RESEARCH ARTICLE

Radiation Use Efficiency and Yield Responses of Clonal Tea (*Camellia sinensis*) to Locations of Production

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Abstract

Tea in Kenya is grown in the high and medium rainfall areas of the Kenyan highlands in east and west of the Rift Valley, at altitudes ranging from 1300 to 2700 m above mean sea level. Variability in responses of tea genotypes to different environments affects the growth, productivity, and quality of tea. The annual receipt of total shortwave radiation received at any site is determined by the latitude and local climate. Within tea growing regions of Eastern Africa, the main receipt of solar radiation varies from 6500–6700 ($MJm^{-2}y^{-1}$) at Mufindi, southern Tanzania and Kericho, Kenya, ($0^0$22'S 35^0 21'E) to 7400 $MJm^{-2}y^{-1}$ at Mulanje, Malawi. Seasonal variations in solar radiation within the year also occur and incident solar radiation at high altitudes can exceed 1000Wm^{-2}. However, the net available energy at the surface of a tea canopy reaches only 100Wm^{-2}. Differences in total light penetration occur among tea varieties. The weight of tea shoots in any one harvest depends on the number developing shoot per unit area, their rate of growth and the average weight of shoots at harvest. Yield components of tea are determined by dry matter production and partitioning. The yield of a tea crop is not primarily limited by the production of dry matter, but by the proportion of the total dry matter partitioned into the "economic yield" of harvestable shoots the harvest index (HI; %). Differences in ground cover, total dry matter and dry matter partitioning between clones and between sites have been attributed to the differences in daily intercepted solar radiation which differ between sites. Nevertheless, dry matter production rates have not been determined for the different Kenyan grown clones in the various tea growing regions of Kenya. A study on 12 clones to evaluate the relationships between the intercepted radiation and its derivatives, environmental factors and yields among selected tea clones in different geographical locations, was conducted on a genotype × environment comprising 20 cultivars laid in a randomized complete block design replicated 3 times, at three locations (Kipkebe, Timbilil and Kangaita). The conversion efficiency, the proportion of radiation intercepted by the canopy, extinction coefficient, incident radiation, and temperature, combined were highly and strongly correlated to yield. However, the only altitude was a significant determinant of conversion efficiency. Altitude is a significant determinant of radiation conversion efficiency and through the efficiency of conversion varies with the location it only contributes to the overall locational parameters that determine yield, the strongest determinant being temperature. Harvest index radiation use efficiency can, therefore, be used as a yield predictor in clonal tea breeding programmes.

Keywords: *Camellia sinensis*, Leaf nutrients levels, Canopy extinction coefficient, Leaf area index.

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Introduction

Kenyan tea is grown in the highland high and medium rainfall areas, in the East and the West of the Rift Valley at altitudes ranging from 1300 to 2700m amsl.[1,2] These regions straddle the equator, and shoots are harvested throughout the year.[3] Yields[4,5] and quality[1,6,7] however, are affected by weather fluctuations within and between the years in any one location. Despite the proximity of the tea growing regions to the equator, the differences in the geographical location have been documented to influence growth rates,[8-11] leaf nutrients levels[12] tea quality[13-17] black tea quality[18] and productivity.[19-21]

Tea is maintained as a low bush by regular pruning and is maintained in a continuous phase of vegetative growth[22,23] The crop is characterized by close planted bushes, pruned to a convenient height for harvesting thus growing to form a canopy. This causes the development of branched twigs in the top 20–40 cm and most of the mature leaves to occur in the top 15cm of the bush. New shoots of two or three leaves and a terminal bud are harvested from the top surface of the bush every 7–21 days after which axils in the topmost leaves of remaining butts develop to become the next crop.[5] The weight of shoots in any one harvest, therefore, depends on the number developing shoot per unit area, their rate of growth and the average weight of shoots at harvest. Yield components of tea have been described as the shoot density, shoot replacement and shoot cycle/rate, shoot extension rate (growth rate). These are determined by the dry matter production and partitioning.[24]

It has also been postulated that the yield of a tea crop is not primarily limited by the production of dry matter, but by the proportion of the total dry matter partitioned into the "economic yield" of harvestable shoots the harvest index (HI; %).[25,26] Partitioning of dry matter to the harvest index can be related to the components of yield which have been identified as shoot extension rate, fresh mass and the dry matter content of the harvested shoots and the shoot density.[25,27] Studies showed variations in dry matter production and partitioning between sites, around Kericho and among clones.[28,29,41,52] Clonal variations in dry matter production and partitioning have been observed, even within a single site.[28] These studies, however, did not relate HI to the yield components.

Correlating photosynthesis with tea crop yield have not been possible because the conditions favorable for photosynthesis also

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favor crop yield.[5] China type tea with photosynthetically favorable semi-erect leaves pose produces four times the yield of Assam tea which has a horizontal leaf pose.[29] The difference, however, was concluded to be related to photosynthetic efficiency of the variety. Differences in stomatal conductances and photosynthetic rates among tea clones demonstrated the differences in photosynthetic rates among tea clones.[32]

The total dry matter produced by tea was reduced by harvesting shoots and which is related to the removal of sinks for photosynthates.[33] However, while ground cover for harvested tea was the same as for unharvested tea, the process of harvesting tea would alter the bush architecture and distribution of radiation which could have reduced photosynthesis.[34] Tea yields are limited by frequent harvesting of tender shoots which prematurely reduced the size of the sink.[25] On the contrary, while harvesting removed available sinks for photosynthates, more sinks were created at the dormant axillary buds, thus assimilates were not reallocated into a structural framework.[35] Clones with higher photosynthetic rates should, therefore, develop new shoots much faster than those with lower photosynthetic rates. Relationships between photosynthetic rates and shoot density or shoot growth rates have, however, not been reported.

The annual receipt of total shortwave radiation received at any site is determined by the latitude and local climate. Within Eastern Africa, tea growing regions received solar radiation varies from 6500–6700 ($MJm^{-2}y^{-1}$) at Mufindi, southern Tanzania (8°36'S, 35°21'E) and Kericho, Kenya, (0°22'S 35°21'E) to 7400 $MJm^{-2}y^{-1}$ at Mulanje, Malawi (16°05'S, 36°36'E).[36] The annual incidence of solar radiation decreases with increasing latitude, the lower receipts in Mufindi than Mulanje are thus probably due to cloud cover.[37] Within the year there are also seasonal variations in solar radiation, as between the wet and the dry season. Incident solar radiation at especially high altitudes can exceed 1000Wm^{-2}. The crop surface reflects 20% of this and a similar amount is re-emitted as longwave radiation.[36] The net available energy at the tea canopy surface reaches 100Wm^{-2}.[26] Most of this short wave radiation is interrupted by leaves in the top 0.3 m of the canopy regardless of the following geometry below 0.1 m.[38] In India, there is a reduction of radiation by 99% within 30 cm of the plucking table for a range of clones while in Malawi only 5% of incoming radiation was reported to reach the ground. In Kenya, the net sum of energy fluxes below the canopy was 4% of net radiation. Variations in total light penetration occur among tea varieties[39] and between locations.[40-42] There are also differences in ground cover, total dry matter and dry matter partitioning between clones and between sites, attributed to differences in daily intercepted solar radiation which differs by as much as 30% between sites.[28] It had previously not been established whether this would vary as much in other sites or among clones. Of the net available energy, a very small proportion is used in photosynthesis, most is dissipated as latent heat (through evaporation) and sensible heat (heating the air).[38] These concepts bear directly onto the effects of sunshine on leaf temperatures, leaf to air temperature differences and the corresponding saturation deficit (SD) between leaf and air. Seasonal differences have a large effect on the leaf to air SDs hence on shoot extension rates and therefore yields. Dry matter (DM) production depends on the conversion efficiency (*e*) (i.e., the proportion of solar radiation intercepted by the leaves $S_{(i)}$ that is converted into DM).

$$DM = S_{(i)} \times e \qquad 1.0$$

Where *e* is the amount of dry matter produced (in grams) per megajoule of solar radiation intercepted by the leaves (g^{-1} mj^{-1}). The crop yield, therefore, is determined by the amount of DM partitioned into the harvestable organs, the harvest Index (HI).[36] Rate and duration of expansion are largely controlled by temperature when other factors (e.g., humidity and moisture) are not limiting. The yield of processed tea, therefore, is determined by the shoot density, their rate of growth and their average dry weight at harvest. In cropping systems the interception and efficient use of radiation to produce dry matter define the potential yield. Therefore the DM production (gm^{-2}) of tea or any crop can be determined from incoming solar radiation (S; MJm^{-2}), the proportion of radiation intercepted by the canopy (f_s) and the dry matter/light conversion ratio or conversion efficiency (E_s; g MJ^{-1}) (also termed the Radiation Use Efficiency-RUE)[42] using the formula 2.0 below:

$$DM = S \times f_s \times E_s \qquad 2.0$$

Estimate of conversion efficiency (Es) for tea in Kericho, Kenya was found to be substantially lower (0.25 g MJ^{-1}) than for most temperate (1.3-1.6 g MJ^{-1}) and tropical annual crops (0.6-0.8 g MJ^{-1}), being closest to natural rainforest (0.20 g MJ^{-1}).32 In a high altitude site in Southern Tanzania (Ngwazi Tea Research Unit at 8°32'S,35°10'E, 1840 m a.m.s.l)[44] recorded higher conversion efficiency values on four contrasting tea clones (0.40 to 0.60 g MJ^{-1}) which corresponded closely to other woody tropical plants. Clone S15/10 a high yielding cultivar from Kenya partitioned a greater proportion of dry matter to leaves and harvested shoots than other clones, recoding a substantially greater maximum harvest index of 24%.[43] The proportion of solar radiation intercepted (f_s) by a discontinuous canopy like young tea depends on ground cover (GC), the leaf area fraction of area of ground covered (LAI) and the extinction coefficient for light (k) as expressed in Equation 3.0.[45]

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

Extinction coefficient (k) values for other crops range from 0.8 for planophiles (flat) leaved canopies to 0.3 for erectophile canopies.[46] For a given leaf area, clones with horizontal leaves are therefore likely to intercept a greater proportion of light than erect leaved clones.[34] However, at full ground cover plants with erect leaves may compensate for this by having higher leaf area indices (LAI). The value of LAI at full ground cover ranged from 4 for Assam type clones with horizontal leaf orientation to 8 for the erect leaved China types.[31] Assimilates produced by photosynthetically active leaves can be relocated within the plant and used for the growth and development of leaves, stem or roots. It has also been argued that it is the proportion of DM proportioned into harvestable shoots that is responsible for determining low yields.[25,26] Variations in HI between two clones were recorded as 6.9% for the lowest yielding clone and 16.0% for the highest yielding.47 The annual DM was similar at 8.7-10.4 t ha^{-1}, so the clonal difference in HI resulted in an increase in annual yield of made tea from 0.6 to 1.7 t ha^{-1}.

Dry matter production rates have not been determined for the different Kenyan grown clones in the various tea growing regions of the East and West of the Rift. This study attempted to use intercepted radiation values to derive light extinction coefficients for different clones as an index for yield estimation among clones in different geographical locations.

METHODOLOGY

Experimental Treatments and Design

The trial was set up in three different tea growing geographic regions in Kangaita (Kirinyaga), Timbilil (Kericho) and Kipkebe (Sotik) (Table 1). Slopes at all the sites were gentle to slightly sloping (0-15%). The experiments were set up on plots of same age mature tea, comprising twenty clones viz. TRFK 6/8, TRFK 31/8, AHP S15/10,

Table 1: Geographic location and climatic attributes of the study sites.

Site	Location	Latitude	Longitude	Altitude (m amsl)	Mean annual Rainfall (mm)	Mean annual T^oC_{Min}	Mean annual $T^\circ C_{Max}$	Mean annual RH (%)
Timbilil	TRFK, Timbilil, Kericho	0°22'S	35°21'E	2180	2154	8.8	23.3	62.4
Kangaita	KTDA Kangaita Tea Farm, Kirinyaga	0°30'S	37°16'E	2100	2016	10.9	20.2	76.7
Kipkebe	Kipkebe Tea Company, Sotik, Nyamira	0°39'S	35°02'E	1800	1623	13.9	25.0	71.4

EPK TN14-3, BBK 35, TRFK 54/40, TRFK12/12, TRFK 12/19, TRFK 31/27, TRFK 11/26, TRFK 57/15, TRFK 7/3, TRFK 7/9, TRFK 56/89, STCK 5/3, TRFK 303/259, TRFK 303/577, TRFK 303/999, TRFK 303/1199 and TRFK 2X1/4 set in Randomized Complete Block Design replicated thrice at each location.[19] Each plot comprised of 20 bushes. The tea was managed under standard management practices in Kenya.[1]

Leaf Area Index

A sample of 200 undamaged leaves from the top bottom, middle and bottom of the canopy of 12 selected plants were randomly detached from the bush. The twelve plants comprised 4 each of mean high, medium and low yielding clones, determined from 2012 yields of the 20 clones in the trial study. The leaves were weighed, the length and breadth (l x w) recorded then bagged and transported to the laboratory for drying. The leaves were oven dried at 105°C for 48 hours to obtain the dry weight. This was used to determine the leaf area per unit dry weight, i.e., specific leaf area (SLA). At the end of the trial period, the selected plants had all pluckable shoots removed then cut at the base of the stem, stripped of all leaves and the leaves weighed to determine the fresh weight. The leaf area was determined by applying the formula:

$$A = l^2 \times 0.24^{50} \qquad (1)$$

Where:

l = length of leaf along the leaf midrib.

The specific leaf area was then used to determine the leaf area of the leaves from the whole bush after weighing and drying all the leaves from the bush. The LAI was then determined by dividing the total leaf area by the canopy ground cover (area of the spacing $0.6x1.21m^2$).

Radiation use Efficiency (RUE)

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

$$DM = S \text{ X } fs \text{ X } Es \qquad (2)$$

where:

DM = Green Leaf dry weight

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

fs = the proportion of radiation intercepted by the canopy

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

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

$$fs = GC\ (1\text{-}e(\text{-}kLAI))^{45} \qquad (3)$$

where:

GC = ground area covered by the canopy

LAI = leaf area index as described above

k = extinction coefficient;

The extinction coefficient was determined using the formula:

$$k = [\log_e (I/I_o)]/LAI^{48} \qquad (4)$$

Where:

I_o = radiation on top of canopy

I = radiation at ground level under the canopy.

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

$$MJm^{-2} = Wm^{-2}\ (3.6\ KJW^{-1})/103^{50} \qquad (5)$$

Where:

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

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

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

Incident and Intercepted Radiation

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

$$I_{Rad} = \frac{I_{RT} - I_{RB} \text{ x } 100}{I_{RT}}$$

Where:

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

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

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

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

Where:

R = Rad = Radiation in Watts/m^2

r = Kipp's solarimeter reading

cf = conversion factor of solarimeter

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

Yields

Green leaves comprising of mostly two leaves and a bud were plucked every 7–10 days and converted to made tea (mt) by multiplying by a factor of 0.225.[1]

Data Analysis

The data collected were subjected to analysis of variance (ANOVA) at a significance level of at least 5%, using MSTAT-C (Version 2.10) statistical package, as a factorial two design, with clone (genotype) as the main factor and location as the second factor. Correlations between yield, radiation, RUE components, and weather parameters were done using SPSS (Version 17.0) statistical software.

Results and discussion

Clonal selection

Four each of the mean highest, median and lowest yielding clones selected from the 20 clones in the study are shown in Table 2.

Weather and geographical locations

The weather characteristics from the three trial sites during the duration of the trial have been discussed in earlier publications.[51] Overall, annual weather patterns varied (Table 3) and the seasonal weather patterns though similar, varied in magnitude across locations, which partially explain the variations of yields across the sites recorded earlier.[51]

Incident radiation showed significant ($p \leq 0.05$) variations with location and seasons (Table 4). Similar results were reported for three countries in East Africa.[36] Kipkebe recorded the highest ($p \leq 0.05$) amount of incident radiation, but there was no significant difference in incident radiation between Timbilil and Kangaita. Similar results were reported for three countries in East Africa.[36] and within Kenya.[55] The annual receipt of total shortwave radiation received at any site depends on the latitude and local climate.[36] The mean annual incidence of solar radiation decreases with increasing latitude; thus the locational variations in incident radiation observed may be due to cloud cover as had been reported earlier for locations in Malawi and Tanzania.[40] These locations were close to the equator (Table 1). The observations from Timbilil and Kangaita concur with the findings that incident solar radiation was unlikely to vary so much between locations[43] at high altitude, but the altitude of Kipkebe was much lower. Indeed differences by as much as 30% between sites within 10 km radius at varying altitudes have been recorded in Kenya.[55] The mean seasonal radiation also varied ($p \leq 0.05$) across the four seasons, similar to earlier findings.[53]

The site and season interactions effects were also significant ($p \leq 0.05$) with the seasonal differences varying between locations. These interactions were demonstrated by the observations that although Kipkebe recorded the highest mean incident radiation (11433 Wm^{-2}), Timbilil received the highest radiation (12522 Wm^{-2}) during January March season and also the least radiation (6637 Wm^{-2}), in July September. The findings contradict earlier prediction[43] that in Kenya tea growing areas, incident solar radiation was unlikely to vary so much as to noticeably affect the yields of tea. This study recorded figures much higher than the 1000 Wm^{-2} earlier predicted for the high altitude areas.[36] A very small proportion of the net available energy is in photosynthesis, most being dissipated as latent heat (through evaporation) and sensible heat (heating the air).[36] These concepts bear directly onto the effects of sunshine on leaf temperatures, on the leaf to air temperature differences and as the corresponding saturation deficit (SD) between leaf and air. In the rainy season the surface leaf temperature is warmer (0.3°C) than the air for each 100Wm^{-2} of solar radiation up to a maximum of 3°C but up to 6°C in the dry season or up to 12°C if the stomata were closed.[26] These differences have a large effect on the leaf to air SDs hence on shoot extension rates and therefore yields. Seasonal yield variations and the locational variations as reported earlier,[55,53,36] can thus be attributed to the prevailing patterns of solar radiation observed. Due to these variations incident, solar radiation can be higher than those previously measured. For purposes of yield estimation, it is, therefore, advisable to use means of values measured over a long period. This may necessitate the installation of radiation measuring equipment in various tea growing areas for more accurate data and modeling.

Table 2: Ranking of mean Annual yields of twelve selected clones (Kg mt /ha/yr)

Clone	*Kangaita*	*Timbilil*	*Kipkebe*	*Mean*
TRFK 303/577	2346	3631	5768	3915[a]
TRFK 303/1199	1684	2554	5389	3209[a]
[A]HP TN 14-3	1427	2511	3821	2596[a]
FK 57/15	1299	986	4846	2377[a]
TRFK 56/89	1151	1952	4023	2375[b]
TRFK 12/12	1395	1337	4123	2285[b]
TRFK 2X 1/4	852	799	4919	2190[b]
BB 35	994	1614	3952	2187[b]
TRFK 31/27	1458	1531	3182	2057[c]
TRFK 7/9	1101	1289	3716	2035[c]
TRFK 7/3	885	764	4279	1976[c]
TRFK 6/8	937	825	3150	1637[c]

[a] = highest yielding; [b] = intermediate yielding; [c] = lowest yielding

Intercepted Radiation (I_{Rad})

The intercepted radiation showed significant ($p \leq 0.05$) genotypic, location and seasonal differences (Table 5). Mean clonal differences in I_{Rad} were significant. The clonal differences varied from location to location as demonstrated by the significant genotype x location interactions. Similar observations were made earlier on four clones in four locations.[54] The abilities of clones to capture solar radiation are related to their canopy architecture.[33] However, characteristic changes from location to location could be attributed to variations in plant growth responses to the environment.

Intercepted radiation was observed to vary with locations, with Timbilil and Kipkebe recording higher ($p \leq 0.05$) I_{Rad} than Kangaita. Similar observations were earlier reported form sites within a 10 km radius in Kericho.[55] Nonetheless, actual differences in daily intercepted solar radiation between studied tea growing locations in Kenya are reported herein (Table 4) for the first time. Such variations in intercepted solar radiation with clone and location have been reported in other tea growing countries. For example, in India 99% of radiation was intercepted by a range of clones[40] in Malawi 95% was intercepted,[28] and in Kenya, 96% was recorded[42] in single locations. Differences in total light penetration occur among tea varieties.[39] The findings of this study, therefore, confirm that as long as canopy architecture differ or environmental growth factors vary, the proportion of intercepted radiation in tea growing areas of Kenya will vary. This in part accounts for differences in growth parameters and yields observed in different clones or even the same clone grown in different locations.

Mean seasonal intercepted radiation varied significantly between seasons. However, in October December season there was no significant difference between clones in intercepted radiation, this being attributable to the conducive growth conditions (Table 3) which precluded conditions that would limit plant growth and hence the expression of genotypic characteristics as discussed in earlier publications.[51] The clones x site interactions were significant in every season, except in October December season as observed in the variations in clonal I_{Rad} values between locations. This was attributed to locational variations in plant canopy growth response to seasonal weather patterns (Table 3). Indeed, the leaf area indices (LAI) showed clonal and locational variations ($p \leq 0.05$) (Table 6). Intercepted radiation varied by between 3% (Kericho and Sotik)

Table 3: Monthly weather parameters at the three study locations, Jan – Dec 2012

	Timbilil							Kangaita							Kipkebe						
	Temp(°C)				Rain			Temp (°C)				Rain			Temp(°C)				Rain		
	max	min	mean	rain	days	rh%	svpd (kPa)	max	min	mean	Rain	days	rh%	svpd (kPa)	max	min	mean	rain	days	rh%	SVPD (kPa)
Jan	25.7	7.7	16.7	0	0	62	1.51	23.5	9	16.25	17.2	3	32	0.95	28.7	11	19.85	0.5	0	47	0.94
Feb	26.3	9.1	17.7	26.8	7	55	1.55	21.4	9.1	15.25	19.7	4	35	1.09	28.4	11.7	20.05	82.9	11	70	0.94
Mar	27.5	8.5	18	27.7	6	63	1.41	23.9	10.3	17.10	40.3	3	36	1.13	28.7	10.1	19.40	50.1	7	70	1.00
Apr	23.3	7.2	15.25	398.4	25	62	0.54	18.8	13.5	16.15	449.6	23	89	0.48	26.7	12.3	19.50	514.4	26	82	0.50
May	22.9	9.8	16.35	391.1	24	71	0.36	19.3	13.5	16.40	692.0	25	96	0.43	27	12.2	19.60	249.4	24	81	0.44
Jun	22.2	9.7	15.95	226.9	20	80	0.44	16.9	12.6	14.75	89.4	16	42	0.51	26	11.2	18.60	178.3	20	85	0.39
Jul	21.7	9.7	15.70	160.9	13	70	0.51	14.6	11.9	13.25	49.1	16	40	0.41	25.6	11.6	18.60	122.6	10	83	0.48
Aug	22.8	9.4	16.10	298.9	18	71	0.51	16.4	10.7	13.55	190.5	14	48	0.32	26.6	11.1	18.85	97.7	11	81	0.61
Sept	22.7	8.7	15.70	239.1	24	71	0.60	17.7	15.3	16.5	121.8	8	44	0.48	24	11.5	17.75	194.5	17	80	0.52
Oct	23.7	10	16.85	269.4	24	73	0.39	18	12.7	15.35	325	11	80	0.33	28.4	12.5	20.45	99.3	16	76	0.53
Nov	24.1	9.7	16.90	227.6	22	80	0.66	18.5	12.4	15.45	234.1	13	70	0.12	27	12.3	19.65	97.1	15	81	0.34
Dec	22.9	9.9	16.40	172.3	15	62	0.74	18.5	11.7	15.10	169.6	17	46	0.42	27.2	12.2	19.70	261.6	17	82	0.42
Total	–	–	–	2439	198	–	–	–	–	–	2398	153	–	–	–	–	–	1948	174	–	–
Mean	23.8	9.1	16.5	–	–	68.3	8.0	19.0	11.9	15.4	–	–	54.8	5.3	27.0	11.6	19.3	–	–	76.5	5.9

Temp = ambient temperature; max = maximum temperatures; min = minimum temperatures; rain = Total monthly rainfall; rh = mean relative humidity; svpd = saturated vapour pressure deficit incident radiation (Wm^{-2})

Table 4: Effect of location (site) and season on Incident radiation (Wm^{-2})

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

and 30% (Kericho and Kirinyaga) between locations. Earlier55 daily intercepted solar radiation differed by as much as 30% between sites in Kericho that were within a 10 km radius.

Radiation intercepted by the clonal teas varied significantly between sites and across the seasons. Interactions were also significant with the clonal radiation intercepted by individual clones varying with locations and seasons. This varied from 97.87% in clone EPK TN 14-3 in Timbilil in Oct-Dec season to 56.9% in clone TRFK 57/15 in Kangaita in Jul-Sept season. It had been posited that in Kenya tea growing areas, intercepted radiation was would be uniform except following hail damage, thus yield variation between fields and clones would be mostly due to the conversion efficiency and dry matter (DM) partitioning to Harvest Index (HI).43 Findings from this study indicate that radiation is not intercepted uniformly across seasons and locations in tea growing areas in Kenya as earlier postulated. The variations can also be much larger than that previously recorded at 30%. These findings further demonstrate that the interaction of the three factors of genotypes, locations and season in determining yields may also explain the large yield variations observed between genotypes, locations and season.

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

The photosynthetically active radiation intercepted by the canopy (*fs*) showed significant ($p \leq 0.05$) clonal and locational differences (Table 6). These observations contradict those earlier made, that across tea growing areas in Kenya *fs* is unlikely to vary significantly as to affect tea yields after attaining of the full canopy.[43]

Interception of PAR by a crop canopy is strongly related to total leaf area. A crop will thus intercept more PAR and hence grow faster if it develops leaf area rapidly. This principle applies to both annual crops which are usually planted at the beginning of a growing season and perennial crops which resume growth after a dormant season.[54] The findings show that though these differences between clones may not be large, locational differences can be quite large as seen in the differences in *fs* values, between clones, between Kangaita in the east of the Rift Valley and Timbilil and Kipkebe in the west of the Rift Valley. This may lead to quite large yield differences (Table 8). It is therefore important that clones are tested in new areas prior to release for commercial exploitation.

Canopy extinction coefficient (k) and Leaf area index (lAI)

The canopy extinction coefficient (k) is an expression of the power of a canopy to capture light. Extinction coefficients showed significant ($p \leq 0.05$) genotypic and locational differences (Table 6). Values recorded ranged from 6.89 in clone TRFK 2x1/4 (Timbilil)

Table 5: Effect of genotype and site on intercepted radiation (measured as % of total incident radiation)

		Jan Mar				*Apr Jun*				*Jul Sept*				*Oct Dec*		
	Kgta	*Tmbl*	*Kpkb*	*Cln mean*	*Kgta*	*Tmbl*	*Kpkb*	*Cln mean*	*Kgta*	*Tmbl*	*Kpkb*	*Cln mean*	*Kgta*	*Tmbl*	*Kpkb*	*Cln mean*
TRF 7/3	59.87	88.87	87.93	78.89	60.17	82.23	90.03	77.48	63.13	93.67	88.23	81.68	61.57	97.17	89.33	82.69
303/577	59.67	93.03	89.07	80.58	64.07	95.70	90.17	83.31	62.27	96.20	89.03	82.50	65.33	97.83	77.00	80.06
TN 14-3	61.33	91.87	87.77	80.26	64.97	93.73	88.00	82.23	60.87	95.50	89.10	81.82	62.97	97.87	89.57	83.47
2X1/4	59.63	87.80	89.37	78.93	64.10	74.30	88.70	75.70	61.67	73.07	88.60	74.44	62.17	90.40	88.60	80.39
STC 5/3	61.00	92.10	88.27	80.46	64.23	93.57	86.73	81.51	62.03	95.43	87.27	81.58	63.40	96.57	87.57	82.51
TRF 11/26	59.83	92.30	88.00	80.04	64.40	88.60	87.60	80.20	60.30	94.57	87.20	80.69	62.50	97.23	88.17	82.63
TRF 12/19	60.50	91.00	87.63	79.71	64.10	88.23	90.00	80.78	60.00	93.30	88.67	80.66	61.50	97.03	89.20	82.58
56/89	59.47	92.00	87.53	79.67	63.33	94.83	88.27	82.14	60.03	95.57	88.83	81.48	63.60	96.30	89.37	83.09
TRF 12/12	59.60	90.47	87.97	79.34	64.30	85.83	89.07	79.73	60.13	94.27	88.20	80.87	62.50	97.07	89.60	83.06
303/999	60.30	90.13	88.97	79.80	63.30	85.20	88.73	79.08	60.47	95.33	87.63	81.14	62.43	96.97	90.23	83.21
S 15/10	60.50	89.23	89.73	79.82	63.87	83.17	87.90	78.31	60.13	91.43	89.47	80.34	63.13	95.73	89.33	82.73
57/15	60.63	88.60	88.17	79.13	63.57	86.23	87.67	79.19	56.90	93.90	87.50	79.43	62.80	99.67	88.33	83.60
31/27	60.53	91.77	89.64	80.64	64.70	88.27	88.63	80.53	60.60	93.93	88.57	81.03	61.53	97.00	88.50	82.34
TRF 6/8	60.87	89.07	86.90	78.94	61.90	86.33	88.87	79.03	58.70	92.93	88.37	80.00	60.40	96.30	89.97	82.22
BB 35	60.17	91.97	87.53	79.89	61.50	83.27	87.93	77.57	60.67	94.03	88.23	80.98	60.57	97.43	90.80	82.93
TRF 31/8	59.67	89.73	87.87	79.09	64.23	80.73	89.57	78.18	58.97	93.94	88.17	80.37	63.13	94.73	89.97	82.61
TRF 7/9	60.23	91.30	89.77	80.43	63.23	90.77	87.97	80.66	60.33	94.90	87.23	80.82	62.60	96.87	88.33	82.60
303/259	60.53	90.60	88.50	79.88	65.23	89.50	87.00	80.58	59.97	94.27	89.10	81.11	62.30	96.90	87.43	82.21
303/1199	60.17	93.07	87.97	80.40	65.13	94.37	87.57	82.36	58.63	95.40	87.53	80.52	62.80	97.37	88.40	82.86
54/40	60.90	89.03	89.10	79.68	64.13	84.50	89.73	79.46	59.33	93.20	88.90	80.68	63.90	95.30	89.07	82.76
Ste mean	60.26	90.70	88.38		63.72	87.47	88.51		60.29	93.24	88.29		62.56	96.59	88.44	
	CV%	1.65			CV%	4.27			CV%	3.65			CV%	4.13		
		Clone	Site	CxS		Clone	Site	CxS		Clone	Site	CxS		Clone	Site	CxS
	LSD (0.05)	1.22	0.47	2.11		3.16	1.22	5.47		2.72	1.05	4.712		N S	1.22	NS
	All 4 Seasons															
	CV%	3.64														
		Kangaita	Timbilil	Kipkebe												
	Site mean	61.707	91.999	88.406												
		SSN1	SSN 2	SSN 3	SSN 4											
	SSn mean	79.78	79.901	80.607	82.527											
		Clone	Site	Season	ClnXSte	ClnxSSn	StexSsn	CxSxSSn								
	LDS ($p < 0.05$)	0.36	0.53	0.61	2.35	NS	2.72	1.05								

to 0.27 in clone TRFK 303/577 (Kangaita). Extinction coefficient (k) values for other crops range from 0.8 for planophiles (flat-leaved) canopies to 0.3 for erectophile (upright leaved) canopies.[46] The clones studied included chinary varieties, e.g. TRFK 303/577, which represent erectophile canopies, and Assamica variety such as TRFK 2x1/4 representing planophiles leaved canopies. The findings herein were thus similar to but wider in range than those earlier reported for tea.46 The larger values obtained in this study could be attributed partly to the heterogeneity of tea and its overlapping morphological characteristics[55-58] which would result in a wide range of leaf areas (Tables 6 and 7), even within the same plant and partly to the fact that this study was conducted on mature tea with well developed deeper canopies that capture light more rapidly than young canopies as those reported.[46] For a given leaf area, clones with horizontal leaves are likely to intercept a greater proportion of light than erect leaved clones.[36] However, at full

Table 6: Effect of genotype and site on the proportion of PAR intercepted by canopy (fs), canopy extinction coefficient (k) and leaf area index (LAI)

	fs				*k*				*LAI*			
	Kgta	*Tmbl*	*Kpkb*	*Cln mean*	*Kgta*	*Tmbl*	*Kpkb*	*Cln mean*	*Kgta*	*Tmbl*	*Kpkb*	*Cln mean*
303/577	0.44	0.67	0.64	0.58	0.27	2.02	1.16	1.15	4.38	1.32	1.74	2.48
303/1199	0.47	0.73	0.68	0.62	0.49	6.66	2.73	3.29	2.05	0.66	0.96	1.22
BB 35	0.46	0.71	0.66	0.61	0.76	5.26	2.13	2.72	1.34	2.31	1.2	1.03
TN14-3	0.45	0.57	0.66	0.56	0.41	1.72	1.57	1.23	2.31	1.2	1.56	1.66
TRFK 12/12	0.45	0.69	0.67	0.6	2.23	2.26	1.17	1.89	0.47	1.19	2.23	1.3
56/89	0.56	0.69	0.68	0.61	0.84	3.56	1.45	1.95	1.33	0.87	1.84	1.35
31/27	0.46	0.67	0.69	0.61	0.55	3.11	2.44	2.03	1.77	0.95	1.18	1.3
TRFK 7/9	0.54	0.66	0.63	0.58	0.54	4.3	1.69	2.18	1.84	0.66	1.12	1.2
2 x 1/4	0.46	0.69	0.65	0.6	1.11	6.89	2.99	3.66	0.94	0.4	0.73	0.69
TRFK 6/8	0.46	0.69	0.64	0.6	0.6	2.09	0.83	1.18	1.61	1.45	2.51	1.86
57/15	0.46	0.68	0.65	0.6	1.41	4.02	1.07	2.17	1.36	0.68	2	1.34
TRFK 7/3	0.47	0.68	0.67	0.6	0.92	2.28	1.22	1.48	1.56	1.42	1.95	1.64
Ste mean	0.45	0.68	0.66	–	0.85	2.02	1.71	–	1.75	0.95	1.57	–
CV%	CV%	0.18	–	–	CV%	46.44	–	–	CV%	48.53	–	–
	Clone	Site	CxS	–	Clone	Site	CxS	–	Clone	Site	CxS	–
LSD(0.05)	0.0011***	0.0006***	0.0017***	–	0.91***	0.45***	1.58***	–	0.65***	0.33***	1.13**	–

C = clone; S = site (location)

Table 7: Effect of genotype and site on specific leaf area (SLA), and radiation use efficiency (Es)

	SLA (Cm2g^{-1})				*Es (gMJ-^{1})*			
	Kgta	*Tmbl*	*Kpkb*	*Cln mean*	*Kgta*	*Tmbl*	*Kpkb*	*Cln mean*
303/577	106.99	27.8	41.39	58.72	21.29	27.74	27.53	25.52
303/1199	96.8	18.4	30.4	48.56	16.41	18.44	23.43	19.43
BB 35	84.69	26.79	47.33	52.93	7.97	12.27	18.67	12.97
TN14-3	124.3	33.72	37.07	65.03	12.71	18.87	17.97	16.52
TRFK 12/12	112.51	27.75	54.46	64.9	12.89	8.83	19	13.58
56/89	108.34	23.16	45.33	58.94	9.18	11.44	18.18	12.93
31/27	94.43	22.33	37.96	51.57	11.94	11.83	14.11	12.63
TRFK 7/9	111.95	20.93	35.29	56.06	9.81	8.95	18.29	12.35
2 x 1/4	96.59	23.56	38.42	52.79	7.97	5.43	22.88	12.09
TRFK 6/8	92.79	26.14	46.72	55.22	8.14	6.45	15.55	10.13
57/15	94.55	18.53	47.77	53.62	11.49	6.74	22.28	13.5
TRFK 7/3	77.15	25.66	48.06	50.28	8.43	5.65	19.7	11.26
Ste mean	100.09	24.55	42.52		11.52	11.9	19.8	
CV%	19.46				CV%	22.99		
	Clone	Site	CxS			Clone	Site	CxS
LSD(0.05)	10.22	5.11	17.71		LSD(0.05)	3.12	1.56	5.41

Table 8: Correlation between yields, RUE components and weather and location parameters

	fs	*I Rad*	*Es*	*k*	*temp*	*Alt*
Yld	0.430***	0.614***	0.541***	-0.093NS	0.872***	-.863***
Fs		0.944***	0.218*	0.568***	0.638***	-0.276**
I Rad			0.382***	0.398***	0.815***	-.501***
Es		.		-0.120NS	.557***	-.558***
K					0.024***	0.249**
temp						-.910***

NS = Not significant.
Yld = Annual yield
I Rad = Intercepted radiation
Es = Conversion efficiency (radiation use efficiency)
K = canopy extinction coefficient

ground cover plants with erect leaves may compensate for this by having higher LAI. In this study, all the canopies were fully developed and had attained full ground cover.

The LAI also showed significant ($p \leq 0.05$) clonal and locational variations. The clone x location interactions were also significant, and clonal differences varied between locations. The variations in LAI observed are an indication, in this instance, of variability in canopy depth as opposed to the extent, which was restricted by the plant spacing. The recorded LAI values varied from 4.38 on clone TRFK 303/577 in Kangaita to 0.40 in clone TRFK 2 × 1/4 in Timbilil. The value of LAI at the full ground cover was reported in North India to range from 4 for Assam type clones with horizontal leaf orientation to 8 for the erect leaved China types.[38] LAI values obtained in this study ranged far lower than those obtained in India[38] a phenomenon, indicative of locational and clonal differences. However, variations of between 5.2 to 6.1 in two, 4-year-old clones in two geographical regions were reported in Kenya[65] which were also higher than but closer to the values obtained in this study. The differences between the earlier findings in Kenya and those of this study could be due to the age of the teas while those from India could be due to the difference in climatic and environmental conditions. LAI showed significant ($p \leq 0.05$) variations with a geographical area of production, a factor once again attributed to the canopy growth response to climate. The variations in LAI values obtained in this study and North India[38,40] could also be attributed to the fact that the LAI determination in the different studies used different methods. Indeed, it had been reported that LAI values will depend on the method used[59] In this study LAI was estimated using a rapid leaf area determination formula.[60] However, the observed variations in LAI with a geographical area of production are sufficient indication that canopy development will vary with area and season of production. Leaf area index is related to crop biomass and radiation use efficiency which is a key factor in determining crop yield.[61] LAI has a direct bearing on tea yields and therefore crop management in diverse environments cannot be expected to be uniform and still attain the same level of yields.

Specific Leaf Area (SLA)

Specific leaf area (SLA) is the leaf area per unit dry weight. The specific leaf area method is a rapid way of estimating leaf area, following length and breadth measurements[62] of crops like tea which bear leaves profusely compared to maize, for example. The SLA varied ($p \leq 0.05$) with clones and location (Table 7), similar to the intercepted radiation and components of radiation use efficiency (Tables 6 and 7). Clonal variations in SLA had been reported before.[63] Clones with higher specific leaf areas had lighter leaves with a higher rate of growth and development and more surface area for photosynthesis.[63] Site differences in specific leaf area were also significant. These parameters are precursors of yield, and their variations are therefore indications of variations of yield with genotype and location, respectively. The significant ($p \leq 0.05$) clone and location interactions demonstrate variations of clonal response to the location. The results further emphasize the tea plant's genetic variability and the variability in the individual plant's response to the environment. As such clones may not be expected to respond the same in all environments and may therefore not be adopted for commercialization before testing.

Radiation Use Efficiency (Es)

The tea crop yield is determined by the amount of DM partitioned into the harvestable organs, the harvest Index (HI).[36] The radiation use efficiency (RUE) (also termed, conversion efficiency (Es; g MJ^{-1})), in this stud, was estimated as the amount of radiation utilised in producing dry matter (DM) in the two leaves and a bud green leaf harvested in a year as opposed to the total plant dry matter as used in other studies in tea.[20,28] This is referred to herein as the "harvest index radiation use efficiency (HIRUE)" and has for the first time been used to estimate crop dry matter in studies in Kenya. There were significant (≤0.05) HIRUE differences due to clones and site (Table 7). The values from 12 clones, ranged from 27.74 gMJ^{-1} in clone TRFK 303/577 to 5.34 gMJ^{-1} in clone TRFK 2x1/4 both in Timbilil (Table 7). One hundred fold lower conversion efficiency (Es) were earlier recorded tea in Kericho (0.25 g MJ^{-1}) (Burgess, 1992), (0.1–0.56 g MJ^{-1})41 and Tanzania (0.40 to 0.60 g MJ^{-1}).[43] The differences could be explained by the difference in parameters used in estimating conversion efficiency. Whereas this study estimated conversion efficiency based on annual yield, the studies mentioned above estimated Es from whole the harvest index at the time of sampling of the whole plant for dry matter determination. Nevertheless, Es expressed as the weight of dry matter produced per unit of radiation intercepted can be used to compare the performance of canopies of very different structure and leaf area indices growing in different climates.[43]

Significant ($p \leq 0.05$) clonal and locational differences in conversion efficiency (Es) were observed. Similar findings had been reported by in Kericho[40] and Tanzania.[45] The HIRUE results showed that conversion efficiency varied with the geographical area of production. In a high altitude site in Mufindi Southern Tanzania (Ngwazi Tea Research Unit at 8032'S,35010'E, 1840 m a.m.s.l), much higher conversion efficiency values on four contrasting tea clones (0.40 to 0.60 g MJ^{-1}) were observed[43] than those recorded in equally high altitude area of Kericho, Kenya. This study, however, recorded significantly lower mean conversion efficiencies for 12 clones at high altitudes (11.52 and 11.90 g MJ^{1}) in Kangaita and Timbilil, respectively), above 2000m a.m.s.l. than at low altitude (19.70 g MJ^{-1}). This is could be due to the lower temperatures associated with the high altitudes in tea growing areas in Kenya compared to those of Southern Tanzania.

Small differences in solar radiation between sites gave rise to large differences in ground cover and harvest indices which were the main contributors to yield variations between sites and clones.[20] It had been proposed those yield improvements in tea would be obtained from an increase in RUE or HI.[44] Other studies suggested that RUE varied little with temperature.[52] and thus yield differences between sites were due to HI and ground cover.[20] Incident radiation may not be limited to Es as long as a critical level of radiation is achieved.[43] This could explain the lack of significance in Es between the two high altitude sites which received lower incident radiation. The results further indicate that while RUE is genetically determined, the potential RUE will vary with the environment under which the clone is grown. The response to this environment varies with a clone as demonstrated by the significant ($p \leq 0.05$) genotype and location interactions. Tea plants have different efficiency potentials to exploit solar radiation. This potential is further modified by the influence of the environment on the plant growth responses, the Genotype × Environment interaction effect. Conversion efficiency (RUE) can, therefore, be used to compare the potential performance of clones in different environments as has also been posited earlier.[43] RUE will vary with genotype and environment and consequently yields, similarly. This is therefore needed for testing or accurately modeling varieties for potential yields before releasing into new environments.

Radiation and Yield Interactions

This relationship supports and explains the findings that tea yields decline with altitude.[64-66,9,11] Tea yields decline due to reduced shoot growth rate with an increase in altitude.

The mean locational HIRUE (Es) correlated positively to the annual yields. (Table 15). Incident radiation and conversion efficiency and its components and ambient temperature gave significant positive correlations with yield but significant negative correlations to altitude. These relationships support and explain the findings that tea yields decline with altitude,[64-67,10,11] but contradict the suggestion that RUE varied little with temperature[52] thereby implying that yield differences between sites were due to HI and ground cover.[20] This difference in findings could be attributed to the parameters used in deriving RUE as indicated above. Since this study used the biomass of actual annual tea yields it is reasonable to expect that the RUE will follow the yield pattern response to temperatures. As tea yields decline due to reduced shoot growth rate with an increase in altitude so does the efficiency of conversion of radiation decline.

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

Conclusion

Altitude is a significant determinant of radiation conversion efficiency. HIRUE should, therefore, be considered as a key yield predictor in breeding programmes.

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