clonal differences in the yield response to air temperature. The yield of clone 6/8 varied linearly with air temperature ($r^2 = 99.4\%$) with a slope of $275 \text{ kg ha}^{-1} \text{ y}^{-1} \text{ }^\circ\text{C}^{-1}$. When the yields at Kaproret were excluded from the analysis, the yields of clone TN14/3 and clone S15/10 were also significantly related to mean air temperature with a slopes of 292 and $441 \text{ kg ha}^{-1} \text{ y}^{-1} \text{ }^\circ\text{C}^{-1}$ respectively.

Table 7.2. Mean clonal annual yields of dried tea (kg ha^{-1}), July 1993 to June 1994.

	S15/10	BB35	6/8	TN14/3	Mean
Timbilil	2340	1910	1610	1740	1900
Kipketer	2380	2200	1790	1910	2070
Kaproret	2230	2110	2090	1970	2100
Changoi	3760	2980	2550	2730	3000
Mean	2680	2300	2010	2090	
LSD	(P=0.05) CV% 6.6				
Sites	215.3				
Clones	107.1				
Interaction	285.0				

Fitting a linear response to temperature across the three sites unaffected by soil conditions enables an estimate to be made of yield losses experienced at Kaproret. These ranged from $1100 \text{ kg ha}^{-1} \text{ y}^{-1} \text{ }^\circ\text{C}^{-1}$ (50%) for S15/10 to only $192 \text{ kg ha}^{-1} \text{ y}^{-1} \text{ }^\circ\text{C}^{-1}$ (10%) for clone 6/8.

Yield distribution

Seasonal yields

Figure 7.1 shows the weekly yield distribution from December 1992 to June 1994 at two sites. Prior to December 1993, there was a general upward trend in weekly yields as crop cover increased. Maximum weekly yields were 220 kg ha⁻¹ at Changoi and just over 100 kg ha⁻¹ at Timbilil. The yield variations at each site seemed to follow a similar seasonal pattern except for a period at Kipketer site where there was a prolonged period of low yields (March to May 1993). Clonal variations in yields were also similar between the sites.

The period during this study was divided into seasons as described in Chapter 3 and by Stephens *et al.*, (1992). The period April to August is a cool wet season, giving way to a warm wet season starting in September to mid-November. December to March is normally a warm dry season where potential soil water deficits can reach 400 mm. There were significant differences between clones during each of the seasons. Clone S15/10 consistently had the higher yield ($P \leq 0.001$), and the lowest yielding clone was either clone 6/8 or TN14/3 (Fig. 7.2). The largest yields were at Changoi ($P \leq 0.001$), while Kipketer produced more than Kaproret ($P \leq 0.05$) and Timbilil ($P \leq 0.001$).

Interactions between seasons, clones and sites were significant. During the period December 1992 to March 1993 Changoi yielded more ($P \leq 0.01$) than the other sites. Yields were least at Kaproret but were no different from either Timbilil or Kipketer. However there significant ($P \leq 0.01$) differences between Kipketer and Timbilil. Only yields at Changoi were more than at the other sites ($P \leq 0.001$) during the cool wet period May to August 1993. Differences between Timbilil and Kaproret were not significant ($P \leq 0.05$) during the short warm wet season (September to November 1993). During the dry season of December 1993 to March 1994, the yields at Kaproret site were lower than the other sites ($P \leq 0.05$). These periods were characterised by low soil moisture and high temperatures (Chapter 3).

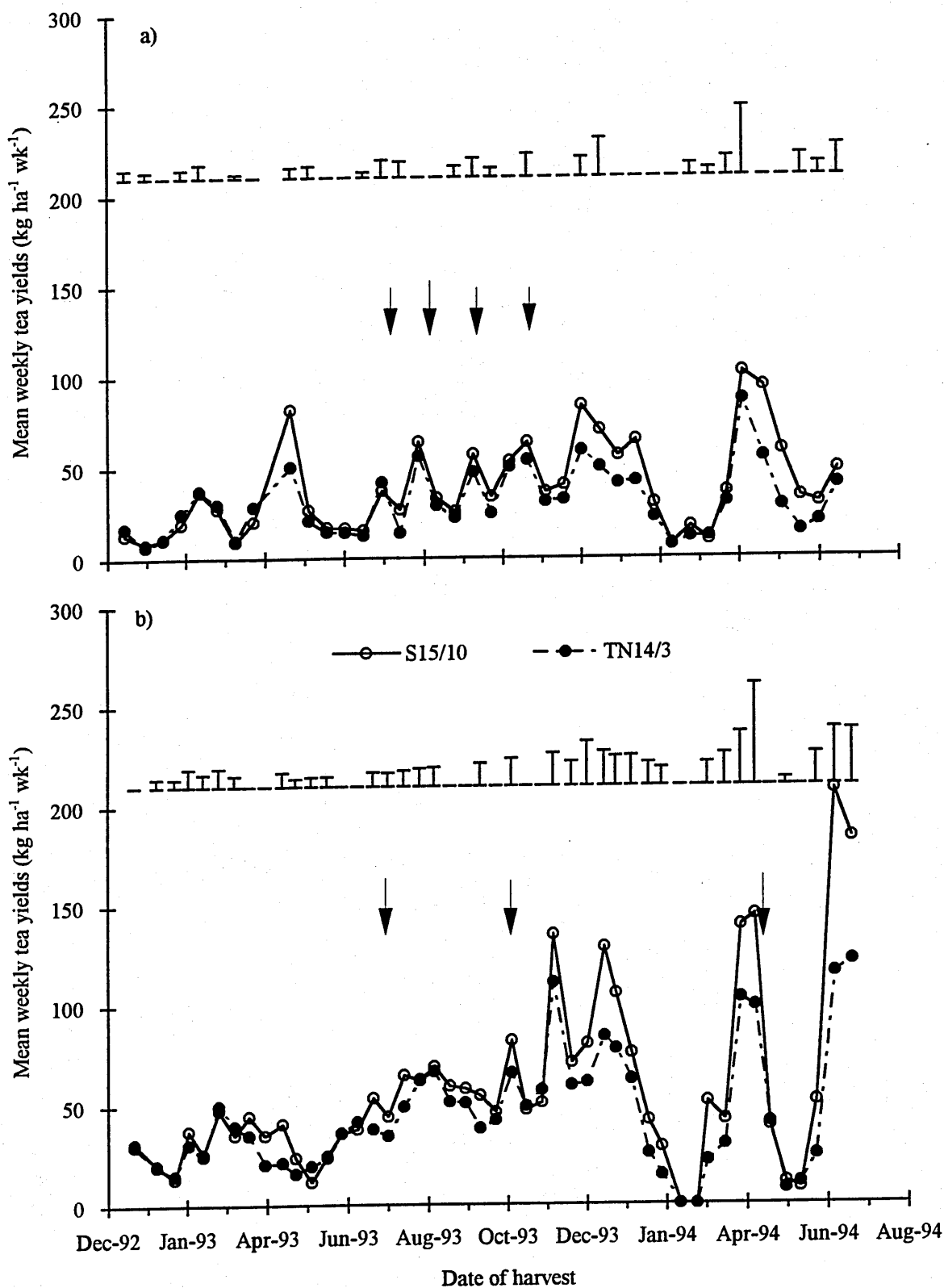


Fig 7.1. Weekly changes in yield of clones S15.10 and TN14/3 at a) Timbilil and b) Changoi during the period December 1992 to June 1994. Dates of hail damage are shown by arrows. LSD (0.05) are shown for clonal differences during each harvest. The other clones behaved in a similar pattern.

The seasonal yield responses to temperature and other environmental variables were further investigated using multiple regression. During the warm dry season of December 1992 to March 1993, clonal responses to mean air temperature across the sites were not linear, there was a trend in yield increase with arise in air temperature. Addition of SD, and SWD in a stepwise regression analysis improved the variance explained, showing that during the periods of water stress, the response to temperature is complicated by the presence of soil water deficits and dry air. Only during the cool wet season in April to June 1994 was there a significant response to temperature alone, with a mean increase in yield of $8 \text{ kg ha}^{-1} \text{ wk}^{-1} \text{ }^{\circ}\text{C}^{-1}$.

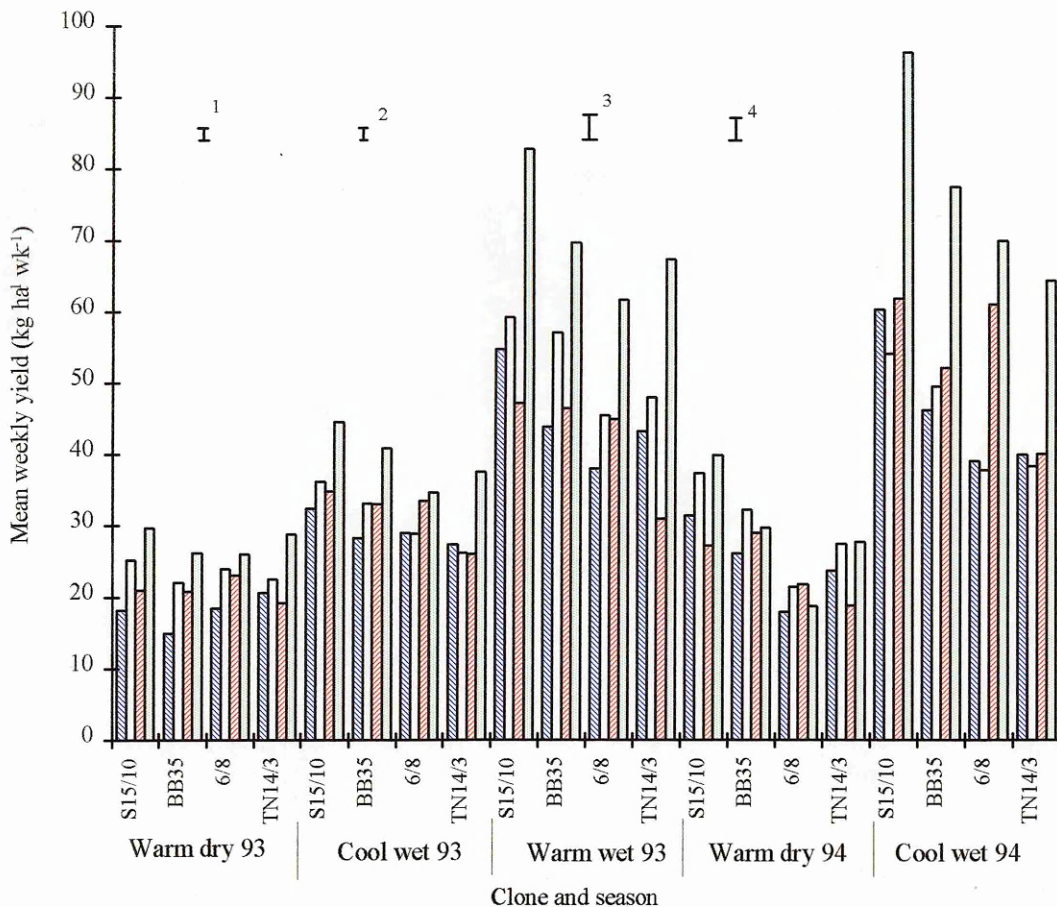


Fig. 7.2. Variation in seasonal tea yields of four clones at Timbilil , Kipketer , Kaproret  and Changoi  expressed as weekly yields. The LSD bars are for (1) season, (2) clones and sites, (3) interactions of season and clones, and season and sites; and (4) interactions for clones and environment all at $P=0.05$.

Though not significant the slope of response to temperature was steeper during the cool wet season as compared to either the warm dry or warm wet season.

During the warm dry seasons in December 92 to March 93 and December 93 to March 94, the response to temperature was significantly improved by addition of both maximum soil water deficits and mean afternoon saturation deficits in a stepwise regression. However, the responses of both clones BB35 and 6/8 were not significant even with addition of SWD or SD. These had more yield at Kipketer than any other site during the period December 93 to March 1994. During the warm wet season September to November 1993, though there appeared to be no response to temperature, removal of Kaproret site improved the linear relationships with air temperature, with a slope of $11.7 \text{ kg ha}^{-1} \text{ wk}^{-1} \text{ }^{\circ}\text{C}^{-1}$ ($r^2=99\%$). There were differences in clonal responses, ranging from 10.9 (clone 6/8) to $13.2 \text{ kg ha}^{-1} \text{ wk}^{-1} \text{ }^{\circ}\text{C}^{-1}$ (clone S15/10).

Due to the correlations between age of tea and yields, a stepwise regression involving age, temperature and the relative transpiration ratio, Tr , were found to be significant when the whole experimental duration was considered. The relative transpiration ratio was defined as

$$\text{Tr} = 1 - \text{Ta}/\text{To} \quad 7.1$$

Where Ta is the actual crop transpiration and To is the potential crop transpiration. The ratio Ta/To is usually regarded as an indicator of plant response to water stress (e.g. Squire and Callander, 1981). The regression equations were:

$$\text{S15/10: } 17.07(\pm 8.58)t + 11.59(\pm 2.68)T - 0.86(\pm 0.265)\text{Tr} - 174(\pm 42.8) \quad r^2 = 81\% \quad 7.2$$

$$\text{BB35: } 30.35(\pm 8.13)t + 6.76(\pm 2.2)T - 0.577(\pm 0.157)\text{Tr} - 142.2(\pm 40.5) \quad r^2 = 74\% \quad 7.3$$

$$\text{6/8: } 4.73(\pm 3.54)T - 47.8 (\pm 62.8) \quad r^2 = \text{NS} \quad 7.4$$

$$\text{TN14/3: } 20.37(\pm 8.64)t + 5.51(\pm 2.34)T - 0.471(\pm 0.166)\text{Tr} - 99.6(\pm 4.3) \quad r^2 = 57\% \quad 7.5$$

where t is the age of the tea in years, T is the mean air temperature and Tr is the relative transpiration ratio. There appeared to be no effect of Tr on clone 6/8, while effect of age in clones BB35 and TN14/3 were large.

Figure 7.3 shows the effects of SWD on yield at the two extreme sites (Timbilil and Changoi). At Timbilil (Fig. 7.3a), the critical SWD appeared to be about 30 mm, with no

apparent clonal differences in yield at lower SWDs. Above this SWD, there was a linear (NS, $r^2 = 0.87$ $n = 3$) decrease in yield of about $1.1 \text{ kg ha}^{-1} \text{ week}^{-1} (\text{mm SWD})^{-1}$ of water. At Changoi (Fig. 7.3b), significantly linear relationships ($P \leq 0.05$) between dry season yield and soil water deficit were found and there was no evidence of a critical deficit. The yield loss of varied between clones from 0.8 (clone 6/8) to $1.49 \text{ kg ha}^{-1} \text{ week}^{-1} (\text{mm SWD})^{-1}$ (clone BB35). The ratio of dry season yield to total transpiration also indicate a similar trend. Changoi had a larger ratio of $2.08 \text{ kg ha}^{-1} \text{ week}^{-1} \text{ mm}^{-1}$ of transpired water while at Timbilil the ratio was $1.01 \text{ kg ha}^{-1} \text{ week}^{-1} \text{ mm}^{-1}$ of transpired water.

Hail damage

Severe hail damage was recorded at Changoi and Kipketer towards the end of April, 1994. Fig. 7.4 shows the relative yield loss as a proportion of previous three weeks. At Changoi, the yield was reduced by 75% for five weeks following the damage, after which there was a period of rapid recovery during the next two weeks.

At Kipketer, the yield reduction was over 80% for seven weeks after the storm, and recovery was only starting to show in week eight.

The yield loss presented for these two sites may not entirely be due to hail damage since the storms occurred at a period when temperatures were falling, after the start of the rains.

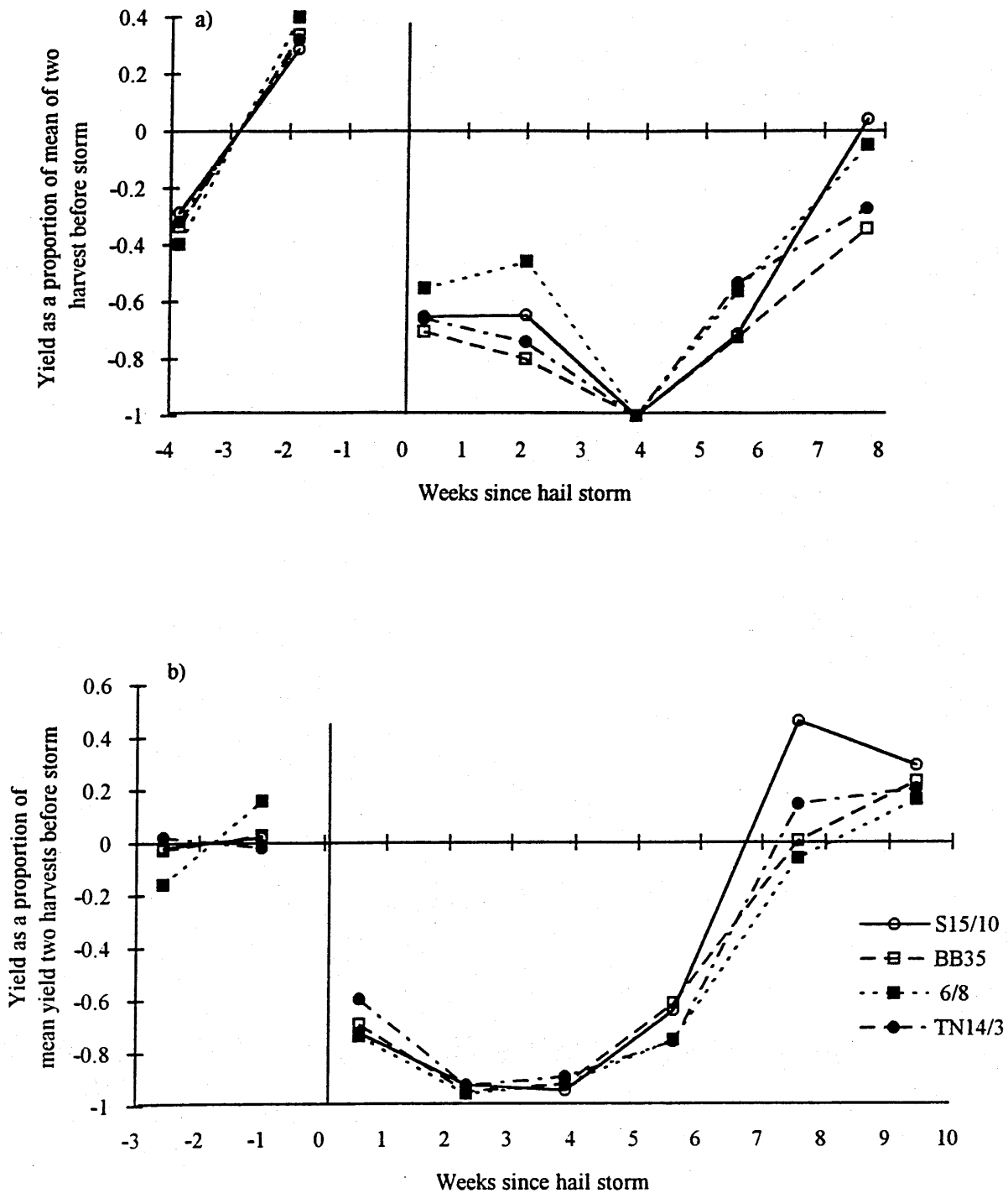


Fig. 7.4 Yield at each harvest as a proportion of mean yield two weeks before a hail storm at a) Timbilil and b) Changoi, during April to June 1994. The hail storm occurred within one week at the two sites.

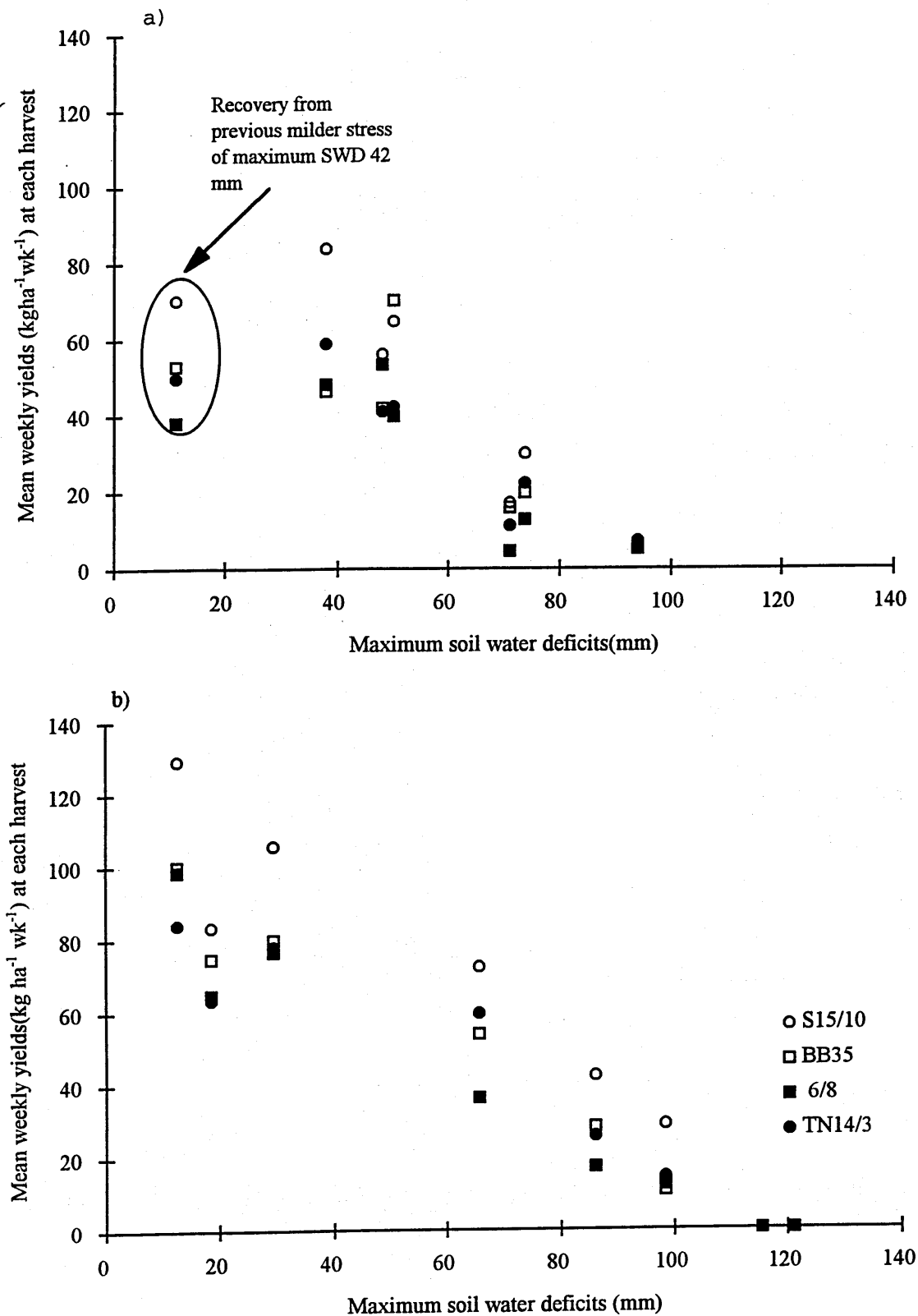


Fig. 7.3. Relationships between mean weekly yields at each harvest and maximum soil water deficits at a) Timbilil and b) Changoi, during the 1994 drought (December 1993 to February 1994). Zero yield denotes no crop could be harvested on a scheduled date due to severe water stress.

DISCUSSION

Annual yields

The annual yields (2550 to 3760 kg ha⁻¹) three years after planting at Changoi, are similar to those reported by Burgess (1992) for irrigated clones BB35, 6/8 and S15/10 in the southern highlands of Tanzania in their third year. However at Kaproret, Kipketer and Timbilil, yields were lower (Table 7.2). The higher temperatures experienced in Tanzania, irrigation and bringing to bearing by pegging may have all contributed to larger yields. In this study no attempt was made to irrigate the tea even though at some of the sites (Changoi and Kaproret) actual soil water deficits exceeded 100 mm (Chapter 3). The ranking of clones BB35 and 6/8 differed from that reported by Burgess (1992). In this study, clone BB35 had more yield at each site and season than clone 6/8. The reasons for these differences in ranking between the two tea growing areas are not clear but seem to suggest that clone BB35 is more suited to Kericho.

The largest yield recorded at Kericho is that of clone S15/10 near the Kaproret (Oyamo, 1992) was three times the largest in this experiment, presumably because the tea was still young.

Seasonal yields

Clonal differences in seasonal yields were similar to those reported for young tea in Tanzania (Burgess, 1992). Clone S15/10 nearly always had more yield than the other clones at each site. However, there were seasonal differences in ranking between clones BB35, 6/8 and TN14/3. That the lowest yield during the warm dry season was that of clone 6/8 may be due to its sensitivity soil water deficits (Othieno, 1978).

Environment

Responses to temperature

Annual

When the Kaproret site, where soil physical and chemical conditions limit yield, was excluded there was a linear yield response to temperature in all clones of between 275 and 441 kg ha⁻¹ y⁻¹ °C⁻¹ for clones 6/8 and S15/10 respectively. These responses are greater than those reported for seedling tea on estates in Kericho (Othieno *et al.*, 1992)

perhaps because there were no differences in ground cover and therefore light interception. This might explain also why TN14/3 showed a greater response than that observed by other authors (Obaga *et al.*, 1988; Wachira *et al.*, 1990; Squire *et al.*, 1993).

Othieno *et al.* (1992) also suggest a non-linear response because ambient temperatures at higher altitudes in Kericho are very close to the base temperature for growth. It was not possible to confirm their assertion since in this experiment, there were too few observations to fit a curve. In addition, the base temperatures reported here (Chapter 8) are lower than the assumed value of 12.5 °C used by Othieno *et al.* (1992). Using a lower base temperature of 8 °C in their calculations results in a more linear response to temperature over the altitude range of 1800 to 2200 m.

Seasonal

Kericho is traditionally regarded as an area with a very even yield distribution. However, in this experiment there were large within-season fluctuations in yield. In addition, though there were seasonal responses to air temperature, these were confounded by the changes in soil water and saturation deficits. Higher temperatures were usually associated with larger water deficits in both soil and air (Chapter 3). The mean response to temperature during the cool wet season of 1994 was similar to that of total yield in clone S15/10. Annual responses to temperature can therefore be expected to vary depending on the severity of water stress during the dry season as shown by Othieno *et al.* (1992).

Yield response to water stress

The lack of a significantly linear yield response to SWD at Timbilil may have been due to the relatively shorter period of stress as compared to Changoi. Some rains during January and late February shortened the period of stress. However the rate of yield loss was lower than the values reported by Burgess (1992) and Stephens and Carr (1991). For Changoi, the yield losses with increasing soil water deficits were slightly greater than those reported by Stephens and Carr (1991). The reason for this difference may be due to the presence of saturation deficits above 2.3 kPa in Kericho during the dry

seasons (Chapter 3) whereas in southern Tanzania the SD rarely exceeds 1.8 kPa (Stephens and Carr, 1991). This could have restricted yield further resulting in larger slopes (rate of relative yield loss with SWD above critical deficits). The differences between Timbilil and Changoi also might be due to the differences in rooting depths at the two sites, the deeper roots at Changoi site implying larger deficits in the root zone than at Timbilil. Though the yield responses to water stress in this study are reported to be linear, these may however be confounded by the fact that the yield was still rising and the peak before the onset of water stress (Fig 7.1) may have been due to other factors. However the yield losses due to water stress were estimated at 14% for Timbilil, rising to 20% at Changoi. The yield:transpiration ratio reported in this study for Timbilil is much lower than those reported for the same clones in Tanzania (Stephens and Carr, 1991; Burgess, 1992), but are similar to the mean value for Changoi. Since there was no control of soil water content in this study, it was difficult to arrive at more accurate conclusions as to the water use at Kericho.

Response to hail and other factors

Though the reduction in yield at both Changoi and Kipketer occurred after a severe hail damage, there may be other factors which are equally important during this period. The hail damage occurred after a peak in yield (Fig. 7.1), after the plants had recovered from stress (SWD), hence this could have also been the beginning of a Fordham cycle (Fordham and Palmer-Jones, 1977). This seems to be borne out by the drop in yield at Timbilil and Kaproret even though no hail damage was reported for this period. Temperatures were also falling during this period, after the start of the rains, though only slightly.

The yields at both Kipketer and Changoi were larger at 7 weeks after the hail damage. While this could be due to compensatory effects after a stress, the yields were still increasing, since the tea was in their 3rd year and evidence of a yield plateau was not yet apparent.

The occasional hail damage at each site, mostly with negligible yield losses, may have also induced changes in partitioning to shoots which affects relationships with temperature.

The other major limit to yield appeared to be the soil conditions at the Kaproret site. The tea growing area in Kericho is dotted with "hut-sites", such as the Kaproret sites, which are characterised by high pH and compact soil. Little work has been carried out to quantify the likely yield reductions in these areas, nor has the total area under hut sites been quantified. However it is interesting to note that yields were 190 to 1100 kg ha⁻¹ below expected indicating that it may be worthwhile investigating methods of rehabilitating these sites. The low yield at Kaproret may have been due to effects on the shoot to root ratio (Chapter 6), caused by compaction and high pH (Chapter 2), and in annual crops such as barley, shoot extension is severely reduced by soil compaction (Goss and Russell, 1980).

On the other hand, low ground cover also contributed to the lower yields at Kaproret. The ratio between annual yields to mean ground cover show that the difference between clones and sites are reduced. This points to ground cover as being a one of the key factors determining yield. This could be due to the effects of ground cover on shoot population density (Chapter 9).

Proportional contribution to yield.

The yield of a crop can be analysed in terms of the product of incident solar radiation, S_0 , fractional interception, f_s , conversion efficiency, ϵ_s , and the harvest index, HI (Squire, 1985).

$$Y = S_0 \cdot f_s \cdot \epsilon_s \cdot HI$$

Since radiation in the tropics is high, the local variations may not be significant in influencing yield directly, and for a closed tea canopy, f_s will be large and uniform Squire (1985), though this is not the case for young tea. While there was only a difference of 12% in incident solar radiation between Timbilil and Changoi, a difference of 21% in ground cover (Chapter 5) and up to 65% in HI (Chapter 6) were the main contributors to yield differences. Squire (1985) proposed that yield improvements in tea would come from either an increase in RUE or HI. Results from this study suggests that RUE is

conservative with temperature (Chapter 5). This means that yield differences between sites is due mainly to HI and ground cover. In mature tea however, ground cover is at maximum (95-99%), which leaves only HI. Indeed the recently reported high yield of clone S15/10 at Kaproret could only be possible with HI of about 37%. While this may seem high for tea, the reports from Tanzania of 24% (Burgess, 1994) for clone 6/8 yielding 6 t ha^{-1} , suggests this may not be unreasonable.

On a shorter time scale yield is determined less by the amount of radiation intercepted and more by the number and size of shoots available to be harvested from the bush. Chapters 8 and 9 examine the effects of genotype and environment on short-term yield fluctuations through their influence on shoot extension and development (Chapter 8) and shoot population density and mass (Chapter 9).

CONCLUSION

Clones responded differently to changes in environment. The yield response to altitude was mainly due to the greater ground cover at the lower altitudes which enabled interception of more solar radiation. This however was not true for all the clones. Clone TN14/3 had the greatest ground cover but was among the lowest yielding. The differences not attributable to ground cover appear to have been due to genotypic differences in partitioning of dry matter. Indeed the harvest index of clone TN14/3 is the lowest (Chapter 6). Clone S15/10 also had large ground cover, which in conjunction with harvest index produced the highest yield. Though a linear response to temperature could be found for all the clones if Kaproret site were excluded from the analysis, the data set used in this study is too small to make any recommendation as to the use of such relationships for yield prediction.

The lower yields reported in this study, compared to a similar study on irrigation in Tanzania, show the advantage of early establishment through pegging, irrigation to control soil water deficit and importance of soil temperature. The potential yield at Kericho could be higher if these factors were controlled since harvesting, unlike in Tanzania, is continuous throughout the year.

The high yield of clone S15/10, even during periods of stress, underscores the importance of this clone even in areas of marginal rainfall or low temperature. However,

the limited range of environments used in this study means that such a conclusion may not be widely adaptable.

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CHAPTER 8

SHOOT EXTENSION AND DEVELOPMENT

INTRODUCTION

Shoot extension and development rates are important aspects of growth in tea which are dependent on temperature variations. In Kenya, shoot extension rates in tea have been found to decrease with increasing altitude (Mwakha, 1985). Clonal variability in tea shoot extension with altitude (Obaga *et al.*, 1988; Obaga and Ng'etich, 1989) and with temperature (Stephens and Carr, 1990) has also been indicated.

Temperature affects the rates of shoot extension and development. In theory above a base temperature T_b , the rates of extension and development increase linearly with temperature, until an optimum is reached. Linear dependence of shoot extension on temperature is controlled by the effect on cell differentiation and expansion. The base temperature, is a threshold temperature below which no extension (T_{be}) or development (T_{bd}) occurs. Thermal time, Θ is the integral of time (days) and temperature above T_{be} or T_{bd} . In Malawi, a thermal time requirement of 475 °C d ($T_{be} = 12.5^\circ\text{C}$) was suggested for a bud released from apical dominance to reach three leaves and a bud (Tanton, 1982).

The effects of temperature on shoot growth can be separated into relationships with rates of development and those with extension (Squire *et al.*, 1993). The reciprocal of the duration to plucking (shoot development) increases linearly with a rise in air temperature T above a base for development (T_{bd}) with a slope:

$$\frac{1}{t_f} - \frac{(T - T_{bd})}{\Theta} \quad 8.1$$

where Θ is the thermal time required for the shoot to extend to harvestable stage. The rate of extension during t_f (duration of extension), RE, similarly increases with temperature T above a base temperature for extension T_{be} given by

$$RE = \rho(T - T_{be}) \quad 8.2$$

where ρ is slope of the linear relationship between rate of shoot extension and temperature.

The shoot length at plucking is given by:

$$L_f = \rho \Theta \frac{\sum(T - T_{be})}{\sum(T - T_{bd})} \quad 8.3$$

L_f will depend only on ρ and Θ and not temperature if the base temperature for extension and development are similar ($T_{be} = T_{bd}$).

Clonal differences in base temperatures for shoot extension and development have been reported (Burgess, 1992; Stephens and Carr, 1990). Clone TN14/3 has been reported to have a low base temperature for extension of 7°C (Obaga *et al.*, 1988) while that for clone BB35 is between 11.1°C (Burgess, 1992) and 14.8°C (Smith *et al.*, 1990). Both T_{be} and ρ have been found to be different between clones (Stephens and Carr, 1990; Burgess, 1992).

Shoot development rates of a shoot can be defined as the reciprocal of the duration from the removal of apical dominance to harvesting. Stephens and Carr (1993) found that between 15 to 20°C, the time taken for axillary buds of clone 6/8 released from apical dominance to develop three leaves and a bud varied from 65 to 95 days. They reported the base temperature for shoot extension in clone 6/8 to be 10°C, 2 to 3°C higher than that for development. Similar findings were reported by Burgess (1992) who also noted genotypic differences in T_{bd} . This implies that shoot lengths in these clones are influenced by temperature since shoot development can continue even below T_{be} .

The amount of thermal time required to overcome the initial phase in shoot growth is almost two-thirds of the total and is clearly a major limitation to yield in current management practices (Squire, 1979). The base temperature of a clone is an important selection criteria especially at high altitudes, where temperatures are close to T_{bd} or T_{be} .

Thermal time analysis can be exploited as a management tool in crop production to predict harvest dates. In tea, the use of thermal time analysis on shoot extension or development would be an important tool in prediction of time of harvest.

Water deficits control plant growth through their effects on cell expansion. Shoot extension rates in Tanzania were found to be limited by soil water deficits in excess of 40 - 100 mm (Carr, 1974; Stephens and Carr, 1993).

Vapour pressure deficits of the air are also important in determining shoot extension rates. Squire (1979) reported correlations between shoot extension in tea and SD (at 14.00 h). He suggested that seasonality of shoot growth in tea can be explained largely by effects of temperature and humidity. Later Tanton (1982) reported that there was a linear decrease in shoot extension rate when saturation deficits rose above 2.3 kPa.

The results presented in previous chapters have shown that the yield of tea shows large differences with environment and genotypes. This chapter describes the contribution of shoot extension and development to these yield differences.

METHODOLOGY

Shoot selection and tagging

Actively growing shoots with at least two leaves and a bud were selected, plucked at two leaves and a bud and the remaining stem butt tagged. After each tagging, the bud lengths were measured. During June 1992 and September 1993, 10 buds, similar to those tagged, were removed and cut longitudinally and length of the enclosed shoots determined using a vernier caliper (± 0.1 mm). The ratio of enclosed shoot length to bud length was used to calculate the actual shoot lengths measured before bud break (Table 8.1).

On each tagged shoot, the length of the topmost axillary bud was measured at 3 day intervals until it had unfurled the first leaf. Thereafter the length of the shoot from the axil to the base of the terminal bud was measured until three true leaves had emerged at which point it was plucked. A total of 24 shoots per clone were tagged at each site during one "generation". For the duration of the study period, a total of six shoots generations were monitored. Each time shoot lengths were measured, the number of unfurled leaves was also counted.

A number of models have been used to describe shoot growth in tea. Squire (1979) used a two stage linear model, while Tanton (1982) used an exponential model to describe shoot growth in Malawi. On the other hand, Smith *et al.* (1990) used both Gompertz and logistic models to describe shoot growth. These models all show shoot growth as moving from a slow phase of development from release of apical dominance to the opening of the first leaf, followed by a rapid expansion phase. Both the

exponential and two stage linear models however, cannot describe the decline in expansion after a number of leaves are opened when shoots go dormant. In addition, estimating the point at which the slow phase changed into the rapid expansion phase in the two stage linear model is difficult, since the date of first leaf opening is required. This was not possible in the experiment since the resolution in measurement was three days. Burgess (1992) in comparing three models, found that the exponential, Gompertz and logistic models overestimated the initial shoot extension rates.

Shoot extension was modelled using exponential function, chosen due to its simplicity and few parameters required. The exponential form used by Stephens and Carr (1993) was adopted:

$$L_t = L_o e^{bt} \quad 8.4$$

where L_t is the shoot length at time t (days since release from apical dominance) and L_o is the initial shoot length (mm), b is the relative shoot extension rate ($\text{mm mm}^{-1} \text{d}^{-1}$). This model accounted for between 92 to 97% of the variation in shoot extension. Both Gompertz and logistic models, though explaining more than 98% of the variation in shoot extension, estimated the final shoot lengths poorly. This was due to lack of enough data during the decline of shoot expansion, since in practice, shoots are harvested before this phase.

L_o and b were subjected to analysis of variance to determine the effect of clone, site and generation. Similar analyses were also performed on final shoot length at harvest (L_f) and the duration of shoot growth to harvest (t_f) which is also termed the shoot replacement cycle duration.

Thermal time and shoot extension rates

The thermal time requirement for shoots to reach harvestable size was estimated by integrating the temperature above a range of base temperatures for the duration of shoot extension. These were analysed by regression with relative extension rates to determine the actual base temperature for extension (Burgess, 1992). The intercepts from regression analysis of relative extension rates and thermal time requirement were then plotted against the estimated base temperatures. The base temperature for a clone was determined as the point at which the curves intercepted the x-axis.

RESULTS

Bud to shoot lengths ratios.

The ratio of bud to enclosed shoot lengths were found to be significantly different between clones. The effects of season could not be established since there were only two samplings. Differences between sites and interactions were however not significant. Clone S15/10 had the largest ratio, while the lowest was clone BB35 during the two periods (Table 8.1).

Table 8.1 *Ratio shoot to bud lengths of enclosed shoots, during two periods.*

		Bud to shoot length ratio	
		June 1992	September 1993
Clone	S15/10	0.324	0.352
	BB35	0.295	0.310
	6/8	0.319	0.334
	TN14/3	0.308	0.327
LSD (P=0.05)		0.026	0.019

Shoot lengths

Initial shoot lengths.

There were significant differences in initial shoot lengths between the six generations studied. Shoots initiated during the cool wet (June 1992, May 1993) and warm dry (February 1993) periods had smaller ($P \leq 0.05$) shoots sizes (0.3 to 0.5 mm) than those in the warm wet period (0.9 to 1.2 mm). Differences between clones were also significant, clone S15/10 had longer ($P \leq 0.05$) shoots than clones 6/8 and BB35 (Table 8.2). Shoots initiated at Changoi were always longer ($P \leq 0.05$) than those at both Timbilil and Kipketer.

The relationship between initial shoot lengths and temperature varied with season (Fig 8.1a). The ranking of the clones was not consistent at the four sites in all seasons

and regressions for individual clones were not significantly different from each other. A regression was therefore fitted to the pooled data. During the cool wet season, there was a strong response to temperature of $0.28 \text{ mm } ^\circ\text{C}^{-1}$ ($r^2 = 87\%$, $n = 16$) but during the warm dry season, the slope of this relationship was less than $0.07 \text{ mm } ^\circ\text{C}^{-1}$ (not significant).

Table 8.2. *Initial shoot lengths: comparison of measured and fitted data between June 1992 and December 1993. Data are the means for all four sites for all six generations.*

Clones	Initial shoot lengths (mm)	
	Measured	Calculated
S15/10	1.2	1.3
BB35	0.9	0.7
6/8	0.8	0.8
TN14/3	1.2	1.1
LSD ($P=0.05$)	0.28	0.19

Shoot lengths at harvesting

Shoots lengths at harvest (with three leaves and a bud) varied with generation, clones and sites. As with initial shoot lengths, shoots released from apical dominance during the cool wet periods in June 1992 and during the warm dry period from February to April 1993 were shorter ($P \leq 0.05$) at harvest than those growing during the warm wet periods. There were clonal differences, with clone S15/10 and BB35 having longer shoots ($P \leq 0.05$) at plucking than clone 6/8. Shoots at Changoi and Kaproret were always longer ($P \leq 0.01$) than at both Kipketer and Timbilil. The largest differences in shoot lengths at plucking between the sites occurred during the cool wet season ($P \leq 0.01$).

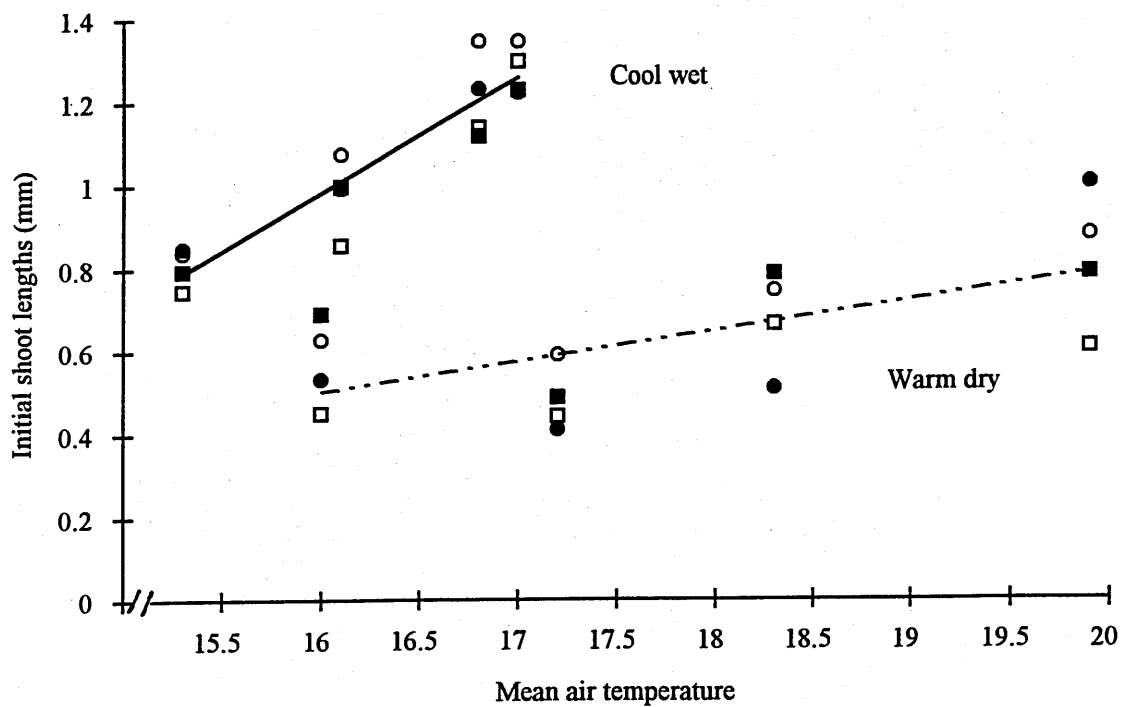
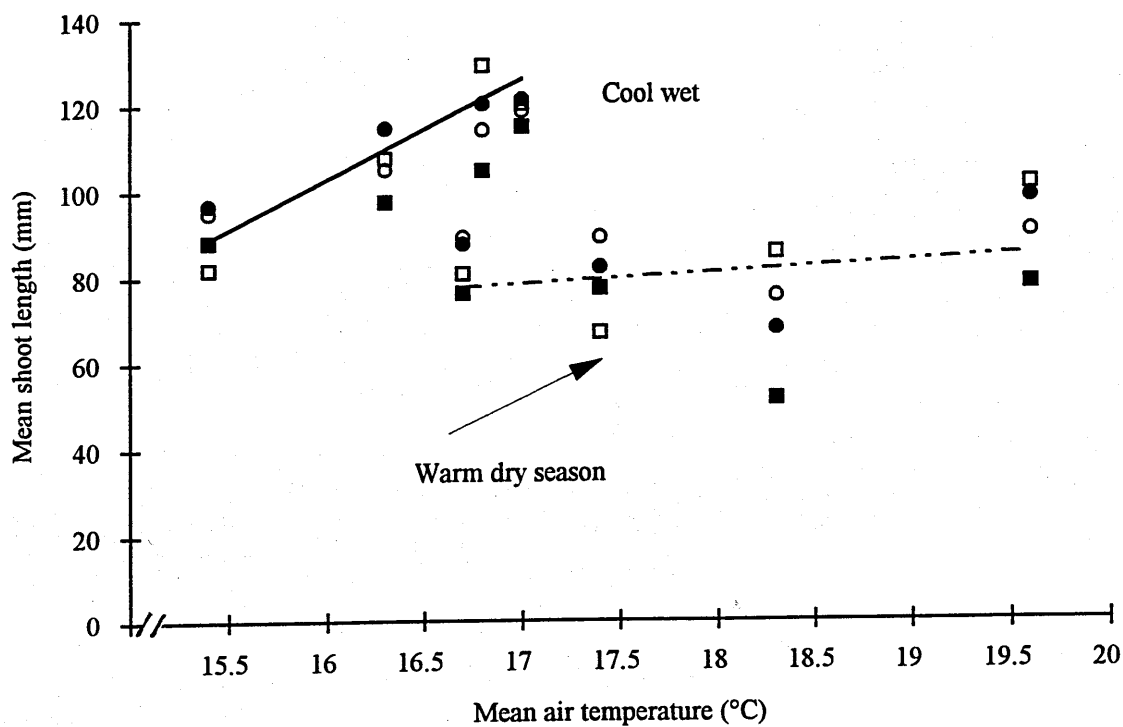


Fig. 8.1 Relationships between shoot lengths and mean air temperature for a) initial shoot lengths and b) harvestable shoots of clones S15/10 (○), BB35 (□), 6/8 (■) and TN14/3 (●), during cool wet season (1992) and warm dry season (1993).

Interactions between generations, clones and sites were significant. Fig. 8.1b shows the variations in mean shoot lengths at harvest at each site with mean air temperature. Clones S15/10 and BB35 had the longest shoots ($P \leq 0.01$) at Changoi. The shoots of clones 6/8 and BB35 were shortest during February to April 1993, reaching an average of 70 mm when they had three leaves and a bud. During this period, afternoon SDs were high (more than 2.3 kPa at Changoi) and the mean shoots lengths at Changoi were between 10 to 30 mm shorter than in the cool wet season, a 27% reduction. The lowest such reduction occurred at Timbilil, where the difference in mean shoot lengths at plucking during the periods December 1992 to February 1993 and March 1993 to May 1993 was 5 to 10 mm (90 to 80 mm), a 11% reduction.

The rate of harvestable shoot length increase with mean air temperature across the sites varied from $18.7 \text{ mm}^\circ\text{C}^{-1}$ ($r^2 = 82\%$) during the cool wet season, to $2.6 \text{ mm}^\circ\text{C}^{-1}$ during warm dry periods.

Shoot development

There were clonal differences in shoot development rates between generations (Fig. 8.2). Shoots at Changoi developed faster ($P \leq 0.001$) than at the other sites during the cool wet seasons (June to August 1992 and May to August 1993). However during the warm dry seasons, shoot development rates to three leaves and a bud were similar among the sites. The fastest development rates were those of clone BB35 at Changoi during the 1992 cool wet season (0.0189 d^{-1}). Linear relationships between shoot development rates and mean air temperature were strong with a response of $0.0035 \text{ d}^{-1}^\circ\text{C}^{-1}$ ($r^2 = 85\%$) during the cool wet season in 1992 (Fig. 8.2). There was a reduction in the temperature response during the warm wet seasons ($6 \times 10^{-4} \text{ d}^{-1}^\circ\text{C}^{-1}$).

Regression analysis of the reciprocal of shoot growth duration with mean air temperatures was used to calculate base temperatures for development. Clone TN14/3 had the lowest base temperature for shoot development while clone BB35 had the highest (Table 8.4). The slope of development rates with mean air temperature are given in Table 8.5. Both clones S15/10 and TN14/3 had similar slopes.

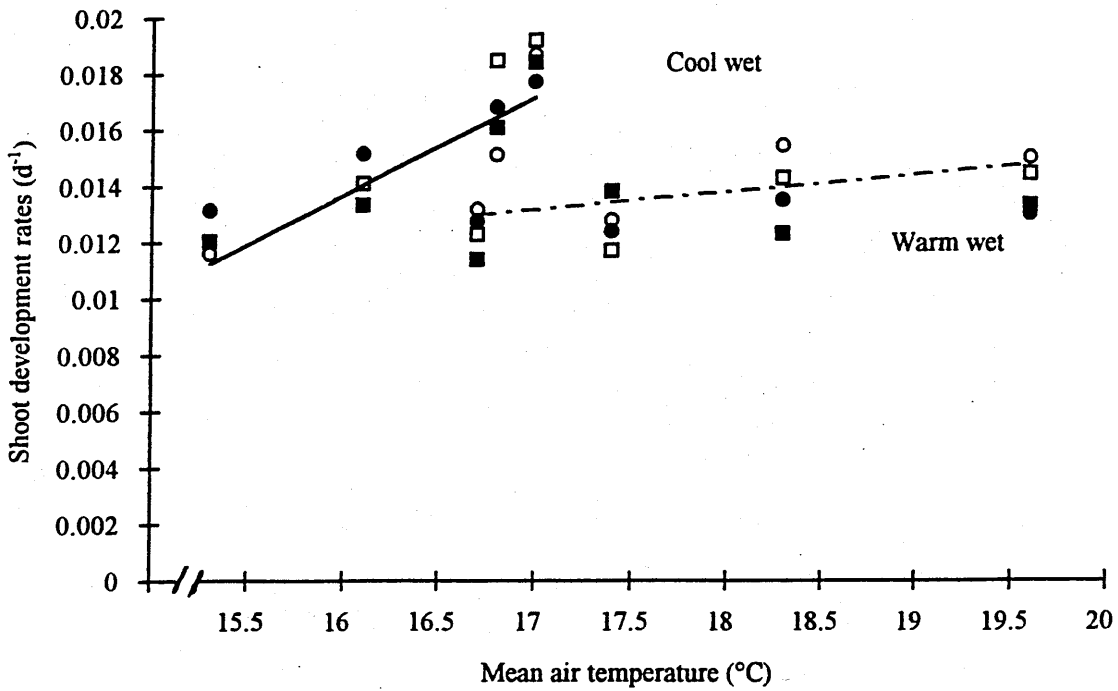


Fig. 8.2. Relationship between shoot development rates (d^{-1}) to three leaves and bud of clones S15/10 (○), BB35 (□), 6/8 (■) and TN14/3 (●) and mean air temperature across the four sites during cool wet (—) and warm wet (- - -) seasons in 1992.

Table 8.3 Relationships between shoot development rates ($1/t$) and mean air temperature from release of apical dominance to harvesting at three leaves and a bud.

Clone	Slope ρ_d ($d^{-1} \text{ } ^\circ\text{C}^{-1}$)	Intercept (d^{-1})
S15/10	0.00164(± 0.00035)	-0.0159(± 0.0023)
BB35	0.00173(± 0.00062)	-0.0186(± 0.0042)
6/8	0.00175(± 0.00031)	-0.0147(± 0.0019)
TN14/3	0.00164(± 0.00065)	-0.0122(± 0.002)

Table 8.4 *Estimated base temperatures for shoot development using mean air temperature from release of apical dominance to harvesting at three leaves and a bud. The upper and lower 95% confidence limits are also shown.*

Clone	Lower 95%	Mean	Upper 95%	r ² (%)
S15/10	5.7	7.9	10.3	79
BB35	7.7	10.4	11.9	64
6/8	5.9	8.0	8.9	78
TN14/3	4.5	6.1	9.1	82

Thermal time

The thermal durations differed between shoot generations. During the cool wet season in 1992, thermal durations ranged from 340 to 380 °C d for clone S15/10 (Fig. 8.3). There were no differences in the relationship between shoot lengths and thermal time during the cool wet and warm wet season at Timbilil, and the cool wet season at Changoi. A single exponential response was fitted to this pooled data of the form:

$$L_t = 0.819e^{0.0142 \cdot \theta} \quad r^2 = 96\% \quad 8.5$$

However during the 1992 warm wet season, the thermal duration increased to 580 °C d at Changoi, while there was no appreciable increase at Timbilil. During this period the exponential response at Changoi took the form:

$$L_t = 0.98e^{0.0093 \cdot \theta} \quad r^2 = 98\% \quad 8.6$$

The variations at the other sites were similar except for Kaproret site which tended to have larger values during warm dry seasons (780 °C d for clone 6/8 during March to May 1993).

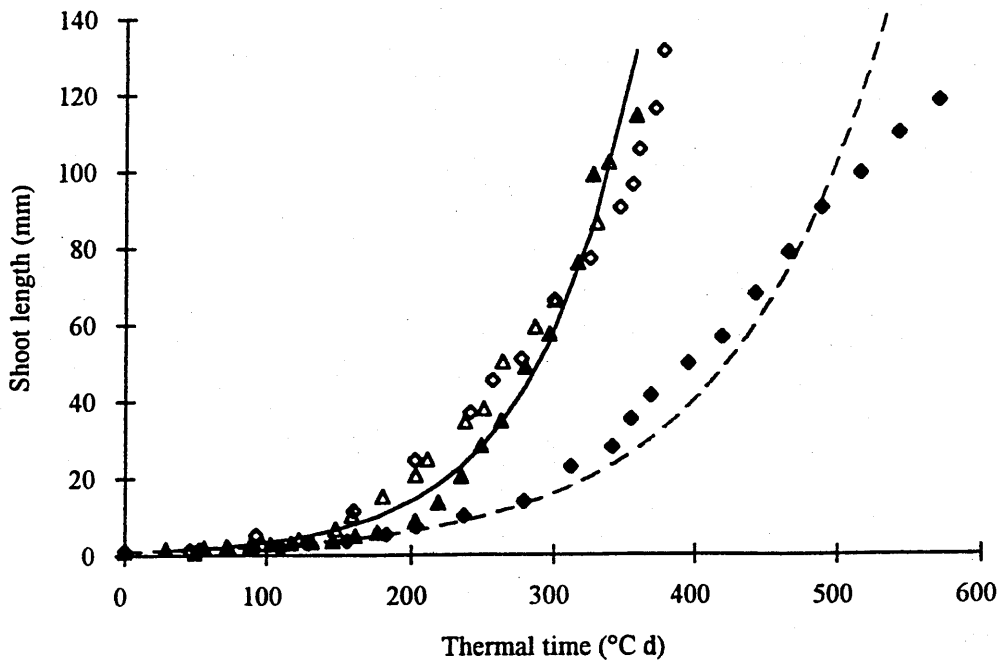


Fig. 8.3. Relationship between shoot length and thermal time ($T_b = 10^\circ\text{C}$) of clone S15/10 at Timbilil (Δ) and Changoi ($\diamond$) during cool wet (open symbols) and warm wet (filled symbols) seasons in 1992. The curves are fitted exponential lines.

Shoot extension rates.

Relative shoot extension rates varied with generation, clone and site. Shoots initiated during the cool wet periods (June to August 1992 and May to August 1993) had the lowest extension rates (reaching $0.05 \text{ mm mm}^{-1} \text{ d}^{-1}$). The largest relative extension rates were found in shoots growing during the period September to November 1992 (0.06 to $0.09 \text{ mm mm}^{-1} \text{ d}^{-1}$).

There were clonal differences in the mean RER, both clones TN14/3 and BB35 had greater RER ($P \leq 0.05$) than clone 6/8 and S15/10 (which were not significantly different from each other). The mean maximum relative extension rates fell from $0.09 \text{ mm mm}^{-1} \text{ d}^{-1}$ for shoots released from apical dominance during September 1992 at

Changoi to $0.03 \text{ mm mm}^{-1} \text{ d}^{-1}$ that started to extend during cool wet period (June to August 1992) at Timbilil.

Changes in RER with mean air temperatures at each site were linear with an overall response of $0.0088 \text{ mm mm}^{-1} \text{ d}^{-1} \text{ }^{\circ}\text{C}^{-1}$ (Fig. 8.4) during the cool wet season. There was no response to temperature during the warm dry season..

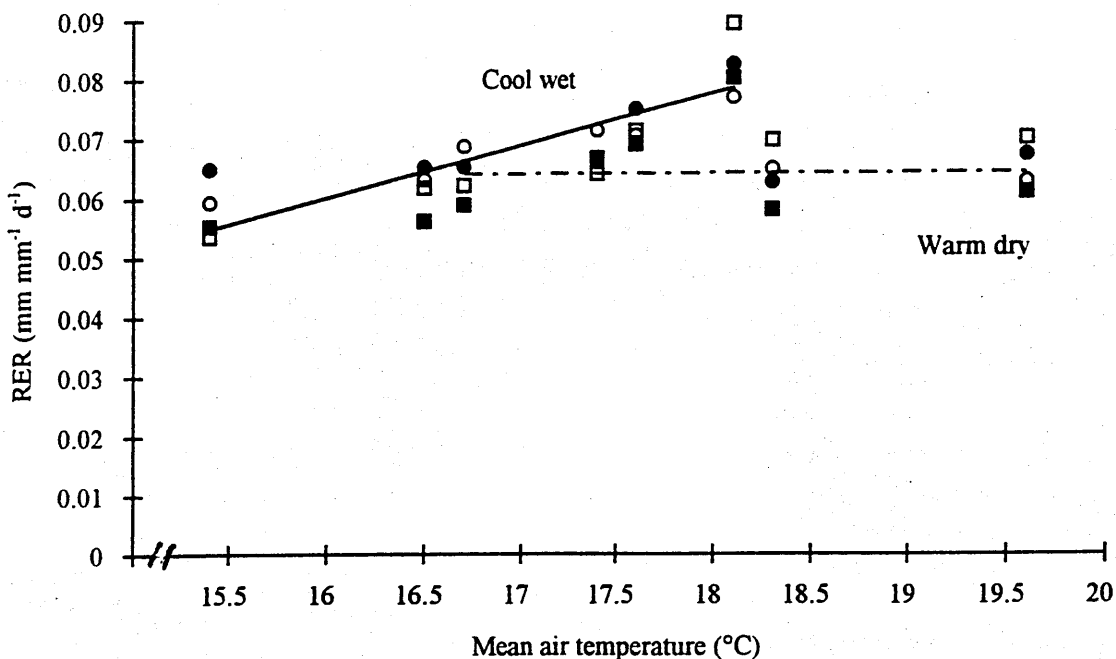


Fig. 8.4. Relationships between RER ($\text{mm mm}^{-1} \text{ d}^{-1}$) and mean air temperature of clones S15/10 (○), BB35 (□), 6/8 (■) and TN14/3 (●) across the four sites during two contrasting periods : cool wet season (June to August 1992) and warm dry season (December 1992 to February 1993).

Clone BB35 had larger thermal extension rates (ρ_e) than the other clones (Table 8.5). Table 8.6 gives the T_{be} calculated from RER and mean air temperatures. Clone BB35 had the highest base temperature for shoot extension.

The data from cool wet seasons of 1992 and 1993, and warm wet periods December 1992 to February 1993 were used in this analysis. The mean reduction in RER at Changoi from a warm wet season to a warm dry season was $0.015 \text{ mm mm}^{-1} \text{ d}^{-1}$,

representing an decrease of 18%. There was, however a smaller increase in rates ($0.01 \text{ mm mm}^{-1} \text{ d}^{-1}$) at Timbilil during this period for fast growing shoots, a rise of 20%.

Table 8.5 *Relationships between relative shoot extension rates and mean air temperature from release of apical dominance to harvesting at three leaves and a bud.*

Clone	Slope ρ_e ($\text{mm mm}^{-1} \text{ d}^{-1} \text{ }^{\circ}\text{C}^{-1}$)	Intercept ($\text{mm mm}^{-1} \text{ d}^{-1}$)
S15/10	0.0125(± 0.0037)	-0.1349(± 0.017)
BB35	0.0126(± 0.0045)	-0.1498(± 0.029)
6/8	0.0112(± 0.0047)	-0.1151(± 0.014)
TN14/3	0.0094(± 0.0034)	-0.0806(± 0.021)

Table 8.6 *Estimated base temperatures for shoot extension from mean air temperature from release of apical dominance to harvesting at three leaves and a bud.*

Clone	Lower 95%	Mean	Upper 95%	$r^2(\%)$
S15/10	9.6	10.8	12.9	82
BB35	8.8	11.7	15.1	75
6/8	9.4	10.3	13.3	87
TN14/3	8.6	8.8	11.8	80

Analysis of RER with thermal time estimated from a range of base temperatures gave T_{be} values which were within the 95% confidence limits of those estimated from mean air temperature (Table 8.6). Clone TN14/3 had the lowest T_{be} , of 9.0°C , while S15/10 had 9.5°C from this method as compared to 8.8°C and 10.8°C for the two clones respectively (Fig. 8.5). Estimates for clones 6/8 (10.1°C) and BB35 (11.5°C) were also in close agreement with those from mean air temperature.

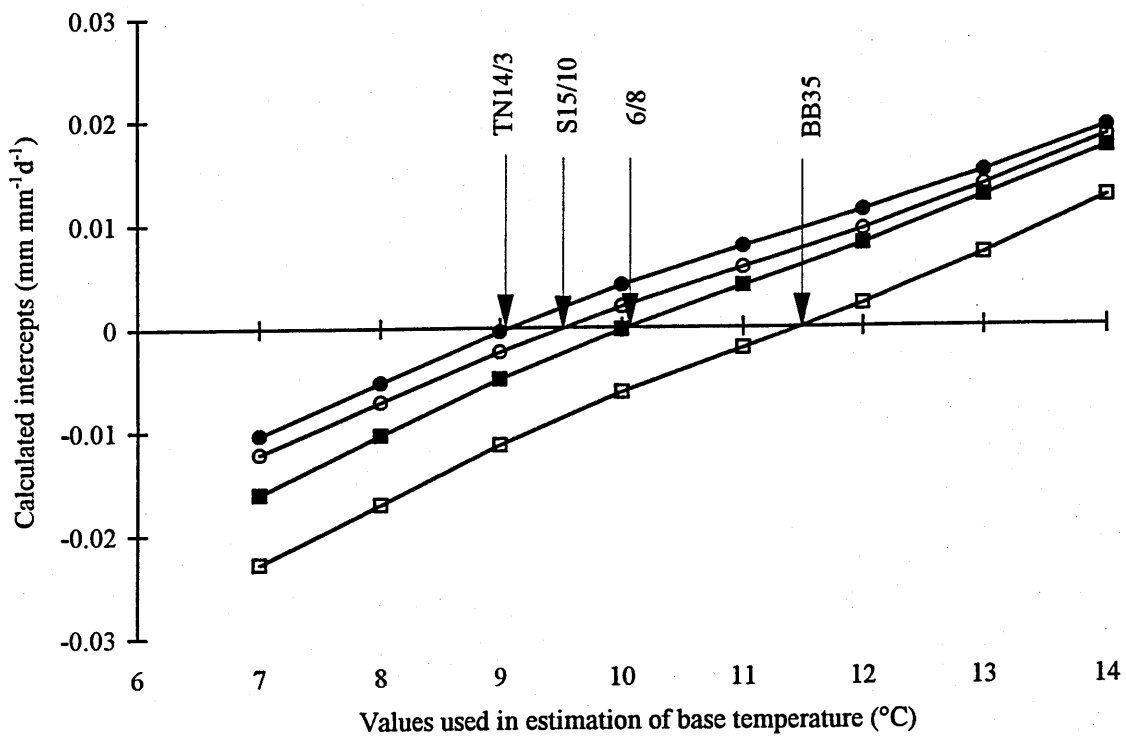


Fig. 8.5 Relationship between calculated RER intercepts and estimated base temperatures used for thermal time analysis. The points shown by arrows represents the actual base temperature of the clones.

DISCUSSION

Response to temperature

Shoot lengths

Both initial and final shoot lengths were influenced by prevailing air temperatures. The increase in shoot lengths with mean air temperature was $18.7 \text{ mm}^{\circ\text{C}^{-1}}$ to $2.6 \text{ mm}^{\circ\text{C}^{-1}}$ similar to those reported by Stephens and Carr (1993) for a wet season, but less than during the “warming phase” from August to November. The shoots go through a period of very slow growth, during which time assimilate reserves are possibly built up in the frame and roots. These would be translocated once temperatures start to rise causing a surge in extension rates.

Shoot Replacement Cycle (SRC)

The SRC found in this study ranged from a maximum of 110 days at Timbilil during the cool wet season to only 57 days at Changoi and Kaproret, giving a difference of three cycles per year. While these are comparable to those found by Squire *et al.* (1993) for similar sites at Kericho, seasonal variations are far lower than those found by Stephens and Carr (1993) in a more seasonal climate in Tanzania. This could be due to the differences in temperatures, since seasonal fluctuations in air temperature at Kericho are lower than those in southern Tanzania.

The differences between clones in shoot development rates and the response to temperature have implications for scheduling of harvesting operations since the harvest interval would need to be adjusted in order to maintain the same proportion of shoots at various stages of growth. For example to maintain a higher proportion of shoots with two leaves and a bud when the rate of leaf unfurling is one per four days, the harvest interval should be kept at eight to ten days. Waiting any longer (for instance 12 to 14 days), most of the shoots will have reached three to four leaves and a bud. Burgess (1992) has developed a system for planning the harvest interval based on the phyllochron, the interval between two leaves emerging which could be applied to determine harvest intervals at different altitudes in Kericho.

Rates of extension and development.

Extension rates at warmer sites were faster than those at cooler ones. The values found in this study were similar to those reported for clones S15/10 and TN14/3 at Kericho (Squire *et al.*, 1993), and for clones BB35 and 6/8 in southern Tanzania (Burgess, 1992; Stephens and Carr, 1993). The base temperatures were however lower than values reported by Smith *et al.* (1990) in Malawi. The lowest value of T_{be} reported was that for clone TN14/3 of 8.8 °C, but the restricted range of temperatures in the study region means that the confidence limits are wide. However the close agreement by two methods (Table 8.6 and Fig. 8.5) used to estimate T_{be} , may have been due to calculation of mean air temperature from continuous hourly data as opposed to daily maximum and minimum. The differences in slope of the relationship between RER and mean air temperatures (ρ_e) meant that clones with lower base temperatures did not necessarily have faster extension rates with increases in temperatures as compared to higher base temperature clones. This can be seen from the response of clone BB35 to changes in mean air temperature and that of clone TN14/3 and S15/10. However there was no evidence of the release of assimilate build up as in the more seasonal climates of southern Tanzania (Burgess, 1992; Stephens and Carr, 1993) or Malawi (Smith *et al.*, 1990).

Table 8.7 *Comparisons of base temperatures for extension and development of the clones used in this study. Data from various authors*

Clone	T_{be}	T_{bd}	Source
S15/10	7.5		Squire <i>et al.</i> , 1993
	10.1	7.8	Burgess, 1992
BB35	14.5		Smith <i>et al.</i> , 1990
	11.3	9.2	Burgess, 1992
6/8	9.5	6.1	Burgess, 1992
		7.7	Stephens and Carr, 1993
TN14/3	7		Obaga <i>et al.</i> , 1988

Stephens and Carr (1993) also reported differences in response to temperature during warming and cooling phases, though this was not explicitly observed in this study, there could have other confounding factors to such a response (Fig 8.4).

Shoot development rates and base temperatures for development were within the ranges found by Burgess (1992) for clones 6/8, S15/10 and BB35, and Stephens and Carr (1993) for clone 6/8. The value for clone S15/10 is also within the range reported by Squire *et al.* (1993) from data collected at similar sites to this study.

Base temperatures for development were 1.3 to 2.9°C lower than those for extension. The lowest value of 6.1°C for clone TN14/3. Squire *et al.* (1993) and Obaga *et al.* (1988) however found this clone did not respond significantly to temperature. While this reported lack of response to temperature may have been obscured by other site factors, the use of continuous hourly air temperature in this study may have contributed to finding an estimate of base temperature. The lower values of T_{bd} than T_{be} implies that shoot lengths are also dependent on temperature, which is evident from the results presented in this study (Fig. 8.3). In areas where ambient temperatures are close to the base temperatures, the differences in T_{be} and T_{bd} mean that fully developed shoots will be shorter than those at warmer areas.

Response to water stress

Shoot lengths

The initial shoot lengths were lower during the warm dry periods. This is probably due to the effect of reduction in bud lengths by SWD through the effects of SD (Squire, 1977). Final shoot lengths at harvest were also reduced during the warm dry periods. Though the soil water deficits were low during the period February and March 1993, the afternoon SDs were large (Chapter 3). The fact that the reduction at Changoi was larger than at Timbilil is supported by the lower afternoon SDs at Timbilil during this period. The large afternoon SDs at Changoi also coincided with higher air temperatures. Reductions in shoot lengths due to water stress has also been reported in southern Tanzania (Burgess, 1992; Stephens and Carr, 1993).

Rate of extension and development

Relative extension rates were also reduced during the warm dry periods. That the relative reduction at Changoi was larger than at Timbilil could be due to the rise in afternoon SDs with the associated mean air temperature. This in turn lowered the temperature response. Burgess (1992) and Stephens and Carr (1993) also reported reduction in extensions rates due to water stress. Rates of shoot development of the clones reported in this study were also affected by water stress, but these responses were not analysed. The difference in response of shoot extension to thermal time in Changoi during the warm wet season in 1992 probably reflects the duration of SD above 2.3 kPa at Changoi compared to at Timbilil during the same period.

Genotype x environment interactions

Shoot lengths, rates of extension and development

That there were significant interactions between generations, clones and sites reported in the analysis and discussed in terms of response to temperature and water means that harvesting policy should be based on knowledge of phyllochrons and temperature and the need to adjust such a schedule at onset of environmental stress (SWD, SD). The interaction of shoot extension rates in clone BB35 across the sites for instance was due mainly to its temperature response because of it's a high base temperature. These interactions also suggest that clone BB35 is more suited to warmer environments when there no limitation by soil water deficits. Similarly the interaction of shoot lengths and RER in clone 6/8, may have been due to water availability, since it did not have a high base temperature as BB35.

Proportional contribution to yield.

The change in parameters reported in this chapter between sites were further analysed for proportional changes. During the cool wet periods, RER at Changoi was 48% more than at Timbilil, while the average over all the seasons was only 32%. The number of shoot replacement cycles per year at Timbilil was 60% of those at Changoi. This suggests that of the components of yield, SRC has the largest contribution to yield.

Since these components of yield were influenced mainly by temperature, the lower than expected yield at Kaproret cannot be explained by their variations alone.

CONCLUSION

Shoot extension up to three leaves and a bud was modelled using an exponential function, which explained between 92 to 97% of the variations.

Variations in RER with altitude were linear during warm and cool wet seasons when linear relationships with mean air temperature were significant (r^2 between 80 and 96%). From these relationships, clonal differences in base temperature for shoot extension were found. Despite the noted shortcoming of extrapolation over a large intervals, the base temperatures found in this study are in close agreement with those from other areas in eastern Africa. The lowest T_{be} found was for clone TN14/3 (8.8°C) and hence is suitable to areas of low mean air temperatures.

Values of T_{bd} found in this study were 1.3 to 2.9°C lower than those for T_{be} . This meant that for the clones studied here, shoot lengths were controlled by temperature, a fact which was demonstrated by the longer shoots at warmer environments. Though there were variations in shoot extension and development rates due to drought, it was not possible to explicitly determine relationships between RER or shoot development rates and SWD, probably due to the relatively short drought experienced in Kericho as compared to other tea growing regions in eastern Africa.

Shoot replacement cycle and shoot extension rates account for most of the variations in yield.

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CHAPTER 9

SHOOT COMPOSITION, POPULATION DENSITY AND MASS

INTRODUCTION

Shoot population density, defined as the number of shoots per unit area, is thought to be the main determinant of yield in tea (Squire and Callander, 1981) and is important in clonal selection in Malawi (Nyirenda and Ridpath, 1984).

Shoot population density is known to vary with genotype, nutrition, drought and temperature (Stephens and Carr, 1990) and altitude (Obaga *et al.*, 1989; Wachira *et al.*, 1990). The number of shoots plucked is determined by two attributes: the basal shoot population and the number of shoot growth cycles per unit time (Squire *et al.*, 1993). Seasonal variations in shoot population density result from the effects of air and soil temperatures, rainfall (through the effects of soil water deficits) and saturation deficits of the air on shoot growth rates (Squire, 1979; Tanton, 1982a & b; Stephens and Carr, 1990).

At the Tea Research Foundation of Kenya, yield is calculated using a fixed dry matter content of shoots but this parameter actually varies with temperature and genotype (Burgess, 1992; Cloughley *et al.*, 1983), drought and nutrition (Stephens and Carr, 1994). In Kenya shoot dry mass has also been shown to increase with altitude and this has been attributed to lower air temperatures (Wachira *et al.*, 1990). Burgess (1992) reported seasonal and clonal variations in dry matter content between clones ranging from 21% to 24% in Tanzania.

Investigations concerning the effects of weather and climate on shoot extension rates have been reported by many workers (Squire, 1979; Burgess, 1992; Squire *et al.*, 1993; Stephens and Carr, 1993) but few studies have concentrated on shoot mass and developmental stage as well as composition of harvested shoots. These are necessary additions to complete our understanding of crop responses and to provide information for crop modeling (Squire *et al.*, 1993; Stephens and Carr, 1994).

This chapter presents the genotypic variability in shoot population density, composition and mass as influenced by prevailing environmental variables. These will be interpreted in terms of their relative contribution to observed yield differences between clones in different environments.

METHODOLOGY

Shoot population density

The number of shoots removed at each harvest and the number remaining per unit area, the 'basal population density' (Stephens and Carr, 1994), were determined at each site. The numbers of both actively growing and dormant shoots were counted in a 0.25 m² grid placed at the center of one bush in each plot, the same bushes used for ground cover measurements. Shoots were counted once the terminal bud had visibly begun to extend (Stephens and Carr, 1994). The total shoot population density was determined just after each harvest. The number of shoots harvested were also counted by identifying and counting all the newly plucked points per 0.25 m² on the same bushes immediately after each harvest. The total shoot population density was taken as the sum of the number of plucked points and the basal shoot population density. The actual proportions of dormant and active shoots in both harvested and basal shoot population densities were determined using data from shoot composition. The basal shoot population density is the difference between harvested and total population densities.

Harvested shoot composition and mass

At each harvest a sub-sample of approximately 200g of harvested shoots was selected at random from each clone. These shoots were sorted in to actively growing and dormant shoots, identified by their shorter terminal buds. The growing or active shoots were further sorted in to those with one, two, three, and four unfolded leaves and a bud. These were counted and weighed to determine their fresh mass. The mass of broken shoots was also recorded, but was only used to assess the percentage of unbroken leaf in the harvest. From December 1992 to June 1993, the sub-samples were taken from two replicates. The number of replicates were increased to four from July 1993 in order to increase the resolution and allow differentiation between the treatments.

The sorted shoots were put in paper bags and oven dried at 85 to 90°C for 24 h to constant mass. The dry mass of these shoots was then used to calculate the ratio of dry to fresh mass so often used in the conversion of fresh mass of shoots to dry mass in estimation of yield.

RESULTS

Shoot population density

There was an upward trend in shoot population density in all the sites. The total shoot population density rose from below 100 shoots m^{-2} in December 1992 to reach over 400 shoots m^{-2} at Timbilil and over 600 shoots m^{-2} at Changoi in June 1994 (Fig. 9.1).

There were also seasonal variations in both basal and harvested shoot population densities. The harvested shoot population density was lowest during the cool wet season and during the warm dry seasons, but high during the warm wet season of September and October 1993, and the cool wet season in 1994 (April to June). A large proportion of shoots was dormant in both the harvested and basal shoot population densities during periods when active shoot population densities were low (Table 9.1).

The active shoot population density of clone 6/8 was higher ($P \leq 0.01$) than all the other clones. There were no significant differences between clones S15/10 and TN14/3, while BB35 had the lowest population density ($P \leq 0.05$).

Significant differences between sites were also found. The shoot population density at Changoi was higher ($P \leq 0.001$) than at other sites, but there were no difference between Kipketer and Kaproret ($P \leq 0.05$). Shoot population densities at Timbilil were more ($P \leq 0.001$) than at both Kipketer and Kaproret.

There were significant interactions in harvested shoot population densities between seasons, clones and sites. Interactions between seasons and clones showed both clones 6/8 and TN14/3 having higher ($P \leq 0.001$) shoot population than both S15/10 and BB35 during the warm dry period of December 1992 to March 1993. Clone 6/8 had the largest population density (139 shoots m^{-2}) during the cool wet season April to June 1994 though this was not significantly different from clone S15/10 in the same period. Except for the warm dry season of December 1993 to March 1994 when clone S15/10 had more shoots ($P \leq 0.001$), clone 6/8 had the most shoots in the other seasons.

Interactions between seasons and sites were also significant. During the warm dry season of December 1992 to March 1993, Timbilil had the smallest shoot population ($P \leq 0.001$), while Changoi had the largest ($P \leq 0.05$). The largest shoot population density ($P \leq 0.001$) was at Changoi during the cool wet period April to June 1994.

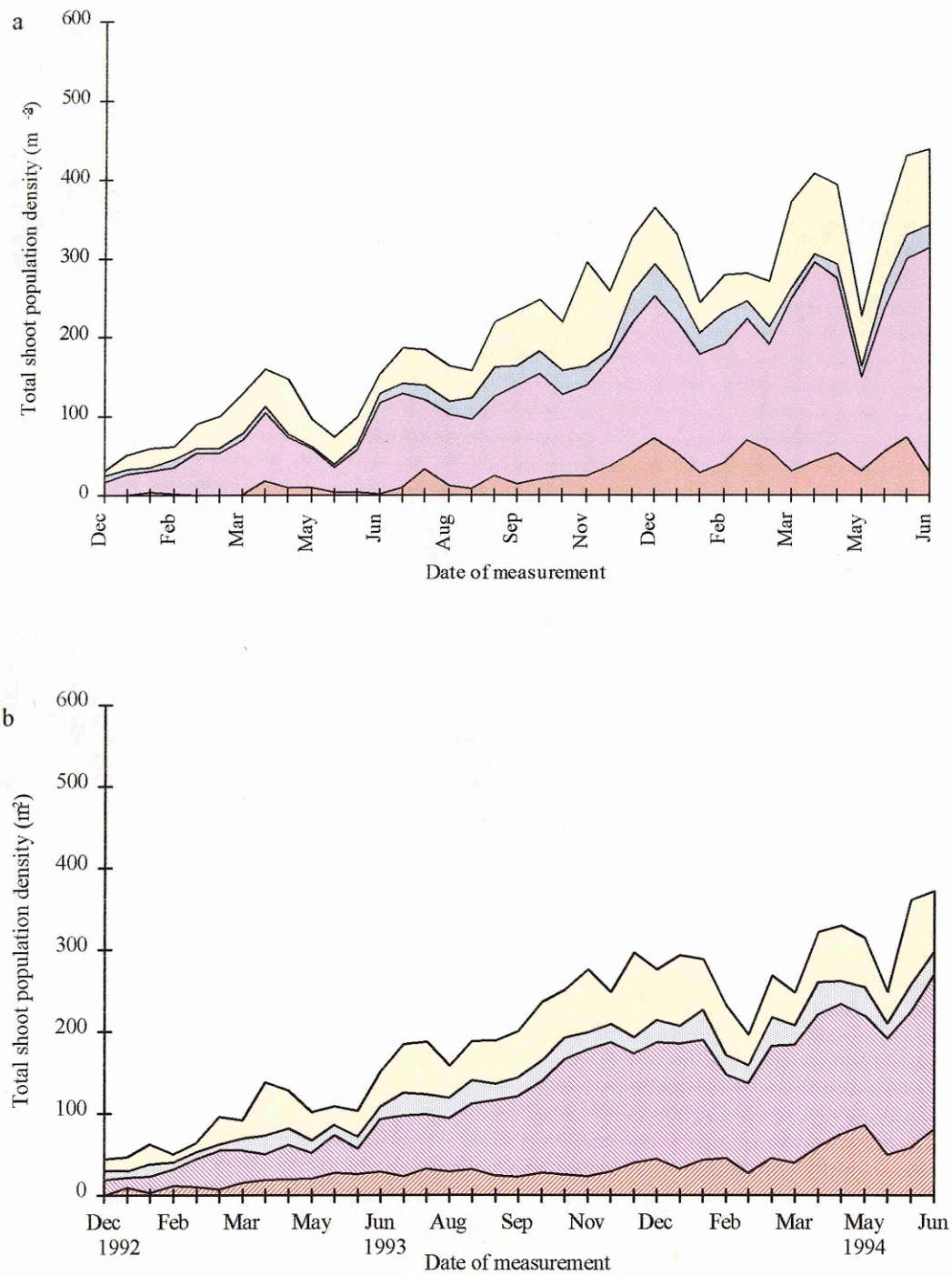


Fig. 9.1(a & b). Seasonal changes in shoot population densities of clones a) S15/10 and b) TN14/3 at Timbilil during the period December 1992 to Jun 1994. Active harvested shoots (□), dormant harvested shoots (■), basal active shoots (■) and basal dormant shoots (■).

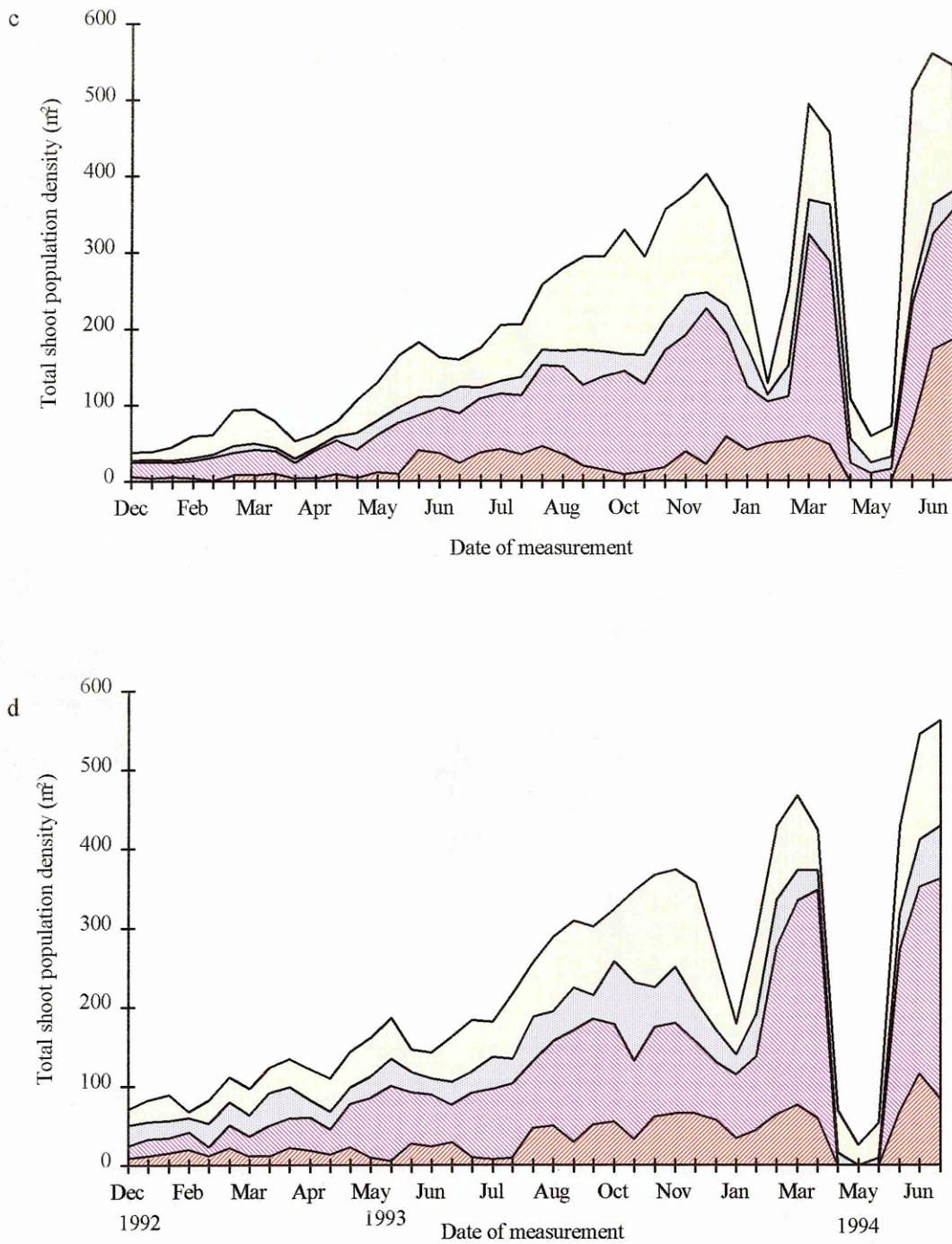


Fig. 9.1(c & d). Seasonal changes in shoot population densities of clones c) S15/10 and d) TN14/3 at Changoi during the period December 1992 to Jun 1994. Active harvested shoots (□), dormant harvested shoots (■), basal active shoots (▨) and basal dormant shoots (▩).

During the warm dry season December 1993 to March 1994, tea at Timbilil had the most shoots ($P \leq 0.001$). The phenomena was also evident during the cool wet season during April to August 1993, though there was no difference from Changoi (Table 9.1).

Table 9.1. *Variation in harvested shoot population densities (shoots m^{-2}), between clones in different seasons and sites. The dormant shoot population density is expressed as a % of the harvested shoot population density.*

		Season											
		warm dry		cool wet		warm wet		warm dry		cool wet		Mean	
		1993		1993		1993		1994		1994			
		Act.	Dorm	Act.	Dorm	Act.	Dorm	Act.	Dorm	Act.	Dorm	Act.	Dor
Sites	Timbilil	50	12	86	25	117	17	92	20	122	21	93	19
	Kipketer	56	28	63	17	113	12	69	25	105	30	81	22
	Kaporet	59	11	70	18	90	20	62	32	120	41	80	24
	Changoi	64	15	79	24	135	15	79	23	171	22	106	20
Clones	S15/10	50	12	72	16	113	16	83	22	138	25	91	18
	BB35	48	24	69	28	108	22	72	31	123	34	84	28
	6/8	67	12	85	17	121	14	74	25	139	25	97	19
	TN14/3	64	17	73	22	112	13	74	22	118	30	88	21
Mean		57	16	75	21	134	16	76	25	129	29	90	21
%CV Active		11.8											
Dormant		14.2											
LSD ($P=0.05$)													
		Clones(G)		Sites(E)		Season(S)		GxE	GxS	SxE	GxSxE		
Active		3.4		3.4		3.8		6.8	7.6	7.6	15.2		
Dormant		4.2		4.2		5.1		8.4	9.6	9.6	NS		

Significant interactions between clones and sites showed clone S15/10 at Changoi as having the most shoots, though this was no different from clone 6/8 at the same site and

at Timbilil. Clone 6/8 at Kipketer had the lowest shoot population though this was similar to clone TN14/3 at the same site and clones S15/10, BB35 and TN14/3 at Kaproret as well as BB 35 at Timbilil.

The population of dormant shoots behaved in a similar manner to active shoot population density. Though the warm dry period (December to February 1994) saw an increase in the proportion of harvested dormant shoots ($P \leq 0.001$), the largest increase was during the cool wet period in 1994 (Table 9.1). The largest proportion of dormant shoots was harvested from clone BB35 ($P \leq 0.001$) and at each site though this was not significantly different from the other sites.

The sharp reduction in shoot population density at Changoi during April and May 1994 (Fig. 9.1 c & d) was due to hail damage.

Shoot mass and stage

Fig. 9.2 shows the relationships between shoot mass and stage. Both clones S15/10 and BB35 had higher shoot mass at each stage than the other two clones ($P \leq 0.05$). This ranking in shoot fresh mass was also similar in shoot dry mass and was consistent throughout the sites, and seasons. Clone 6/8 had the lowest shoot mass. The variation in shoot fresh mass with stage in clones 6/8 and TN14/3 were better explained by linear relationships ($r^2 > 99\%$), while clones BB35 and S15/10 had exponential relationships ($r^2 > 98\%$) (equations 9.1 to 9.4).

S15/10: $0.327(\pm 0.012)e^{0.480(\pm 0.005).S}$	$r^2 = 99.9\%$	9.1
BB35: $0.237(\pm 0.113)e^{0.531(\pm 0.0414).S}$	$r^2 = 98.8\%$	9.2
6/8: $0.271(\pm 0.0069).S + 0.0395(\pm 0.019)$	$r^2 = 99.8\%$	9.3
TN14/3: $0.346(\pm 0.02338).S - 0.054(\pm 0.0135)$	$r^2 = 99.9\%$	9.4

There were seasonal changes in shoot dry mass. Shoots growing during the period December 1992 to February 1993 were heavier ($P \leq 0.05$) than during any other period (Fig. 9.3). There were no significant differences during the other seasons. Clonal differences in shoot dry mass were significant. Clone S15/10 had heavier shoots

($P \leq 0.05$) than both clones 6/8 and TN14/3, but they were no different from those of clone BB35 (Table 9.2). Heavier shoots were harvested at Timbilil ($P \leq 0.05$), though this was similar to shoot mass at Kaproret. Differences between Kipketer and Changoi were not significant.

Table 9.2. *Mean shoot dry mass (g/shoot) of all sampled shoots from four clones during the period July 1992 to June 1994.*

Site	Clone				Mean
	S15/10	BB35	6/8	TN14/3	
Timbilil	0.233	0.214	0.150	0.174	0.193
Kipketer	0.212	0.193	0.160	0.161	0.182
Kaproret	0.214	0.211	0.156	0.170	0.188
Changoi	0.212	0.191	0.158	0.164	0.181
Mean	0.218	0.202	0.156	0.167	
% C.V. = 12.1					
LSD ($P=0.05$)	Clones(G)	Sites(E)	G x E		
	0.032	0.011	0.069		

Though interactions between clones and sites were significant, only shoots of clone S15/10 harvested at Timbilil were heavier than those of clone 6/8 at each site and those of clone TN14/3 at Kipketer and Changoi.

The significant seasonal difference between shoots growing between December 1992 and March 1993 was investigated further by looking at the relationships between population density and mean shoot mass. Though inverse relationships were found between total shoot population density and shoot mass, these were however not significant ($r^2 < 0.47$).

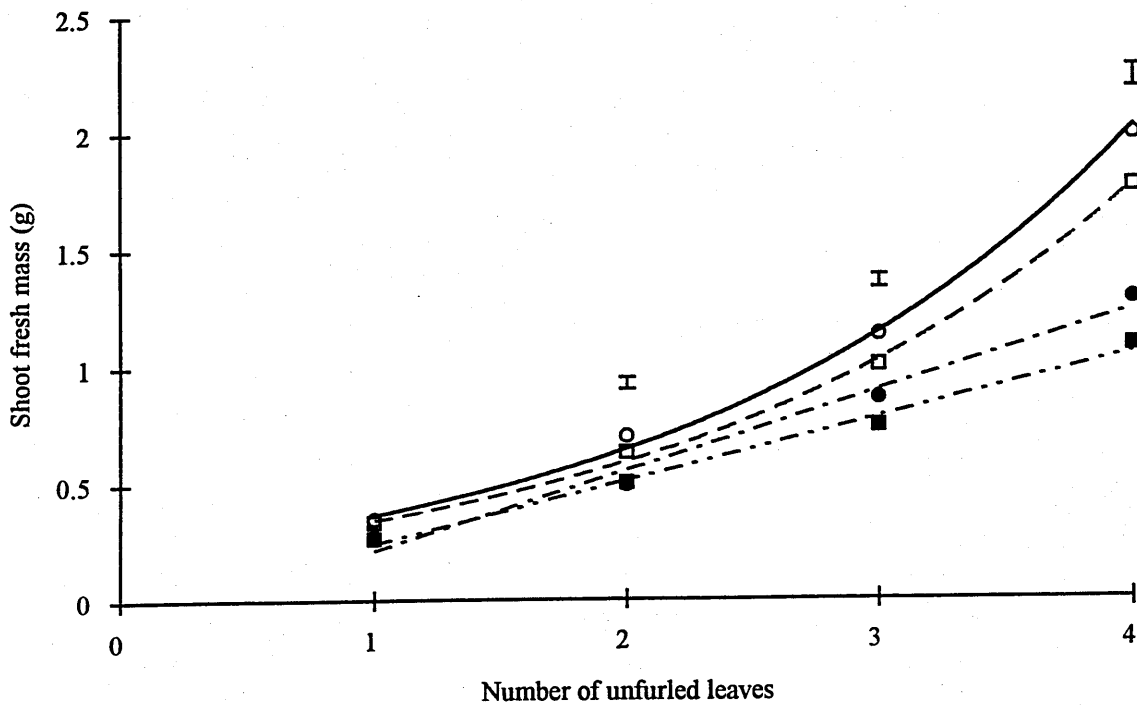


Fig. 9.2. relationships between shoot fresh mass and number of unfurled leaves of clones S15/10 (○), BB35 (□), 6/8 (■) and TN14/3 (●) at four sites during the period December 1992 to June 1994. The LSD bars shown are at $P=0.05$.

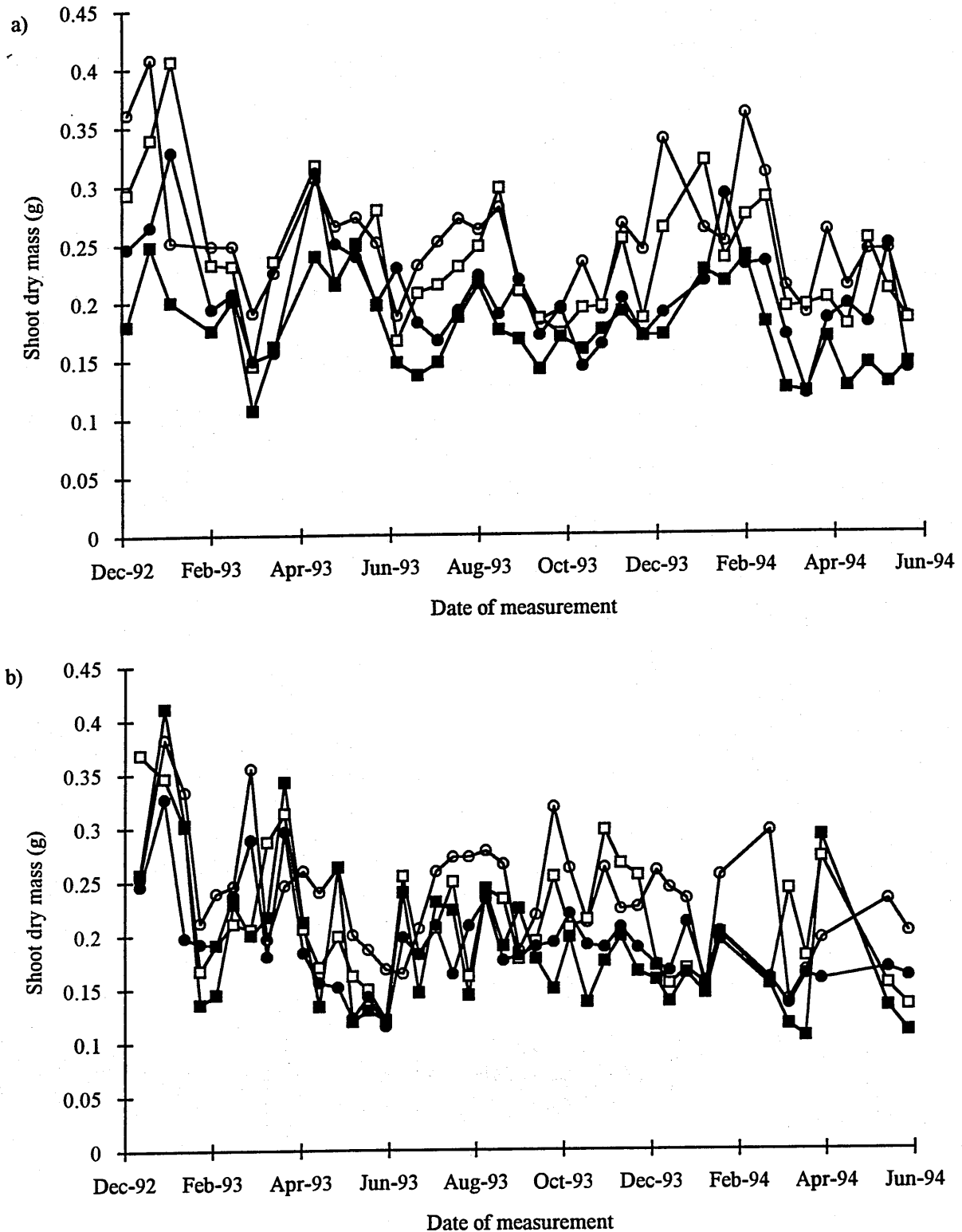


Fig 9.3 Mean shoot dry mass of four clones, S15/10 (○), BB35 (□), 6/8 (■), TN14/3 (●) at a) Timbilil and b) Changoi from December 1992 to June 1994.

Dry matter content

Seasonal changes in dry matter content of shoots were observed in all the clones and are illustrated for clones S15/10 and TN14/3 (Fig. 9.4). The shoot dry matter content of clone TN14/3 was generally larger than that of the other clones during most parts of the year at each site. During September to early November 1993, the lowest dry matter content was that of clones S15/10 and BB35 at Changoi and Kaproret. During the cool/wet season (May to June 1993) the pattern of dry matter content was lower in all clones but increased in July, reaching a peak in August before declining again.

Effects of water stress

Fig. 9.5 shows the relationship between shoot dry matter content and soil water deficits. There were significant linear relationships ($r^2 = 99.7\%$) between dry matter content and soil water deficits at Changoi. There was a mean increase in dry matter content of $0.077\% (\text{mm SWD})^{-1}$, and the intercepts were not significantly different from the mean dry matter content with no moisture deficit (0.23). However inclusion of dry matter content data during decreasing soil water deficits reduced the correlation coefficient ($r^2 = 86\%$). The analysis was further extended to include afternoon saturation deficit (SD) and mean air and soil temperatures prevailing during the dry period. A stepwise regression showed the most contribution from SWD accounting for 77 to 97% of the variation, while SD accounted for 37 to 63%. Air and soil temperatures contributions were negligible. There were clonal differences in these responses. Percentage contributions by partial regressions (equations 9.5 to 9.8) with SD or SWD are shown in brackets.

$$\text{S15/10: } 0.189(\pm 0.0177) + 0.031(\pm 0.0102)\text{SD} + 0.00045(\pm 0.00011)\text{SWD} \quad 9.5$$

(SD = 63%, SWD = 76%; both = 90.1%)

$$\text{BB35: } 0.227(\pm 0.0084) + 0.00856(\pm 0.00485)\text{SD} + 0.000656(\pm 0.000052)\text{SWD} \quad 9.6$$

(SD = 37.1%, SWD = 96.9%; both = 97.7%)

$$\text{6/8: } 0.220(\pm 0.0086) + 0.0115(\pm 0.0049)\text{SD} + 0.00061(\pm 0.000053)\text{SWD} \quad 9.7$$

(SD = 41.6%, SWD = 95.6%; both = 97.4%)

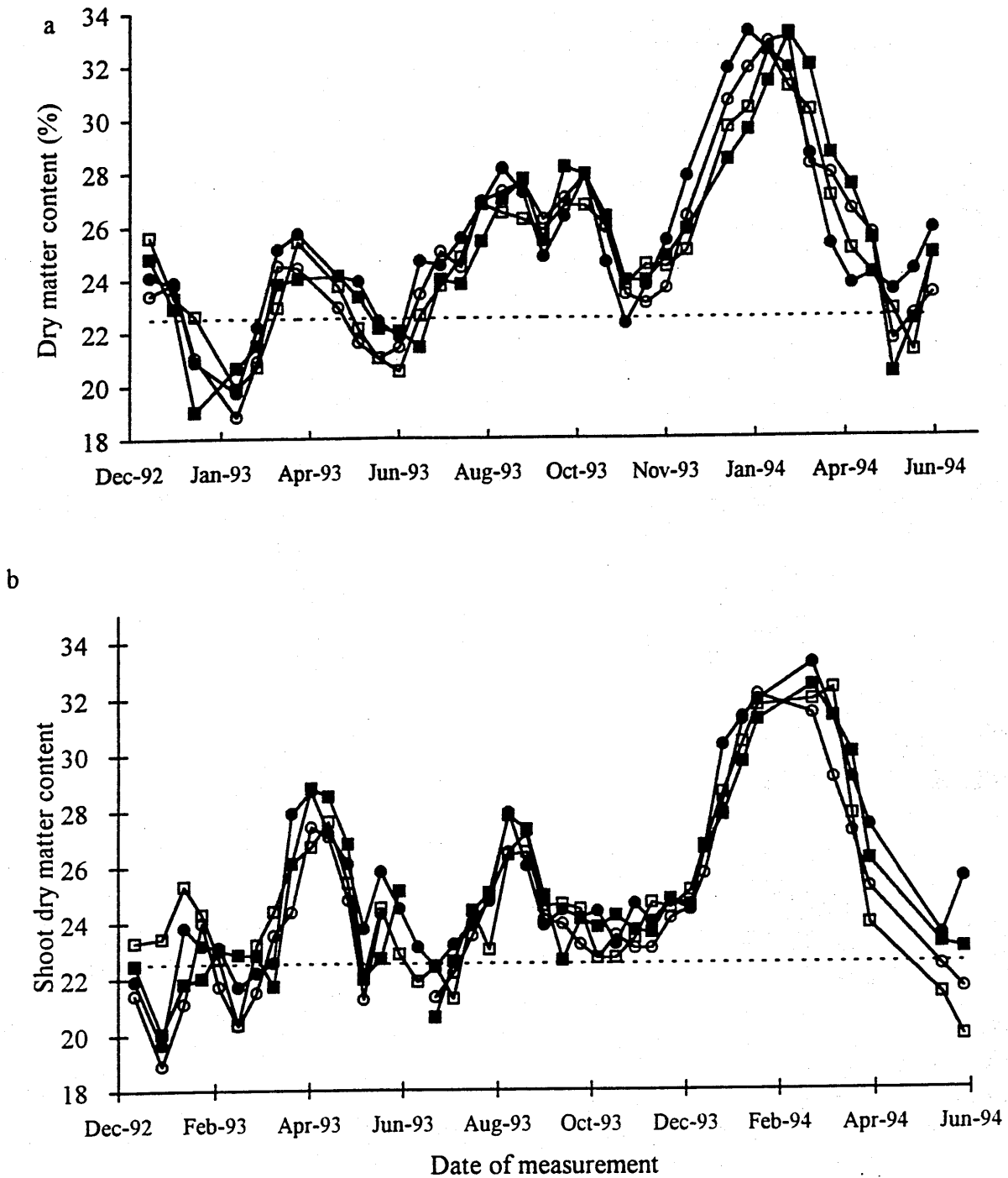


Fig. 9.4. Changes in dry matter content of shoots of clones S15/10 (○), BB35 (□), 6/8 (■) and TN14/3 (●) determined at two sites a) Timbilil and b) Changoi, during the period December 1992 to June 1994. The dotted lines represent a constant value of 22.5%, used by TRFK as dry matter content.

TN14/3: $0.204(\pm 0.0011) + 0.0229(\pm 0.0064)SD + 0.0006(\pm 0.00007)SWD$ 9.8
 (SD = 53.8%, SWD = 90%; both = 96.6%)

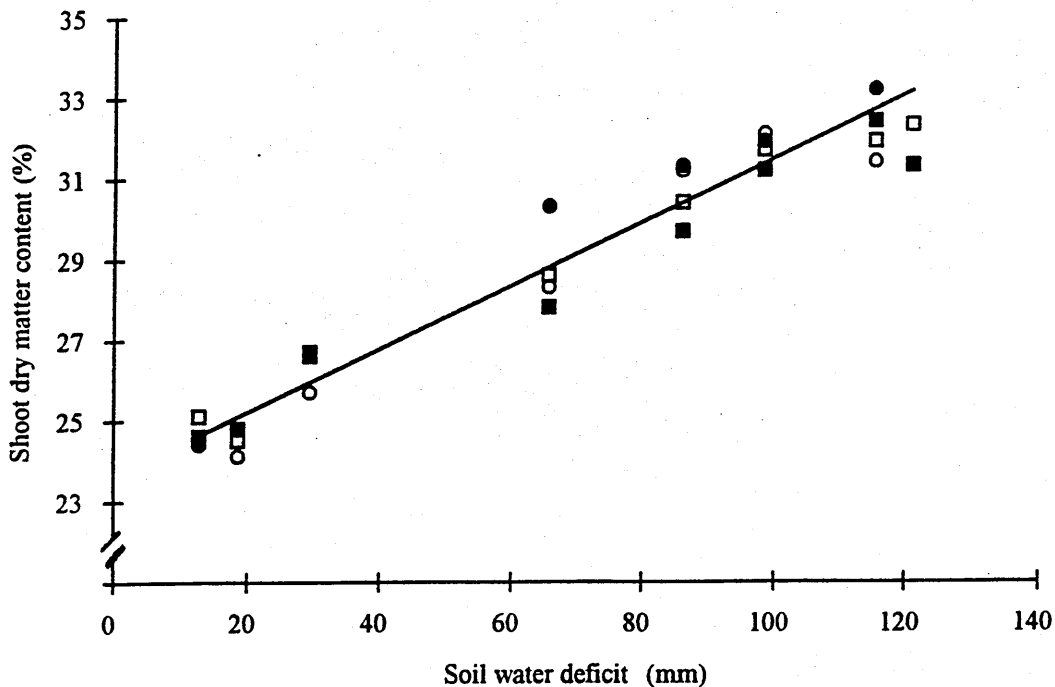


Fig 9.5 Seasonal changes in shoot dry matter contents with SWD of clones S15/10 (○), BB35 (□), 6/8 (■) and TN14/3 (●) at Changoi during the long dry season December to March 1994. The solid line is the mean linear relationship between dry matter content and SWD.

Shoot composition (harvested shoots)

Fig. 9.6 shows the harvested shoot composition of two clones (S15/10 and TN14/3) at Timbilil and Changoi. The shoot composition was also season dependent. During the closing stages of the dry season and coolest parts of the year, the composition comprised of up to 30% dormant shoots. While there were variations in composition of one and a bud, two and bud, three and bud and four and bud shoots during each harvest, the overall variations were not marked. The proportion of shoots with two leaves and bud ranged from 10% to at best 60%, almost in the same proportion to three and a bud. The smallest proportions of active shoots were the one leaf and bud and the four leaves and bud shoots which accounted for less than 20% of the total, the rest being taken up by the dormant shoots.

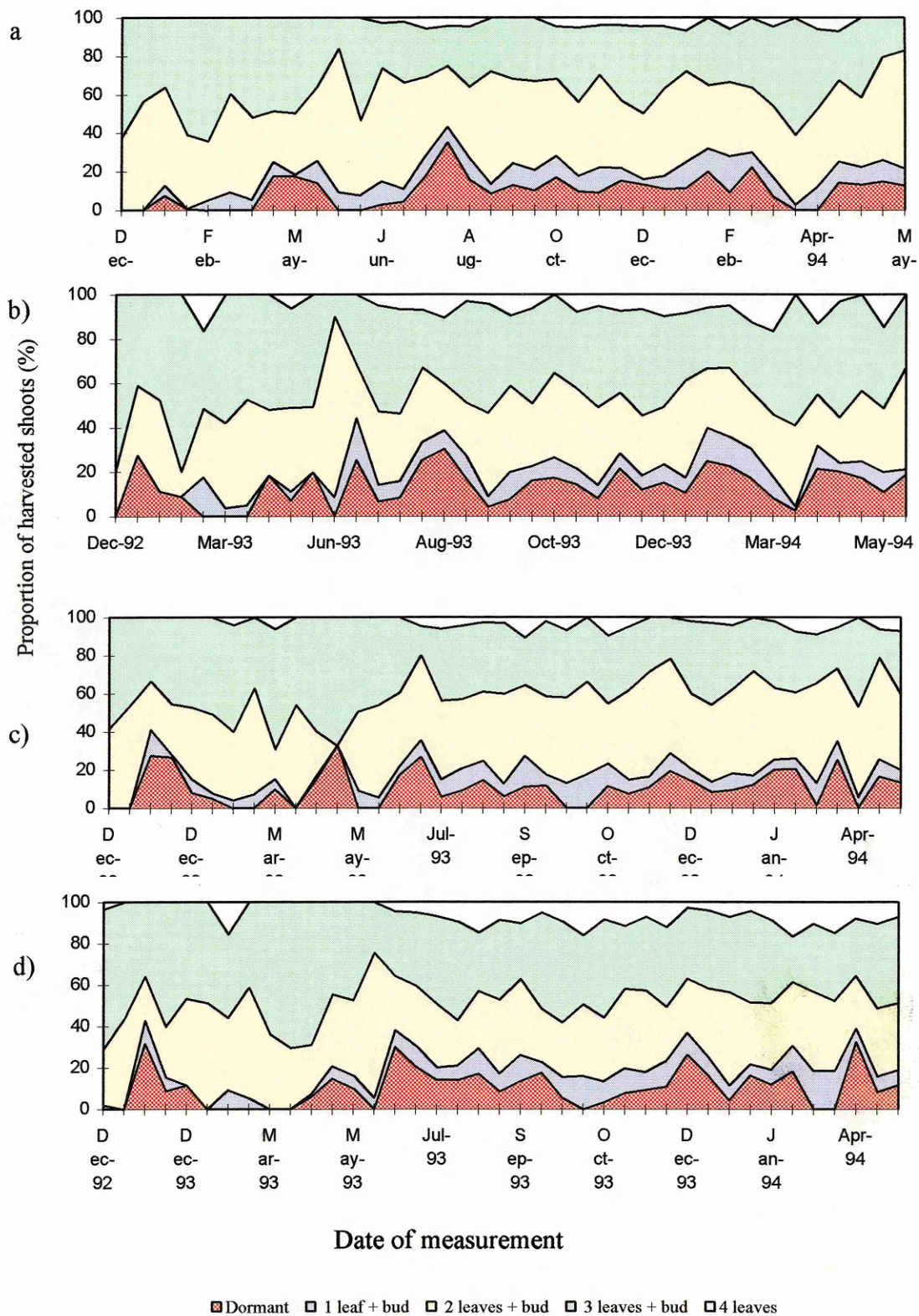


Fig. 9.6 Variations in proportions of harvested shoots at various stages of growth (number of unfurled leaves and physiological states) during the period December 1992 to June 1994, (a) and (c) clone S15/10, (b) and (d), clone TN14/3, each at Timbilil and Changoi.

DISCUSSION

Response to temperature

Shoot population density

The increases in basal shoot population density with time found in this study were similar to those reported from other studies (Stephens and Carr, 1994; Burgess, 1992; Squire *et al.*, 1993). These increases with time are related to ground cover development (Chapter 5). Burgess (1992) reported similar correlations between ground cover and shoot population density. Shoot population density is also known to increase in time since pruning (Stephens and Carr, 1994). The larger population density at lower altitudes observed in this study confirms the results reported by Squire *et al.* (1993).

The sudden increase of harvested shoot population density after a drought (December 1993 to March 1994) may have been as a result of the synchronization of growth by stress, since this was followed by a decrease. This could, however, have been confounded by the fall in both air and soil temperatures at the onset of rains, which may have influenced the observed changes through reduction of extension rates (Chapter 8).

Shoot mass

The consistently larger fresh shoot mass of clone S15/10 than other clones may in itself be a major contributor to the differences in yield observed between these clones. Reports from other studies with this clone (Burgess, 1992; Squire *et al.* 1993) also show similar results in shoot fresh mass.

The relationships between shoot fresh mass and stage reported in this study are close to those shown for clones S15/10 and BB35 in Tanzania (Burgess 1992). However Stephens and Carr (1994) found a linear relationship between shoot mass and stage for clone 6/8, which was comparable to that found in this study. Such relationships are useful in modeling components of yield. These relationships have implications on the ease of harvesting of these clones. Leaving clones S15/10 and BB35 to continue growing from 2 leaves and a bud to three and a bud will result in increases in shoot mass of 60 and 70% respectively, while those of 6/8 and TN14/3 will give only a 47 and 54% change. While it is tempting to leave harvesting until maximum shoot mass has occurred, leaf

quality is known to drop with coarseness of plucking. Hence timing of harvesting to optimize both shoot mass and quality is important.

The lack of response of dry matter content to temperature was surprising (equations 9.5 to 9.8), given that differences in dry matter contents between site exist (Fig 9.4) largely due to temperature. This suggests that the rate of dry matter accumulation in shoots may be having the same relationship with temperature as shoot development.

Response to water stress

Shoot population density

The reduction in shoot population density during the warm dry seasons found in this study are similar to reductions reported by Stephens and Carr (1994) for clone 6/8 in southern Tanzania. During the warm dry season of December 1993 to March 1994, there was an overall reduction of 43% in harvested shoot population density, and an increase in the proportion of dormant shoots from 16% to 25%. After the release of the stress, there was an increase of shoot population density of 70%, while the proportion in of dormant shoots also increased from 25% to 29%.

Shoot mass

Since seasonal changes in shoot dry mass were small, the effects of water deficits on shoot mass in this study were negligible. The changes in dry matter content with season followed similar patterns to those observed for SWD and SD (Chapter 3). Whereas during warm wet periods shoot extension rates were high (Chapter 8), the shoot dry mass is lower than during dry periods. Responses to both SWD and SD were significant. Clone S15/10 had the lowest slope of response to SWD ($0.045\% (\text{mm SWD})^{-1}$) as compared the other clones ($0.06\% (\text{mm SWD})^{-1}$), but had the largest response to SD. This suggests that clone S15/10 is more sensitive to water deficits in the atmosphere than in the soil as might be expected in a clone with rapid shoot extension and development rates.

Responses to other factors (hail)

Hail reduced the shoot population density in April 1994 at Changoi (Fig. 9.1 c & d). However the rapid increase in population density afterwards suggest some form of compensatory growth.

GxE interactions

Shoot population density

Significant interactions between clones and sites found in this study have a number of implications on this aspect of component of yield. Though Squire *et al.* (1993), reported no response of clone TN14/3 to altitude, the results from this study suggests that it has below average adaptability in shoot population density (coefficient of regression = 0.64, $r^2 = 92\%$). The other clones did not show any significant response to environmental index (shoot population density). Whereas the plants were used in this study were younger than those used by Squire *et al.* (1993), there is currently no indication to suggest that the response to environment will change with age.

Shoot mass

The significant interactions between clone and site in shoot dry mass observed in this study is similar to other reports (Wachira *et al.*, 1990). Clones BB35 and TN14/3 showed significant positive response to environmental index (mean shoot dry mass at each site), with regressions coefficients 0.45 and 0.92 respectively ($r^2 > 0.92$). The response of clone 6/8 however was negatively correlated to environmental index (regression coefficient -1.2, $r^2 = 0.88$). There are no clear indications why this clone behaved differently from the others. However analysis of variance (Table 9.2) shows it to have a similar mass at each site. Squire *et al.* (1993) reported that shoot dry mass did not vary systematically with altitude and though not significant, warmer or higher yielding environments had shoots with more dry mass than those at less favourable ones. Results from this study suggests that the response of shoot dry mass to altitude are positive though not linear. The differences in shoot dry mass between clones and sites is an important factor which may explain some of the observed differences in yield. The

reduction in shoot dry mass with temperature (across sites, Table 9.2) may be associated with the corresponding increase in shoot extension rates.

Modelling annual yields

Annual yield variations have been related to components of yield through a multiplicative relationship (Stephens and Carr, 1994):

Yield = Mean total shoot population density $\times$ number of shoot replacement cycles in per year $\times$ mean dry mass per shoot.

This simple model was used to predict annual yields for the period July 1993 to June 1994. The number of shoot replacement cycles in a year was taken as the reciprocal of the mean duration of shoot growth in three generations (Chapter 8) and the mean shoot dry mass was that determined in this study (Table 9.2). Comparison of predicted and actual yields (Fig. 9.7) showed positive linear relationships ($r^2 = 91\%$).

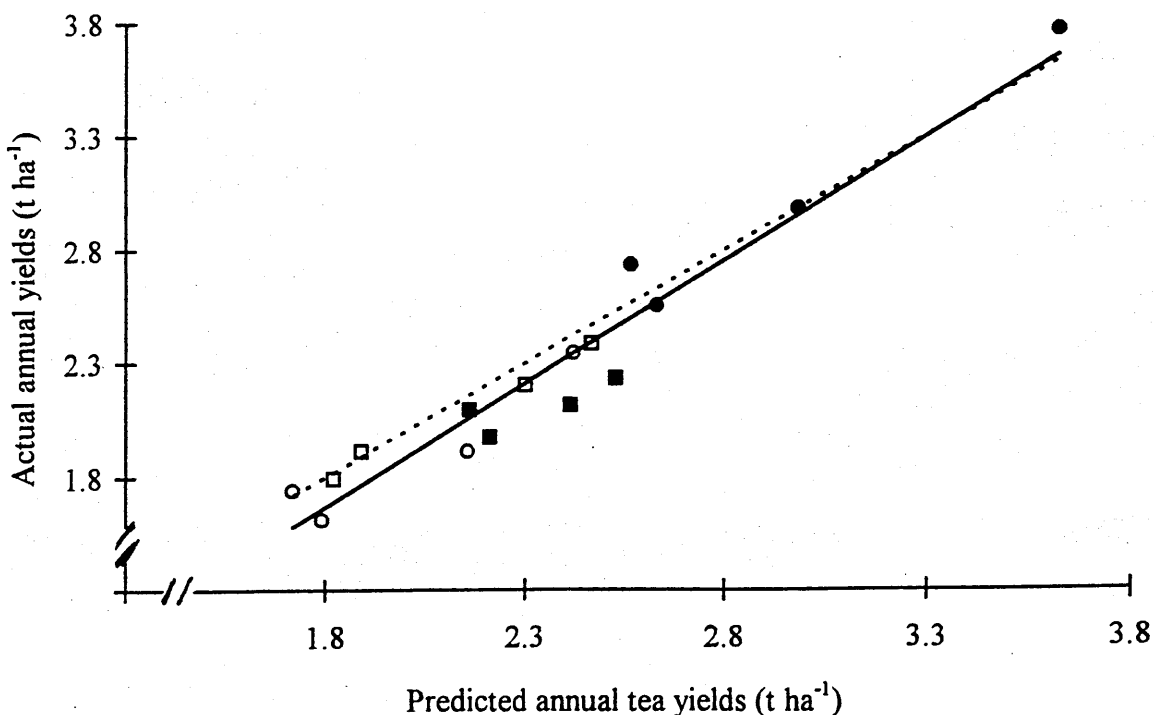


Fig. 9.7 Plot of actual and predicted tea yields of four clones at four sites Timbilil (○), Kipketer (□), Kaproret (■) and Changoi (●) from July 1993 to June 1994. The dotted line represents a 1:1 fit while the solid line is fitted with equation 9.9.

Though the predicted yield were different from actual yields, the slope and intercept of the regression line were not different from a 1:1 relationship (95% confidence limits). The relationship between actual yield Y_{act} and predicted yield Y_{prd} was found as:

$$Y_{\text{act}} = 1.0848(\pm 0.0745)Y_{\text{prd}} - 2.857(\pm 1.7882) \quad r^2 = 91\% \quad 9.9$$

Though the relationship between actual and predicted yields agrees closely, Stephens and Carr (1994) found differences in modelling yields of clone 6/8 in Tanzania. The relationship found in this study could have been influenced by the small variations in harvested shoot population between seasons as compared to those in Tanzania. This might also be a reason for the failure of the model to account for the seasonal variations in yield in their study.

Proportional contribution to yield

The changes in the attributes of yield between sites were lower in shoot dry mass than in shoot population density. There was an overall 13% increase in shoot population density from Timbilil to Changoi, but there was a lowering of mean shoot dry mass by 6%. These differences alone do not account for the observed variations in yield between the two extreme yielding sites (58%). This contradicts Squire and Callander (1981) assertion that the main determinant of yield is shoot population density and indicates that the major cause of the differences in yield observed was a temperature induced variation in shoot extension. Indeed the differences in shoot extension rates during the cool wet season increased by 48% from Timbilil to Changoi (Chapter 8). However the lower than expected yield at Kaproret was due to the smaller ground cover, which implies that shoot population density is equally important in influencing yields.

CONCLUSION

Shoot mass, population density and composition were found to vary between the clones studied, seasons and sites. The largest variations observed were those of shoot population density showing a 13% difference between extreme sites. Clone 6/8 with the largest population density, also had the lowest shoot dry mass, a factor which may

explain its observed lower yield than the other clones. On the other hand clone S15/10 was found to have heavier shoots than the other clones.

The relationships between shoot mass and stage (number of leaves) reported in this study are important when considering optimisation of yield and quality. Leaving shoots to grow from two leaves and a bud to three leaves and a bud increases yield (fresh mass) by 40 to 70%. On the other hand shoots with three leaves and a bud are known to have lower quality than two leaves and a bud.

The dry matter contents were also found to vary between clones, sites and seasons. The use of a single conversion factor of 22.5% to convert green leaf to dried tea yields need to be used with caution during periods when SD's are high. The determination of such conversion factors for each site is therefore necessary.

The interactions between clones and environment reported here for shoot population density and mass have various implications in harvesting, clonal selection and breeding work. Warmer environments induce larger shoot population densities but lower shoot mass as compared to cooler environments.

Yield prediction from components of yield used in this study showed good correlation with observed yields, however seasonal yield fluctuations were more difficult to model due to lack of detailed data on seasonal changes in shoot replacement cycles.

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CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

The status of tea as a major foreign currency earner in Kenya may be under threat through lack of land for expansion in either the small holder or large estate sectors. The focus should then be on optimisation of yields on land presently under tea, and clonal improvement through our understanding of their responses to environment. The objectives of this study were to quantify the effects of climate and weather on clonal variability in yield by measuring the differences in dry matter production and partition, and components of yield in some tea clones of known commercial and scientific interest. It was also necessary to determine how changes in environment affect these components.

These objectives have been met in this study and this chapter summarises the main conclusions and addresses some of the issues raised in terms of the responses of tea to the environment and the wider implications for the tea industry in Kenya.

CLIMATE AND WEATHER OF THE SITES

The differences in environment between the sites were small as would be expected given the small range of altitudes used. In the period of this study, the largest difference between sites in rainfall was 700 mm between Timbilil and Kaproret, while the differences in solar radiation showed that in general, Changoi receives about 12% more radiation annually than Timbilil. The mean difference in both air and soil temperatures was about 3°C giving a lapse rate of 6 °C km⁻¹, while the mid-afternoon SDs between extreme sites differed by 50%. While these differences are relatively small compared to seasonal variations in other tea growing regions in eastern Africa, they are nevertheless important since the mean air temperature at higher altitudes in Kericho is close to the base temperature for shoot extension.

Temperature differences between locations in the study area can be predicted using the lapse rate determined in this study if the altitude of is known.

Table 10.1 *Ranking of the four sites in terms of measured meteorological parameters (1 greatest, 4 least).*

Site	Rainfall	Temperature		SD	Wind speed	Solar radiation
		Soil	Air			
Timbilil	1	4	3	3	2	2
Kipketer	2	3	2	2	-	-
Kaprorret	4	2	-	1	-	-
Changoi	3	1	1	1	1	1

- indicates variable could not be measured.

Rational explanations for yield variations are difficult to make in the absence of good weather data even over short distances. Few data are currently recorded so its is therefore recommended that commercial tea companies and the KTDA should be encouraged to record key variables such as temperature, humidity and rainfall. These data could then be used to help predict potential yields in the major tea growing areas of Kenya.

YIELD POTENTIAL AND CLONAL SELECTION

The measured plant physiological parameters were used to assess the proportional contribution to yield. In the third year after planting, the maximum yield from clone S15/10 (Table 10.2) had reached 3760 kg ha⁻¹ at Changoi. However the maximum yield declined as the altitude increased, such that at the highest altitude, the maximum yield recorded was 2340 kg ha⁻¹. Clone S15/10 had a mean yield of 2680 kg ha⁻¹ over all the sites, which was almost 400 kg ha⁻¹ more than the next clone. This response to altitude varied between the clones, with various implications for clonal selection.

The interactions between clones and environments in this study were significantly linear, though three of the clones were similar in their response. This however may have been due to the small number of clones used, and the low yielding Kaprorret site. Existence of a genotype x temperature interaction in yield and dry matter production points to the importance of clonal selection. Plants that do well in one environment may

not necessarily do so over all environments. Indeed clonal selection cannot be complete without multi-locational testing of the desired material.

It is therefore recommended that existing experiments should be repeated over a wide range of environments, with a wider range of commercially important and new clones.

Table 10.2 *Ranking of the four clones in terms of total dry matter production, yield ground cover (GC), harvest index (HI), shoot population density, shoot dry matter content and base temperatures (T_{be} and T_{bd}) (1 greatest, 4 least).*

Clone	Dry matter	Yield	GC	HI	Pop. density	DM ratio	T_{be}	T_{bd}
S15/10	4	1	2	1	2	2	3	3
BB35	3	2	3	2	4	3	1	1
6/8	2	4	4	4	1	4	2	2
TN14/3	1	3	1	3	3	1	4	4

RESPONSES TO TEMPERATURE AND ALTITUDE

The responses to altitude in most of the measured parameters were not statistically significant since they were confounded by the atypical results at Kaproret, but this does not invalidate the yield or dry matter prediction based on temperature (altitude). Changoi was the most favourable environment in the measured plant variables (Table 10.3), and Timbilil the least.

The significant Genotype x Environment interactions in temperature for most of the attributes in Table 10.3 has implications on clonal selection. Extrapolation of the responses to areas outside those studied here show the clones cross-over in yield. Assuming a linear dependence of yield on temperature, at mean air temperature below 14 °C, the yield of clone S15/10 would be lower than that of BB35. However below 12 °C, the yield of S15/10 would be lower than all the clones in this study.

In this study, temperature was the overriding environmental variable determining the potential dry matter production, harvest index and therefore yield of tea. The actual

differences in the rates of dry matter production and yield with temperature were strongly dependent on genotype and temperature. These differences were greater in young tea in this experiment than would be expected in mature tea since canopy development and hence light interception were also related to temperature.

The small temperature differences were so important because the mean temperatures at higher altitudes in Kericho (above 2000 m) are close to the base temperature for growth (7 - 9 °C).

Table 10.3 *Ranking of the four clones in each environment in yield, dry matter production, harvest index (HI), ground cover (GC), shoot population density (pop density) and shoot dry matter ratio (DM ratio) (1 greatest, 4 least).*

Clone	Dry matter	Yield	GC	HI	Pop. density	DM ratio
Timbilil	4	4	4	4	=2	=3
Kipketer	3	3	=2	2	=2	=3
Kaporet	2	2	=2	3	4	=1
Changoi	1	1	1	1	1	=1

Water stress

During the warm dry seasons the response to temperature was overridden by the effects of water stress. These were particularly severe during 1994, when a potential soil water deficit of 460 mm resulted in a greater than 60% yield reduction during the dry season in Changoi. In some cases, dry season yields at the higher altitude sites such as Timbilil were greater than at Changoi because there was less water stress. Potential soil water deficits of this magnitude can be expected on average once every 3 years. So this degree of yield loss is therefore not an unusual situation.

Drought reduced annual yields at Changoi by about 20%, while at Timbilil it was 14%. While these losses are in the same range as those due to hail, yield reduction due to drought would be easier to correct through irrigation. More studies are needed to

assess the extent of yield losses due to drought especially in lower altitude areas similar to Changoi and in regions such as Sotik and Nandi hills, where the dry season has a longer duration. It is therefore recommended that further studies on the economics of yield losses due to drought are undertaken.

Soil factors

The lower than “expected” yields at Kaproret were due to soil compaction and high pH. The mean difference between expected yield and actual yield was almost 600 kg ha⁻¹, a reduction of 22% in expected yield. The clones however varied in the response to these soil conditions. Clone S15/10 showed the largest yield reduction, about 50% of actual yield, while the smallest was that of clone 6/8 with a loss of about 10%. Even clone TN14/3 which is traditionally grown in “hut sites” suffered a 20% yield reduction though plots of clone TN14/3 did appear to be on the worst affected areas. While this might attest to the known attributes of this clone in areas of high pH, this could not be confirmed objectively in this study.

Within the commercial tea plantations, the area with similar soil conditions to the Kaproret site is not known and no proper study has been conducted to assess the yield losses from such areas. A loss of 50% in a small plot is quite considerable in the small holder sector. It is therefore recommended that further study is required to assess these yield losses and the extent of such areas. More efficient ways of rehabilitation of such areas could also be sought.

Hail

Though the hail damage recorded in this study and its effect may have been mild compared to some of the worst cases, the yield losses from two sites during one hail storm were substantial. It was shown that production after a hail storm was less than expected for at least eight weeks. This has implications on labour requirements given that hail usually occurs during periods of peak productions. The problem is confounded more by the unpredictability of occurrence and prevention methods have not been successful in the past.

Hail damage may be something worth considering in the light of inconclusive results so far: but generally, moderate to severe storms will result in a loss in yield for at least eight weeks when the fields will be below average. This lost yield may not be recovered even though there appear to be compensatory effects, when the yield after recovery from stress is more than the mean yield two harvests before the storm.

IMPLICATIONS FOR THE TEA INDUSTRY

A number of areas touched on need further studies. The issues of more locations for clonal trials, loss in yield due to drought and the effects and extent of 'hut sites' need to be addressed.

The other factors to be considered in this conclusion are the dry matter content of shoots, bringing to bearing, and plucking standard.

Results from this study have shown that the dry matter content of shoots varies with clone, site and season. The use of a constant dry matter content may lead to underestimation of yield during drought and an overestimation during wet season. Warmer areas may need to use a higher dry matter content than cooler areas. In experiments on clonal field trials, use of a constant dry matter content may lead to errors since this study has shown that there are clonal differences.

Although bringing to bearing by the continuous tipping method seems to be appropriate for Kericho conditions, the benefits of rapid canopy development induced by pegging need to be re-assessed. Results from this study in comparison to a similar study in Tanzania suggests that bringing to bearing by pegging leads to higher initial yields. Although rapid canopy development will induce lower soil temperatures, and this may be an important factor at Kericho, the benefits of early canopy closure are numerous and include weed control and ease in harvesting.

The plucking standard practised at Kericho is that of harvesting shoots with two leaves and a bud. This implies leaving behind shoots with one leaf and bud and immature ones with two leaves and bud. This results in an increased proportion of shoots with more than two leaves and a bud during the next harvest, with losses in yield if the plucking standard is maintained. However in practice, as shown in this study, a

significant proportion of shoots with three leaves and bud, and even four leaves and bud are also harvested. Since this lowers quality, shorter plucking intervals with harvesting only shoots with two leaves and a bud may be desirable than is the current practice.

Overall this study highlights the immense importance of environment, even in places such as Kericho with seemingly uniform climates. It also underlies the importance of selecting the correct genotype to grow in different environments and the necessity to test clones in as wide a range of environments as possible.

The results from this study can be applied to a broader view of the tea industry, which can be summarised in three points:

- a) Since the potential yield is determined by among other factors, temperature, the value of land at higher altitudes should be less than at lower altitude because of differences in potential yield.
- b) the choice of area to re-plant should reflect how well the yield compares with the potential for that site rather than with the average from a few estates. It may therefore for instance, be better to replant a field yielding 3500 kg ha^{-1} in a low altitude estate rather than one yielding 2000 kg ha^{-1} on an estate above 2000 m since yield potential declines with altitude.
- c) when replanting or developing new areas, the time taken to bring to bearing i.e. to establish maximum yield will depend on temperature and will be longer at higher altitudes.

This work should be of great value to the tea industry since it highlights for the first time that drought in Kericho is important since it significantly affects yield. It also identifies the major influence of soil on yields. Perhaps most important is the GxE interactions which shows the need for clonal selection to be conducted in contrasting environments.

Though this study concentrated on tea alone, the results are applicable to other crops as well. Tea is a perennial crop and in this study, the work on dry matter production and partition would be useful in evaluation of other tree crops. Comprehensive studies on responses of woody crops to temperature are few and this work goes a long way in increasing our understanding of the behaviour of such crops. This is especially important

since the world climate is constantly changing. Global climate change models predict a rise in temperature of 1 to 2 °C as a result of the so called 'greenhouse effect' (Viner and Hulme, 1994). This work is therefore very relevant in helping to predict the likely changes in plant response that will result from global warming. The results presented here highlight how small changes close to the base temperature have large effects on plant physiology and yield. The increase in the yield potential of tea growing areas in Kenya especially at altitudes above 2000 m, may be substantial.

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