The influence of geographical area of production and nitrogenous fertiliser on yields and quality parameters of clonal tea

Article *in* Journal of Food Agriculture and Environment · April 2010

WFL Publisher
Science and Technology

Meri-Rastilantie 3 B, FI-00980
Helsinki, Finland
e-mail: info@world-food.net

Journal of Food, Agriculture & Environment Vol.8 (2): 682-690. 2010

www.world-food.net

The influence of geographical area of production and nitrogenous fertiliser on yields and quality parameters of clonal tea

Okinda P. Owuor [1]*, David M. Kamau [2] and Erick O. Jondiko [1]

[1] Department of Chemistry, Maseno University, P.O. Box 333, Maseno – 40105, Kenya. [2] Department of Chemistry, Tea Research Foundation of Kenya, P.O. Box 820 – 20200, Kericho, Kenya.
**e-mail: owuorpo@africaonline.co.ke, okindaowuor@maseno.ac.ke*

Received 20 December 2009, accepted 28 March 2010.

Abstract

Variations in requirements for tea production in Kenya and factors controlling growth and production of secondary metabolites responsible for the quality parameters are indicative of the need for non-uniform recommendations. Nitrogen is the main nutrient for which tea shows easily demonstrable yield and quality responses. Fertilizer applications at rates between 100 and 250 kg N/ha/year of NPKS 25:5:5:5 are currently recommended in tea production. Although yield and black tea quality variations with nitrogen rates had been observed in the past, the studies were at single geographical locations. Where comparisons were done at different locations, the genotypes were different making it impossible to isolate environmental and genotypic effects. The response of single genotype to varying rates of nitrogen in the major tea growing areas has not been reported. Consequently, it is not known if the recommended nitrogen rates are optimal in all tea growing areas for production of high yields and good quality black teas. Trials were conducted in five major tea growing regions of Kenya to quantify the yields and illustrate plain tea quality parameters responses of cultivar BBK 35 to varying rates of NPKS 25:5:5:5 fertiliser applied at 0, 75, 150, 225 and 300 kg N/ha/year. Yields were recorded for a period of ten years (1998 to 2007). Pluckable shoots from the plots were processed into black tea and analyses for quality carried out in 2007. Yields significantly ($P \leq 0.05$) increased while quality declined with increasing rates of nitrogen. The mean yield varied in the following order: Sotik Highlands ≥ Changoi > Karirana > Kipkebe ≥ Timbilil. Also plain black tea quality as measured by theaflavins, thearubigins, total colour, brightness and sensory evaluations varied with geographical area of production. The theaflavins declined in the order: Changoi ≥ Karirana > Timbilil ≥ Kipkebe > Sotik Highlands. There was significant ($P \leq 0.05$) interaction between geographical area of production and nitrogen fertilizer rates in yields demonstrating that yield response of BBK 35 to nitrogen varies with localities. The actual optimal nitrogen for the individual locations, however, will also be affected by quality, cost of production including cost of fertilisers and realised tea prices. Location specific recommendations need to be developed to promote high yields and production of high quality black teas in the different tea growing regions.

Key words: Tea, *Camellia sinensis*, yields, quality parameters, geographical area of production, nitrogen fertiliser rates, Kenya.

Introduction

Tea beverages are processed from the tender shoots of *Camellia sinensis* (L.) O. Kuntze. The plant is widely adaptable to geographical regions with diverse climates ranging from sea level in Japan to 2700 m above mean sea level (amsl) in Olenguruone, Kenya and Gisovu, Rwanda and tropical, sub-tropical and temperate regions as far north as 49ºN, outer Carpathians to as far south as 30ºS, Natal, South Africa [1]. These variations cause differences in photosynthetic [2, 3] and growth [4, 5] rates resulting in differences in yields [5, 6] and quality [7] of the resultant made tea. In Kenya, tea is grown on the foothills of Aberdares ranges and Mount Kenya in the East of the Great Rift Valley and the Mau ranges, Nandi, Kisii and Kakamega Hills in the West of the Great Rift Valley at altitudes ranging from 1300 to 2700 m above mean sea level (amsl). Several studies have demonstrated variations in tea yields [6, 8, 9], yield partitioning [8], growth [10] and shoot population density [4] of tea genotypes to different environments [6] including temperatures [11] and altitudes [5]. Similarly, large variations in quality of tea have been recorded due to changes in climatic [12], environmental conditions [13] and geographical areas of production [14-16]. From these variations, it has been claimed black teas can be discriminated by country of origin based on phenolic compounds [17] and trace metals composition [15]. Although it had been thought that large variations are necessary in these factors for quantifiable yield and quality differences, quality [18] and yields [6] can vary even within Kenya, where tea grows almost uniformly throughout the year due to proximity of the equator. Despite these differences, agronomic practices are standardised and uniform within the country [19]. Indeed, in some instances, these agronomic practices are adopted in other tea growing regions with large variations in climatic and environmental conditions without further evaluations. The uniform recommendations may be subjecting many plantations to low yields or productions of low quality teas due to use of inappropriate agronomic recommendations. This is despite the continuous rise in cost of tea production which is forcing some growers to abandon the enterprise.

Fertiliser applications are the second most expensive agronomic inputs in tea production after harvesting [20]. Nutrients are lost via crop harvesting and leaching. To continue producing economic yields, it is necessary that lost nutrients are replenished. Several studies have shown yield benefits from applying fertilisers especially nitrogenous fertilisers [20-22]. Tea plant has high demand for nitrogen; therefore it is the nutrient on which fertiliser formulation for tea is based [19, 20, 23]. The annual fertiliser application rates to tea vary from country to country. The lowest annual application rates per hectare in Vietnam is at 36 to 40 kg N, while the highest one in Japan at 800 kg N [20]. Although phosphorus [24] and potassium [24, 25] are important major nutrients for tea, no significant yield responses have been observed in Kenya due to application of the two nutrients. However, the nutrients are included in the formulation of recommended fertilisers for tea as insurance against possible deficiencies. The recommended fertiliser for tea in Kenya is NPKS 25:5:5:5 or NPK 20:10:10 in its absence [19]. This is applied at rates varying from 100 to 250 kg N ha^{-1} $year^{-1}$ depending on tea yields [19]. Tea plantations or genotypes producing low yields receive lower fertiliser rates of N 100 kg/ha/year while higher yielding fields or varieties get higher rates up to N 250 kg/ha/year. It is presumed that the fertiliser requirements are uniform throughout the country and solely dependent on previous yields of the previous years. With this system of fertiliser application, it is possible to subject tea plantation to continuous low yields due to continuous under-fertilisation arising from production during the year the application rate is decided or to unrealistically high rates of nitrogen when the genotype has high potential to produce high yields even without fertilizer input [26]. High yielding fields are believed to loose more nutrients with harvested crop and therefore require higher rates of fertilisers. However, economic analysis of various genotypes of tea grown in different regions of Kenya showed that optimal fertiliser rates varied with region of production, but the study [27] used different genotypes planted in different regions making it difficult to isolate the variations arising from the genotypes and those from the environment. Yields of tea vary from region to region even in one genotype [6]. The fertiliser requirements for one tea genotype may vary with geographical location of production for realisation of high yields.

Factors causing variations in growth and yield of tea cause changes in the production of various metabolites in tea plant resulting in variations in the chemical composition and quality of resultant black teas. On trials conducted at one location, nitrogen fertilisers caused changes in the quality of resultant black teas [22, 28]. There was a general decline in black tea quality with increase in the nitrogenous fertiliser rates. However, conflicting results have been obtained on black tea responses to phosphorus and potash fertilisers. Although quality improvement was observed in India [25], there were no effects of the nutrients on black tea quality in Kenya [29]. The quality responses to fertilizer applications observed in these past studies were conducted at single locations. It is not known if the pattern and extent of the responses of the same genotype to fertilisers would vary with geographical area of production within Kenya causing a significant change in the requirements of nutrients.

This trial was conducted to evaluate if fertiliser recommendations currently used are appropriate for all major tea growing areas in Kenya. The study assessed the changes in yields, plain black tea quality parameters and sensory evaluations of black tea from same genotypes receiving same fertiliser treatments to establish if the levels and/or patterns of the changes varied with geographical area of production due to rates of nitrogenous fertiliser.

Materials and Methods

The study was conducted in five main tea growing regions of Kenya at Karirana (altitude 2260m amsl, latitude 1º6'S, longitude 36º39'E), Timbilil (altitude 2180 m amsl, latitude 0º22'S, longitude 35º21'E), Changoi (altitude 1860 m amsl, latitude 0º29'S, longitude 35º14'E), Sotik Highlands (altitude 1800 m amsl, latitude 0º35'S, longitude 35º5'E), and Kipkebe (altitude 1800 m amsl, latitude 0º41'S, longitude 35º5'E). Clone BBK 35 fields, that had been uniformly managed and with known past cultivation histories, were selected in each of the locations in 1997. The experimental design adopted in the 5 locations was randomized block design with 5 nitrogenous fertiliser rates (0, 75, 150, 225 and 300 kg N/ha/year) replicated three times. However, the data analysis was done as factorial 2 with locations as the main treatments and fertiliser rates as the sub treatments. Each plot consisted of 60 tea bushes arranged in 6 x 10 bushes and each effective plot was surrounded by a line of tea bushes that served as a guard row. The fertiliser was applied as NPKS 25:5:5:5. Tea leaves from the experimental plots were harvested after every 7 days. The plots were managed in accordance to the individual company policy in terms of pruning month and year, and weeding. Prior to the trials, all the plots were receiving 150 kg N/ha/year. The experimental plucking and recordings started in November 1997. In subsequent years the fertiliser treatments were applied in November. Green leaf produced per plot was converted to made tea (mt) per hectare [19].

In 2007, one kilogram of leaf was plucked from each plot and processed by the miniature CTC method. The leaves were withered for 12 to 16 hours and macerated four times using a miniature CTC machine followed by fermentation for 90 minutes at 26-28ºC before drying using a miniature tea dryer (TeaCraft). The unsorted black teas were subjected to plain tea quality parameters chemical analysis and sensory evaluations. The total theaflavins were analysed by the Flavognost method [30] while thearubigins, brightness and total colour were determined by the methods of Roberts and Smith [31]. Sensory evaluations were done by professional tea tasters at tea broking firms in Mombasa, Kenya. Black tea sensory evaluations were based on briskness, brightness, colour, thickness and infusion on scale of 0 to 20 and 0 to 10 for each item for testers designated herein as Taster A and B.

Results and Discussion

Clone BBK 35 used in the study is a popular clone exploited widely in the East African tea growing areas. It is classified as high yielding with good tea quality potential [10]. In southern Tanzania, it has yielded up to 6000 kg made tea (mt) per hectare per year [32]. Although tea is grown in Kenya at altitudes varying from 1300 to 2700 m amsl, most economic tea farming activities are located in the higher altitudes of 1600 m amsl and over. Thus, the lowest field identified with well managed clone BBK 35 was at 1800 m above mean sea level while the highest altitude field was at 2260 m amsl. While the responses reported here may not represent the whole spectrum of Kenya tea growing areas, they will confirm whether the current uniform fertiliser rates recommendations [19] are suitable for all tea growing regions.

The benefits of applying fertilisers can be lost if the harvesting intervals are not optimised. Since plucking standards are preset at two leaves and a bud [19] with long plucking intervals the shoots over grow leading to excessive breaking back which reduces yields but improves quality [28]. The quality improvement due to breaking back, however, could not compensate for the lost production. In previous studies conducted at single locations using one clone or seedling tea genotype, short plucking intervals of 7 days were demonstrated to enhance both yield and quality [26, 28, 33]. Short plucking rounds were therefore used in these studies. The previous studies were all conducted at altitudes of 2180 [33] and 1900 m [26, 28] amsl and it was assumed the tea would respond in a similar manner in all the tea growing districts of Kenya. The yields were recorded for 10 years from 1998 to 2007 in this study. Such long experimentation times are necessary in perennial crops like tea since annual responses can be very variable [26]. Yield data recorded after only a few years of experimentation may therefore be misleading. Indeed, similar variable annual yield data were observed in this study confirming that tea yields agronomic recommendations based on single year or one pruning cycle yield recording can be misleading. Field agronomic trials on a perennial crop like tea should be conducted for longer periods to establish true trends.

The yield responses of clone BBK 35 to varying rates on NPKS 25:5:5:5 fertilisers for the 10 years are presented in Tables 1 and 2. There were yield responses to fertiliser rates every year and at each location the control (0 kg N/ha/year) produced significantly ($P \leq 0.05$) lower yields compared to the other treatments. Similar yield responses to rates of nitrogen had been widely recorded for trials conducted on single locations or one geographical region [20, 21, 23, 26, 28]. These results demonstrate that nitrogenous fertilizers application is important in all tea growing of Kenya for

Table 1. Effects of geographical area of production and nitrogenous fertiliser rates on the yields of clone BBK 35 from 1998 to 2002.

Year	Location	Rate of nitrogen (N kg ha^{-1} year^{-1})					Mean location
		0	75	150	225	300	
1998	Kipkebe	4326	5189	5394	5463	5646	5202
	Sotik Highlands	4795	5203	5681	6000	6228	5582
	Karirana	4329	3892	4371	4351	4460	4280
	Changoi	4260	4218	4468	4257	4320	4305
	Timbilil	4027	4510	4801	4868	4664	3474
	Mean rate	4345	4602	4943	4988	5064	
	CV (%)			8.93			
	LSD ($P \leq 0.05$)			434			434
1999	Kipkebe	2521	3376	3840	3783	4284	3561
	Sotik Highlands	1858	2424	2828	3030	3218	2672
	Karirana	3244	3102	3511	3310	3680	3369
	Changoi	5127	5152	5053	5468	4913	5143
	Timbilil	3223	3750	4334	4255	4322	3977
	Mean rate	3194	3561	3913	3969	4083	
	CV (%)			8.35			
	LSD ($P \leq 0.05$)			317			317
	Interactions			541			
2000	Kipkebe	1266	1659	1821	2012	2151	1782
	Sotik Highlands	3010	3624	5087	5786	6574	4816
	Karirana	2397	2530	2614	2672	2828	2608
	Changoi	5899	5961	5978	6503	6186	6105
	Timbilil	2278	2438	2705	2337	2432	2438
	Mean rate	2970	3242	3641	3862	4034	
	CV (%)			12.02			
	LSD, ($P \leq 0.05$)			433			433
	Interactions			739			
2001	Kipkebe	2052	3426	4475	4505	5095	3910
	Sotik Highlands	3349	4439	6410	6912	7417	5706
	Karirana	2166	1923	2041	1999	2131	2052
	Changoi	4524	5556	5347	5314	5721	5293
	Timbilil	1974	2529	2927	2695	2978	2621
	Mean rate	2813	3575	4240	4285	4669	
	CV (%)			11.20			
	LSD, ($P \leq 0.05$)			445			445
	Interactions			760			
2002	Kipkebe	1648	2716	3682	3767	4066	3176
	Sotik Highlands	2503	3591	4677	5205	5177	4231
	Karirana	3760	3820	3975	3848	4388	3958
	Changoi	3799	4331	4450	4380	4396	4271
	Timbilil	2080	2693	3438	3431	3666	3062
	Mean rate	2758	3430	4044	4126	4339	
	CV (%)			7.63			
	LSD, ($P \leq 0.05$)			289			289
	Interactions			494			

Table 2. Effects of geographical area of production and nitrogenous fertiliser rates on the yields of clone BBK 35 from 2003 to 2007.

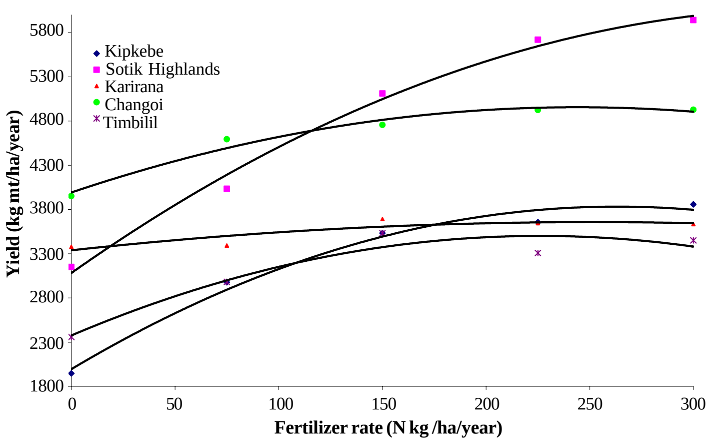
Year	Location	Rate of nitrogen (N kg ha^{-1} year^{-1})					Mean location
		0	75	150	225	300	
2003	Kipkebe	1479	2441	3003	3265	3609	2760
	Sotik Highlands	2104	2768	3222	3817	3633	3109
	Karirana	3537	3831	3976	3828	3363	3707
	Changoi	3565	4414	4793	5132	5087	4598
	Timbilil	1862	2294	2990	2498	2714	2471
	Mean rate	2509	3150	3597	3708	3681	
	CV (%)			8.75			
	LSD ($P \leq 0.05$)			295			295
	Interactions			504			
2004	Kipkebe	1353	2553	2475	2677	2758	2363
	Sotik Highlands	4198	5359	6675	8027	8097	6471
	Karirana	3649	3787	4322	4233	4066	4011
	Changoi	3472	4971	5313	6218	5823	5159
	Timbilil	1660	2669	2677	2420	2529	2391
	Mean rate	2866	3868	4292	4715	4655	
	CV (%)			7.66			
	LSD ($P \leq 0.05$)			317			317
	Interactions			541			
2005	Kipkebe	1786	2799	3807	3758	4105	3251
	Sotik Highlands	3487	4626	6054	6639	6938	5549
	Karirana	5077	4981	5083	5127	4396	4933
	Changoi	3468	4248	4461	4803	4853	4367
	Timbilil	2446	3071	4241	4410	4340	3702
	Mean rate	3253	3945	4729	4947	4926	
	CV (%)			10.88			
	LSD ($P \leq 0.05$)			481			481
	Interactions			821			
2006	Kipkebe	1428	2731	3389	3808	3382	2948
	Sotik Highlands	3189	4245	5475	6379	6768	5211
	Karirana	1879	1965	2273	2273	2253	2129
	Changoi	2362	2722	3089	2824	3267	2853
	Timbilil	1841	2863	2556	2656	2813	2746
	Mean rate	2140	2905	3557	3588	3697	
	CV (%)			8.17			
	LSD ($P \leq 0.05$)			263			263
	Interactions			449			
2007	Kipkebe	1625	2829	3460	3534	3495	2989
	Sotik Highlands	3020	4393	5011	5403	5369	4639
	Karirana	3751	4098	4759	4831	4777	4443
	Changoi	3344	4377	4616	4357	4717	4282
	Timbilil	2194	3006	3313	3519	3721	3150
	Mean rate	2787	3741	4232	4329	4416	
	CV (%)			6.92			
	LSD ($P \leq 0.05$)			274			274
	Interactions			467			

realisation of high yields. In the previous studies, recommended rates of nitrogenous fertilisers were developed at single locations. It was therefore thought that these responses would be replicated in other tea growing regions. During the ten years of this study, the yields of BBK 35 significantly ($P \leq 0.05$) varied with geographical area of production. These results demonstrate for the first time that yields of BBK 35 are not stable to environmental variations. Consequently yields obtained at one location may not be replicated at another location. This, however, is not surprising since tea is known to respond differently growing environments [4, 6, 8, 9] due to several factors including temperatures [11], rainfall and rainfall distribution [34] and altitudes [5]. Again, the tea growing areas in Kenya normally suffer from sporadic hail damage [8, 10, 34, 35]. In Kericho, about 50% of the year to year variation it tea yields was attributed to soil water deficits while 16% was due to hail damage [35]. The factors responsible for year to year variations, even at one location cannot therefore remain the same. The extents of the variations may be large at the various geographical regions. For example, total rainfall and rainfall distributions at the single and/or different locations were variable. Similarly the sporadic hailstorms were variable and uncontrollable at the different locations. However, the results show that before extensive plantation of a cultivar, it is necessary for tea growers to assess its performance relative to the other available genotypes [6]. The assessment will determine the cultivar that is best suited for a particular geographical area for realisation of high yields.

Every year there were significant ($P \leq 0.05$) interaction effects between rates of nitrogenous fertiliser and geographical area of production. These results demonstrate that yield responses to nitrogenous fertilisers vary with geographical area of production even within Kenya. The mean data for the 10 years of study are presented in Table 3 and Fig. 1. At all the locations data was better represented by polynomial quadratic relations between yield and nitrogenous fertiliser rates (Fig. 1), but the maximum response varied from region to region. For the significant (R^2 at $P \leq 0.05$) quadratic equations generated, maximum responses were recorded at 226, 246, 263 and 362 kg N ha^{-1} $year^{-1}$ at Timbilil, Changoi, Kipkebe and Sotik Highlands, respectively. The yields at the Karirana site did not reach significance. The optimal rates of fertiliser are usually much lower than the point at which maximum yields are recorded [27]. The data presented here demonstrate that the blanket rate currently recommended for tea in Kenya and adopted in eastern African tea growing areas may be inappropriate for all the growing areas. Although Sotik Highlands is only 10 km away from Kipkebe Estate, at 0 kg N/ha/year the mean yields at the two locations varied by more than 1000 kg mt/ha/year with Sotik Highlands realising higher yields (Table 3 and Fig. 1). Again the yield response at Sotik Highlands was much better than at Kipkebe even though both were at the same altitude. These results demonstrate that there are many micro environmental and management factors affecting yield responses. The earlier reported declines in tea yields with rise in altitude [5] occur when management and micro environmental factors are uniform.

Although there were significant ($P \leq 0.05$) quadratic yield responses to rates of nitrogenous fertilisers in all regions, a careful examination of the data revealed that the yield response at Karirana was very low. Indeed the difference between the highest yield and the lowest yield occurred between control (0 kg N/ha/year) and 150 kg N/ha/year was only 314 kg mt/ha/year. The difference in mean yields between same rates in Sotik Highlands was 1961 kg mt/ha/year. Application of the recommended [19] rates of 150 kg N/ha/year, in Karirana may not be correct. Indeed, even in the individual years when Karirana location recorded very high yield like 1998, 2002, 2003 2004, 2005 and 2007, the difference between control and fertilisers treated plots remained low. The rates of nitrogenous fertilisers used under plantation management are normally arbitrarily decided depending on production of the previous year. Years with high production or good tea prices are usually preceded by application of high rates of fertilisers. The annual realisation of high yields in some locations was due to the environmental conditions that prevailed during the growth periods[34, 35]. Thus, there is no need of adjusting optimal fertiliser for a location due to performance of the previous year. The data presented suggest that the present blanket fertiliser recommendation needs a review. More trials are needed to develop location specific fertiliser use recommendations.

Based on the actual data, closer examination show that in all locations except Sotik Highlands, the best mean responses to nitrogenous fertilizer was obtained by applying the first 75 kg N/ha/year. Application of the next 75 kg N ha^{-1} $year^{-1}$ produced 262, 302, 552, 562 and 1086 kg mt/ha/year at Changoi, Karirana, Timbilil, Kipkebe and Sotik Highlands, respectively. Additional 75 kg N/ha/year beyond 150 kg N/ha/year gave responses of 46, 123, 168, 223, and 608 kg mt ha^{-1} $year^{-1}$ at Karirana, Kipkebe, Changoi, Timbilil and Karirana, respectively. Depending on the cost of fertilizers, it may not be beneficial to apply beyond 150 kg N/ha/year in Karirana and Kipkebe when quality considerations are not factored in. The actual optimal rate for realisation of profitable high yields will change from year to year depending on costs of fertilizers. However, at Sotik Highlands application of up to 300 kg N/ha/year will still be viable.



$Yield_{Sotik\ Highlands} = -0.0228x^2 + 16.517x + 3082.2$, ($R^2 = 0.9925$, $P \leq 0.05$), Max at 362 kg N ha^{-1} $year^{-1}$
$Yield_{Karirana} = -0.0051x^2 + 2.5375x + 3339.3$, ($R^2 = 0.7694$, $P \leq 0.1$), Max at 248 kg N ha^{-1} $year^{-1}$
$Yield_{Changoi} = -0.0162x^2 + 7.896x + 3993$, ($R^2 = 0.9752$, $P \leq 0.05$), Max at 244 kg N ha^{-1} $year^{-1}$
$Yield_{Kipkebe} = -0.0265x^2 + 13.967x + 1995.4$, ($R^2 = 0.9858$, $P \leq 0.05$), Max at 263 kg N ha^{-1} $year^{-1}$
$Yield_{Timbilil} = -0.022x^2 + 9.9575x + 2376.5$; ($R^2 = 0.9261$, $P \leq 0.05$), Max at 226 kg N ha^{-1} $year^{-1}$

Figure 1. Annual mean (ten years) response of BBK 35 to varying rates of nitrogenous fertilizer at different sites.

Table 3. Effects of rates on nitrogenous fertilisers on mean (1998-2007) tea yields in different regions.

Location	Rate of nitrogen (N kg ha^{-1} $year^{-1}$)					Mean location
	0	75	150	225	300	
Kipkebe	1947	2977	3534	3657	3859	3194
Sotik Highlands	3151	4034	5112	5720	5942	4792
Karirana	3379	3393	3693	3647	3635	3549
Changoi	3952	4595	4757	4925	4928	4632
Timbilil	2359	2982	3532	3309	3451	3126
Mean rate	2957	3595	4126	4252	4363	
CV (%)			5.55			
LSD ($P \leq 0.05$)			217			217
Interactions			371			

In commercial tea production agronomic practices are only worth implementing if they result in profits or in sustaining the life span of the tea bushes. The commercial worth of agronomic undertaking should be based on the return per unit of the undertaking. Application of a rate of nitrogen is only worth making if it leads to additional economic yield response. Different tea concerns set their desired profit margins at different levels but it can be assumed a minimum return of 5 kg made tea per kg N per year applied is necessary for the farmers to breakeven. Although this figure will vary from year to year depending on costs of production and world tea prices, it was used to estimate the varying rates at which, based on yields alone, tea growers would break even in different regions. This point was considered a hypothetical maximum possible rate a farmer can apply for sustainable production. Although the data is hypothetical it is difficult to get information from tea growers as to what they consider is the optimal return. From the significant quadratic relationships observed between yields and nitrogen rates at different locations (Fig. 1), data was generated establishing the benefits of applying different rates on nitrogen. The return in terms of kg made tea per kg N applied was determined from the first order differential equations of the quadratic yields equations. The returns at different rates of nitrogen are presented in Table 4. The breakeven points were about 250, 175, 125, 100 and 0 for Sotik Highlands, Kipkebe, Timbilil, Changoi and Karirana, respectively. Application of nitrogen could not be justifiable on cultivar BBK 35 at Karirana since even at the lowest rate practical it was impossible to realise even 3 kg made tea per kg N applied. The results demonstrate that by applying 150 kg N/ha/year as was being practiced at the different locations when the trials started, Timbilil, Changoi, and Karirana estates were not breaking even. The data presented illustrate that different geographical areas require different rates of nitrogen to optimise profits from growing tea.

Based on yields (Table 3), fertiliser applications as currently recommended [19] suggest that Changoi would require higher rates of nitrogen than Kipkebe and Timbilil, while Karirana would receive equal or more fertiliser than Timbilil and Kipkebe. However, from these calculations such applications would lead to economic losses. It is necessary to revise the current method of assessing fertiliser requirement so that it is based on yield response rather than the total yields as is currently done [19]. However, care must be taken on the total fertiliser that can be applied. Although the data herein (Table 4) show that in Sotik Highlands rates up to 300 kg N/ha/year are profitable, high rates of nitrogen cause soil nutrients imbalance [20] making future tea production uncertain.

Several studies in the past have demonstrated yield benefits from fertiliser applications [20, 21, 23, 26-28], although such yield benefits are usually accompanied by quality reduction [22, 25, 26, 28]. Consequently the recommended fertiliser regimes should be a compromise or balance between yields and quality. In tea trade, Kenyan black teas are classified as plain to medium flavoury. Such black teas sell for their plain black tea quality parameters, i.e. theaflavins, thearubigins and caffeine. Theaflavins contribute to the astringency (briskness) and brightness while thearubigins contribute to the colour and thickness (mouth-feel). Caffeine is responsible for the stimulatory effects of black tea, however, caffeine levels were not monitored in this study. The effects of geographical area of production and nitrogenous fertiliser rates on the plain black tea quality parameters and sensory evaluations are presented in Table 5. Although sensory evaluation is subjective [28, 36], it is the most practical method of assessing quality in tea trade. Similar to previous studies [22, 25, 26, 28], all the plain tea quality parameters monitored significantly ($P \leq 0.05$) declined with changing nitrogenous fertiliser rates. Thus although significant yield responses were recorded in this study due to increase in rates of nitrogen, the resultant black teas from high rates of nitrogen were of inferior quality. It is therefore necessary that recommended rates of nitrogen take into account quality considerations. The recommended rate should be that which compromises yield and quality.

Except for thearubigins, all the quality parameters monitored (theaflavins, total colour and brightness) and sensory evaluations (Tasters A and B) significantly varied with geographical areas of production. The different geographical areas of production produced different plain tea from the same genotype. Quality of tea produced in one area can not be reproduced in another area by same genotype. The extent of variation in quality at different nitrogenous fertiliser rates due to geographical area of production was estimated using theaflavins which have been shown to have higher significance to quality than other plain tea quality parameters since significant relationships between the theaflavins and quality have been established [37, 38]. The rates of decline in theaflavins levels were in the order Changoi ≥ Karirana ≥ Timbilil ≥ Kipkebe > Sotik Highlands. The results show that the extent the nitrogenous fertilizers cause decline in plain tea quality varies with geographical area of production.

There were no significant interaction effects between the geographical area of production and nitrogenous fertiliser rates in all the quality parameters assessed or sensory evaluations. The response of the plain black tea quality parameters to nitrogen fertiliser rates followed a similar pattern at the different locations.

Table 4. Predicted return (kg mt/kg N/ha/year) of tea by applying various rates of nitrogen at different geographical areas of tea production in Kenya.

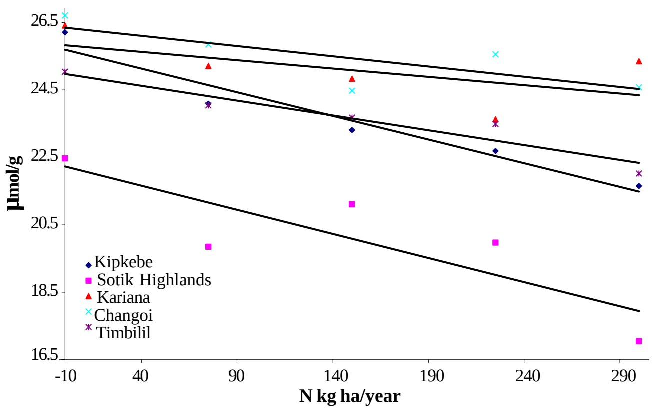
Rate of N (kg N ha^{-1} $year^{-1}$)	Kipkebe	Sotik Highlands	Karirana	Changoi	Timbilil
50	11.3	14.2	2.0	6.3	7.8
75	10.0	13.1	1.8	5.5	6.7
100	8.7	12.0	1.5	4.7	5.6
125	7.3	10.8	1.3	3.8	4.5
150	6.0	9.7	1.0	3.0	3.4
175	4.7	8.5	0.8	2.2	2.3
200	3.4	7.4	0.5	1.4	1.2
225	2.0	6.3	0.2	0.6	0.1
250	0.7	5.1	0.0	-0.2	-1.0
275	-0.6	4.0	-0.3	-1.0	-2.1
300	-1.9	2.8	-0.5	-1.8	-3.2

Table 5. Effects of geographical area of production and rates of nitrogen on the plain tea quality parameters and sensory evaluations of clone BBK 35 black teas.

Parameter	Location	Rate of nitrogen (N kg /ha/year)					Mean location
		0	75	150	225	300	
Theaflavins (µmol/g)	Kipkebe	26.21	24.09	23.31	22.69	21.65	23.59
	Sotik Highlands	22.47	19.85	21.11	19.97	17.05	20.09
	Karirana	26.41	25.21	24.83	23.63	25.35	25.09
	Changoi	26.71	25.85	24.48	25.56	24.58	25.44
	Timbilil	25.04	24.04	23.68	23.49	22.02	23.66
	Mean rate	25.37	23.81	23.48	23.07	22.13	
	CV (%)			13.50			
	LSD ($P \leq 0.05$)			3.23			3.23
Thearubigins (%)	Kipkebe	17.86	17.94	16.75	15.00	14.67	16.44
	Sotik Highlands	16.82	17.91	16.67	16.87	15.05	16.67
	Karirana	16.53	16.88	15.82	15.64	15.09	15.99
	Changoi	17.68	17.87	16.41	16.67	15.99	16.93
	Timbilil	18.38	16.23	15.82	15.44	14.46	16.07
	Mean rate	17.46	17.37	16.29	15.93	15.05	
	CV (%)			9.51			
	LSD ($P \leq 0.05$)			1.58			NS
Total colour (%)	Kipkebe	4.48	4.24	4.04	3.78	3.48	4.00
	Sotik Highlands	4.27	4.33	4.50	4.37	3.96	4.29
	Karirana	5.14	5.23	5.21	4.88	4.77	5.05
	Changoi	5.40	5.39	5.34	5.27	5.04	5.29
	Timbilil	5.14	4.99	5.08	5.04	4.39	4.93
	Mean rate	4.89	4.84	4.83	4.67	4.33	
	CV (%)			14.29			
	LSD ($P \leq 0.05$)			NS			0.68
Brightness (%)	Kipkebe	29.48	28.89	27.64	27.11	26.67	27.96
	Sotik Highlands	27.36	24.18	22.84	23.01	22.64	24.01
	Karirana	31.67	30.09	29.08	28.05	27.23	29.22
	Changoi	25.30	27.36	25.10	23.53	25.09	25.28
	Timbilil	28.91	27.09	25.29	25.46	23.61	26.07
	Mean rate	28.55	27.52	25.99	25.43	25.04	
	CV (%)			10.3			
	LSD ($P \leq 0.05$)			2.77			2.77
Taster A	Kipkebe	78	67	73	73	62	71
	Sotik Highlands	107	110	104	59	55	87
	Karirana	104	90	84	76	78	86
	Changoi	85	74	72	62	55	70
	Timbilil	105	98	94	96	79	94
	Mean rate	96	88	86	73	66	
	CV (%)			24.38			
	LSD ($P \leq 0.05$)			20			20
Taster B	Kipkebe	22	21	21	20	20	21
	Sotik Highlands	21	20	20	19	19	20
	Karirana	23	22	21	20	20	21
	Changoi	20	20	20	19	19	20
	Timbilil	22	21	20	20	19	20
	Mean rate	21	21	20	20	19	
	CV (%)			5.94			
	LSD ($P \leq 0.05$)			1			1

This was further illustrated using the theaflavins (Fig. 2), which fitted a linear regression model best. The regression equations were: $TF_{Kipkebe} = -0.0140x + 25.694$, ($R^2 = 0.9406$), $TF_{Sotik\ Highlands} = -0.0143x + 22.234$, ($R^2 = 0.7174$), $TF_{Timbilil} = -0.0088x + 24.972$, ($R^2 = 0.9109$), $TF_{Changoi} = -0.0061x + 26.346$, ($R^2 = 0.5989$), $TF_{Karirana} = -0.0049x + 25.826$, ($R^2 = 0.3402$). While the regressions for Kipkebe and Timbilil were significant ($P \leq 0.05$), those of Sotik Highlands, Changoi, and Karirana were insignificant. For Karirana, it was also observed that even yield responses were poor at this location. The different rates of nitrogen seemed not to have been causing appreciable growth differences at Karirana. Consequently there were no significant yield and quality responses to the rates of nitrogen at this location. Application of high rates of nitrogen cannot therefore be advocated for at this location.

Sotik Highlands and Kipkebe are within 10 km from each other and are both at 1800 m amsl implying that the locations have relatively close environmental conditions. Under their conditions, quality response to nitrogen fertiliser was most sensitive (Fig. 2).



$TF_{Sotik\ Highlands)} = -0.0143x + 22.234, (R^2 = 0.7174)$
$TF_{Kipkebe} = -0.014x + 25.694, (R^2 = 0.9406)$
$TF_{Timbilil} = -0.0088x + 24.972, (R^2 = 0.9109)$
$TF_{Karirana} = 0.0049x + 25.826\ (R^2 = 0.3402)$
$TF_{Changoi} = -0.0061x + 26.346\ (R^2 = 0.5989)$

Figure 2. Changes in theaflavin levels due to nitrogen rates at various sites.

This is similar to the responses observed in yields (Fig. 1). The locations with good yield response to nitrogenous fertiliser seemed to undergo the highest decline in quality due to rates of nitrogenous fertiliser. The data presented here demonstrate that for both yield and quality, responses to nitrogen vary with geographical area of production. The responses occur such that areas with good response to nitrogen suffer more in quality decline due to high rates of nitrogen. The current blanket fertiliser recommendation for all tea growing areas in Kenya that are also used all over the eastern Africa region may be inappropriate. This study has demonstrated that in one genotype yield and quality responses patterns to nitrogenous fertilisers vary from one location to the other. The observations recorded in this study possibly apply to the other major tea growing regions of the world. Indeed, environmental conditions controlling growth are more variable in some major tea growing areas of the world which are further away from the equator. The variations in yields and black tea quality reported here are more likely to be larger further from the equator. It is necessary that location specific recommendations are developed for the realization of high yields and production of high quality black teas.

The developed optimal fertiliser requirements for optimal returns based on yields alone are likely to be lowered further due to the quality implications. This is particularly in the estates sector of the Kenya tea industry that apply uniform agronomic practices as it is likely to notice the nitrogenous fertiliser effects considering that all processed leaf are uniformly managed. In the smallholder tea sector, with variable agronomic practices (management) quality decline may be less since there are growers who do not apply nitrogenous fertilisers. Due to lack of extensive research on tea, the eastern Africa countries of Uganda, Tanzania, Rwanda and Burundi have largely used agronomic production technologies developed from Kenya, sometimes without further testing for appropriateness. Results presented here suggest that such adoption of technologies may be subjecting tea growers there to low yields or production of low quality black teas or production of tea at low profit margins. Indeed it was recently demonstrated that processing conditions for realization of good quality black tea vary widely between Kenya and Malawi, even when same genotypes are processed under identical conditions [1]. These variations were attributed to the growing conditions rather than the methods of manufacture. The growing conditions are largely uncontrollable in tea production being a rain-fed crop. While across border collaboration may be useful, production technologies developed in different countries should be validated in the countries importing the technologies before they are adopted for general use.

Acknowledgements

Financial support to complete chemical analyses in this work was received from the Inter-University Council of East Africa as VicRes Research Grant. Yield data recording by staff of the Department of Chemistry, Tea Research Foundation of Kenya is acknowledged.

References

[1]Shoubo, H. 1989. Meteorology of the tea plant in China. A review. Agriculture and Forestry Meteorology **47**:19–30.

[2]Joshi, S. C. and Palni, L. M. S. 1998. Clonal variation in temperature response of photosynthesis in tea. Plant Science **137**:225–232.

[3]Smith, B. G., Burgess, P. J. and Carr, M. V. K. 1994. Effects of clone and irrigation on the stomatal conductance and photosynthetic rate of tea (*Camellia sinensis*). Experimental Agriculture **30**:1–16.

[4]Balasuriya, J. 1999. Shoot population density and shoot weight of clonal tea (*Camellia sinensis*) at different altitudes in Sri Lanka. European Journal of Agronomy **11**:123–130.

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

[6]Wachira, F. N., Ng'etich, W., Omolo, J. and Mamati, G. 2002. Genotype x environment interactions for tea yields. Euphytica **127**:289-296.

[7]Owuor, P. O., Horita, H., Tsushida, T. and Murai, T. 1986. Comparison of the chemical composition of black teas from main black tea producing parts of the world. Tea **7**(2):71-78.

[8]Ng'etich, W. K., Stephens, W. and Othieno, C. O. 2001. Responses of tea to environment in Kenya. 3. Yield and yield distribution. Experimental Agriculture **37**:361-372.

[9]Wickremaratne, M. T. 1981. Genotype-environment interactions in tea (*Camellia sinensis* L.) and their implications in tea breeding and selection. Journal of Agricultural Science **28**:556-580.

[10]Ng'etich, W. K. and Stephens, W. 2001. Responses of tea to environment in Kenya. 1. Genotype x environment interactions for total dry matter production and yield. Experimental Agriculture **37**:333-342.

[11]Tanton, T. W. 1982. Environmental factors affecting yield of tea (*Camellia sinensis* L.): Effects of air temperature. Experimental Agriculture **18**:47-52.

[12]Howard, G. E. 1978. The volatile constituents of tea. Food Chemistry **4**:79–106.

[13]Gulati, A. and Ravichranath, S. D. 1996. Seasonal variations in quality of Kangra tea (*Camellia sinensis* (L.) O. Kuntze) in Himachal Pradesh. Journal of the Science of Food Agriculture **71**:231-236.

[14]Fernandez, P. L., Fernando, P., Martin, J. and Gonzalez, A. G. 2002. Study of catechin and xanthine tea profiles as geographical tracers. Journal of Agricultural and Food Chemistry **50**:1833–1839.

[15]Moreda-Pineiro, A., Fisher, A. and Hill, S. J. 2003. The classification of tea according to region of origin using pattern recognition techniques and trace metal data. Journal of Food Composition and Analysis **16**:195–211.

[16]Peterson, J., Dwyer, J., Jacques, P., Rand, W., Prior, R. and Chui, K. 2004.Tea variety and brewing techniques influence flavonoid content of black tea. Journal of Food Composition and Analysis **17**:397–405.

[17]McDowell, I., Taylor, S. and Gay, C. 1995. The phenolic pigment composition of black tea liquors. Part II: Discriminating origin. Journal of Science of Food Agriculture **69**(4):475-480.

[18]Owuor, P. O., Tsushida, T., Horita, H. and Murai, T. 1988. Effects of geographical area of production on the composition of the volatile flavour compounds in Kenya black teas. Experimental Agriculture **24**:227-235.

[19]Othieno, C. O. 1988. Summary of recommendations and observations from TRFK. Tea **9**:50-65.

[20]Bonheure, D. and Willson, K. C. 1992. Mineral nutrition and fertilisers. In Willson, K. C. and Clifford, M. N. (eds). Tea: Cultivation to Consumption. Chapman and Hall, pp. 269-329.

[21]Kamau, D. M., Spietz, J. H., Oenema, O. and Owuor, P. O. 2008. Productivity and nitrogen use of tea in relation to plant age and genotype. Field Crops Research **108**:60-70.

[22]Venkatesan, S., Murugesan, S., Ganapathy, M. N. K. and Verma, D. P. 2004. Long-term impact of nitrogen and potassium fertilisers on yield, soil nutrients and biochemical parameters of tea. Journal of the Science of Food and Agriculture **84**:1939-1944.

[23]Ranganathan, V. and Natesan, S. 1985. Potassium nutrition of tea. In Munson, R. D. (ed.). Potassium in Agriculture. ASA-CSSA-SSSA, USA, pp. 981–1015.

[24]Dang, M. V. 2005. Soil-plant nutrient balance of tea crops in northern mountainous region, Vietnam. Agriculture, Ecosystem and Environment **105**:413-418.

[25]Vankatesan, S., Murugesan, S., Pandian, V. K. S. and Ganapathy, M. N. K. 2005. Impact of sources and doses of potassium on biochemical and green leaf parameters of tea. Food Chemistry **90**:535-539.

[26]Owuor, P. O., Othieno, C. O., Kamau, D. M., Wanyoko, J. K. and Ng'etich. W. K. 2008b Effects of long term fertiliser use on a high yielding tea clone AHP S15/10: Yields. International Tea Journal **7**:19-31.

[27]Kamau, D. M., Owuor, P. O. and Wanyoko, J. K. 1998. Economic analysis of nitrogen fertilisers in different tea cultivars East and West of the Rift Valley. Tea **19**:27-37.

[28]Owuor, P. O., Ng'etich, W. K. and Obanda, M. 2000. Quality response of clonal black tea to nitrogen fertilisers, plucking intervals and standards. Journal of the Science of Food Agriculture **80**:439-446.

[29]Owuor, P. O., Wanyoko, J. K., Obanda, M. and Othieno, C. O. 1998. Potash and phosphorus fertilisers on black tea quality in the western Kenya highlands. Tea **19**:43-48.

[30]Hilton, P. J. 1973. Tea. In Snell, F. D. and Ettre, L. S. (eds). Encyclopaedia of Industrial Chemical Analysis. Vol. 18. John Wiley, New York, USA, pp. 453–516.

[31]Roberts, E. A. H. and Smith, R. F. 1963. Phenolic substances of manufactured tea. II. Spectroscopic evaluation of tea liquors. Journal of the Science of Food Agriculture **14**:889–900.

[32]Burgess, P. J. 1992. Responses of Tea Clones to drought in Southern Tanzania. Ph.D. thesis, Cranfield University, United Kingdom.

[33]Owuor, P. O., Odhiambo, H. O., Robinson, J. M. and Taylor, S. J. 1990. Chemical composition and quality of black tea (*Camellia sinensis* (L.)) variations due to plucking intervals. Journal of the Science of Food and Agriculture **52**:63-69.

[34]Othieno, C. O., Stephens, W. and Carr, M. K. V. 1992. Yield variability at the Tea Research Foundation of Kenya. Agriculture and Forestry Meteorology **61**:237-252.

[35]Stephens, W., Othieno, C. O. and Carr, M. K. V. 1992. Climate and weather variability at the Tea Research Foundation of Kenya. Agriculture and Forestry Meteorology **61**:219-235.

[36]Owuor, P. O., Othieno, C. O., Odhiambo, H. O. and Ng'etich, W. K. 1997. Effect of fertiliser levels and plucking intervals of clonal tea *Camellia sinensis* L. O. Kuntze. Tropical Agriculture (Trinidad) **74**:184-191.

[37]Wright, L. P., Mphangwe, N. I. K., Nyirenda, H. E. and Apostolides, Z. 2002. Analysis of the theaflavin composition in black tea (*Camellia sinensis*) for predicting the quality of tea produced in Central and Southern Africa. Journal of Science Food Agriculture **82**:517–525.

[38]Owuor, P. O., Obanda, M., Apostolides, Z., Wright, L. P., Nyirenda, H. E. and Mphangwe, N. I. K. 2006. The relationship between the chemical plain black tea quality parameters and black tea colour, brightness and sensory evaluation. Food Chemistry **97**:644–653.