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HIGH FERTILIZER RATES INCREASE SUSCEPTIBILITY OF TEA TO WATER STRESS

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□ *A study to determine the association of fertilizer with soil water deficit in tea [*Camellia sinensis *(L.) O. Kuntze] was conducted in a rain-out shelter using potted plants, in which five rates of fertilizer (0, 75, 150, 225 and 300 kg Nitrogen ha^{-1}) and six levels of soil water content (38, 34, 30, 26, 22 and 18% v/v) were applied in a complete randomized design and replicated three times. The soil water treatment was maintained for a period of 12 weeks during which shoot growth, plant water relations, and dry matter partitioning in tea were determined. A parallel field experiment with the above fertilizer rates was conducted at three sites in which shoot density and shoot weight were determined during the dry season. Fertilizer improved leaf-to-root and leaf-to-total mass ratios ($P < 0.001$), reduced shoot growth, shoot water potential and specific leaf area ($P < 0.001$). The fertilizer exacerbated drought effect on tea through disproportionate assimilate partitioning which consequently weakened the ability of tea to tolerate water stress. Results suggest an indirect contribution of fertilizer supply to drought susceptibility in tea.*

Keywords: drought, dry matter partitioning, fertilizers, leaf-to-root ratio, soil water content

INTRODUCTION

Fertilizer nutrition is one of the regular field management practices with significant bearing on both yield and quality of tea [*Camellia sinensis* (L.) O. Kuntze]. Tea leaf yield responds favorably to large amounts of nitrogen (N) fertilizer under suitable growing conditions of adequate rainfall amounts

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(1400–1500 mm), fairly distributed throughout the year and mean air temperature of 22°C (Carr, 1971). The incredibly high response of tea to N supply could be due to frequent loss of N through harvest of shoots whose N content is about 4%. Even though a positive tea yield response to N supply rate of up to 500 kg N ha^{-1} has been reported in tea (Owuor et al., 1994), N application rarely exceeds 300 kg N ha^{-1} partly due to the negative effect it has on plain black tea quality (Owuor et al., 1995, Owour, 1997). Consequently, the recommended N rate that gives the best compromise for both yield and quality of black tea in Kenya has been estimated as 150–200 kg N ha^{-1} (Owuor, 1997), supplied as N- phosphorus (P)- potassium (K)- sulfur (S) (25-5-5-5), NPK (25-5-5) or NPK (20-10-10) fertilizer sources.

Drought effects on tea have been reported in numerous tea growing areas of the world including South Africa (Olyslaegers et al., 2002), Kenya, Tanzania and Sri Lanka (Stephens and Carr, 1989; Wijeratne, 1996; Ng'etich, 1999) and in India (Panda et al., 2003). Yield losses due to drought vary with location, but available data gives a range of 14–20% in Kenya (Ng'etich 1999; Ng'etich et al., 2001), 33% in Ngwazi in Tanzania (Nixon et al., 2001), 26% in Sri Lanka (Wijeratne, 1996), 17% in Siligur and 31% in Tezpur, both in India (Panda et al., 2003). Besides the yield loss, drought frequently leads to plant deaths. Burgess and Carr (1993) recorded 6–19% plant deaths due to drought with variation due to clones.

A worrying situation has emerged following observation that fertilizer could be compounding the effect of drought, and thus negating the potential gains of prudent management practice in tea. Ng'etich (1999) reported plant deaths during drought in tea supplied with higher fertilizer rates, suggesting an association between rates of fertilizer supply and plant susceptibility to water stress. A similar observation was made in cotton, where plants supplied with low rates of N fertilizer were found to be tolerant to dehydration compared to plants supplied with higher rate of N (Radin and Parker, 1979). Though N improves crop productivity, it seems to compromise plant tolerance to water stress. It is not clear whether lack of tolerance to water stress by tea, as a result of high rate of N, could be due to interference of N in plant biosynthesis, soil-plant hydraulic conductivity, and/or assimilate partitioning.

This study was conducted to investigate the relationship between N nutrition and drought susceptibility of tea. It was hypothesized that high rates of N fertilizer in tea raises the optimal soil water content required for tea and subsequently reduce tea productivity during drought.

MATERIALS AND METHODS

Site Characteristics

A pot experiment was conducted at Tea Research Foundation of Kenya (TRFK) Timbilil station (0°22′S, 35°21′ E), along with a parallel field experiment at three locations namely; TRFK, Karirana (1°10′S 36° 20′E), and Changoi (0°29′S 35°14′E). TRFK is at 2,200 m above sea level (a.s.l.) and receives 2100 mm of rainfall annually, which ranges from 70–270 mm monthly and with dry months in December–February. Karirana is at 2300 m a.s.l. and receives 1,900 mm of rain annually, ranging from 50–260 mm monthly, with lowest amounts in December to February. Changoi is at 1,800 m a.s.l. and receives about 1,700 mm of rainfall annually and experiences a dry spell in December to February (Jaetzold and Schmidt, 1983; Ng'etich, 1995). The study was conducted between 2003 and 2005.

Pot Experiment

Set-Up of a Rain-Out Shelter

This study was conducted in a rain-out shelter, which was constructed as described previously (Cheruiyot et al., 2007).

Study Materials and Treatment Application

Clone BBK 35 of *Camellia sinensis* was used in this study. The plant materials were developed from vegetative leaf cuttings and raised in a nursery as recommended (Tea Research Foundation of Kenya, 1986). Each seedling was transplanted into a 1000 gauge black polythene sleeve with a diameter of 0.22 m and a depth of 0.40 m. A total of 270 seedlings were transplanted in the polythene sleeves and given three months to establish after which nipping-off of the shoots, at the third leaf from the tip, was done to encourage regeneration of more shoots. The plants were transferred to the rain-out shelter, two months later.

The soil medium for raising seedlings from stem cuttings in the nursery was a mixture of top and subsoil from undisturbed area. The same soil medium was used for raising transplanted plants in the polythene pots. Analysis of the soil was as follows; 3.5% N, 0.16% P, 169 ppm K, 255 ppm calcium (Ca), pH 4.3, organic matter 9.3%. Its textural class was clay, with 25% sand, 67% clay, and 8% silt.

Tea plants were subjected to six different levels of soil water content and five rates of NPKS fertilizer. The soil water content (SWC) levels were 38, 34, 30, 26, 22, and 18% v/v while NPKS rates were, 33.91, 25.43, 16.96, 8.48, and 0 g per pot, which was equivalent to 300, 225, 150, 75, and 0 kg N ha^{-1} respectively, when a minimum 30 cm depth plough layer was considered. The 6 × 5 treatments were arranged in a completely randomized design and replicated three times. Each experimental unit had three potted plants which were maintained uniformly except for the specified treatments.

The basal application of the fertilizer was done soon after placing the plants in the rain-out shelter (about five months after transplanting), which was sufficient time to allow for roots to establish in the pot media. Following fertilizer treatment, the plants were adequately supplied with 160–200 mm of water per pot which was given in two splits daily during the first one week, with caution against drainage. The water supply was progressively reduced to 80–100 mm per day for four days and further reduced to 50 mm per day for another four days, after which the SWC level for each experimental unit was set. The SWC was checked and maintained manually twice daily using a Trime FM-2 TDR (Eijkelkamp Agrisearch Equipment, Giesbeek, the Netherlands) soil moisture meter. Tagging of shoots and leaves for growth measurements, followed during the second week of water treatment.

Growth Measurement

Growth as influenced by both soil water content and fertilizer treatment was determined by shoot extension, leaf expansion, and dry matter partitioning.

Shoot Growth

Two shoots, each from separate plants, were randomly selected and tagged for subsequent measurements. The shoots were tagged at between the first and second leaf from the tip, in the second week of soil water treatment, and were labeled as S1 and S2 respectively, in each experimental unit. Initial shoot measurement was done immediately after tagging and repeated weekly. Shoot length was measured from the node above the tag to the uppermost visible node, using vernier caliper. Increase in shoot length was calculated by subtraction the previous reading from every successive measurements and results expressed as shoot growth over time.

Leaf Expansion and Specific Leaf Area

Two leaves from separate shoots in two different plants in each experimental unit were randomly selected and tagged for leaf growth. The first opened leaf in the shoots was tagged at the petiole. Leaf area was determined as previously described (Ng'etich and Wachira, 1992; Cheruiyot et al., 2007). Leaf area measurements were initially done after tagging and repeated weekly, for four successive weeks. Increase in leaf area on a weekly basis was determined by subtracting the previous from the successive leaf area.

After the fourth weekly measurement, the tagged leaves were harvested and their dry weight determined by oven-drying at 65°C to constant weight. Leaf area-to-mass ratio (LMR) or specific leaf area (Younis et al., 2000) was calculated as leaf area/dry weight.

Dry Matter Partitioning

Destructive sampling to determine dry matter partitioning was done during the 12th week after water treatment. One of the three potted plants in each experimental unit was randomly picked and then soaked by immersing the root section in a bucket of water for a period of 10 minutes. The soaked plant was removed and placed on a polythene mart which was spread on flat surface. The shoot was cut at the crown level (point separating the root system and the stem), and all leaves were plucked leaving the stems and branches. The leaves were placed in labeled paper bags while stem and branches were cut into small pieces of 8–10 cm length and placed in a separate labeled paper bag. The polythene tube carrying the soaked root section was cut-open and roots washed slowly in running water. When most of the soil was removed, the roots were placed in a 2 mm mesh grid and the water pressure was increased to remove soil particles attached to roots. Care was taken to retain all roots including tiny feeders. After washing, the clean roots were left briefly in the sun to drain off water before putting them in a third labeled paper bag. The three different plant parts in 3 separate paper bags were oven dried at 70°C to constant weight and the dry weight taken. Shoot to root ratio, leaf to root and leaf to total mass ratios were calculated using the obtained data.

Monitoring Environmental Conditions of Rain-Out Shelter

Growing conditions of tea in the rain-out shelter was monitored using an automatic weather station. The components used in the weather determination set up were a pyranometer (LiCor, Lincoln, NE, USA), an anemometer, and copper thermocouples which were connected to a CR10 micro-logger (Campbell Scientific, Logan, UT, USA) for measurements of wet and dry bulb, and soil temperature.

Field Experiment

The experiment was conducted at three sites using tea clone BBK 35, which was supplied with five different rates of N fertilizer (0, 75, 150, 225 and 300 kg N ha^{-1} $year^{-1}$ supplied as NPKS, 25-5-5-5). The experiment was arranged in randomized complete block design and replicated three times. Each experimental unit measured 6 × 3.6 m with a total of four rows of established tea bushes spaced at 1.2 × 0.6 m. The fertilizer was supplied in one doze in July annually, which corresponded to the farmers' practice.

Data on tea response to drought was determined based on shoot density and yield during the dry period between December and March in 2003/04 and 2004/05 seasons. Sampling and harvesting of shoots was done at two week intervals between December and March. During sampling, a 0.5 m quadrant was randomly thrown on the tea plucking table in each plot and all shoots at two leaves and a bud within the quadrate harvested. The shoots were counted and oven dried at 70°C to constant weight. Both the shoot density and shoot dry weights were recorded during the dry season.

Determination of Soil Water Content

Soil water content during the dry season was monitored at Timbilil and Changoi during 2004/05 season using Trime FM2 TDR soil moisture meter (Eijkelkamp Agrisearch Equipment).

Data Analysis

Data analysis was processed by analysis of variance (ANOVA) using SAS (SAS Institute, Cary, NC, USA), and means separated using the Least Significant Difference (LSD) statistic. Regression analysis was done using a Gompertz exponential function (GenStat 5 release 4.2, IACR, Rothamsted, UK). The functional Gompertz model provided the best fit curve with relatively low residual and higher R^2 value compared to other growth models and was therefore used in this work.

RESULTS

Influence of N Fertilizer and SWC on Shoot Growth of Tea

Inorganic nitrogen supply increased shoot growth in tea while growth was noticeably constrained in unfertilized tea. However, the growth response to fertilizer for each rate applied was influenced by SWC. Shoot growth was limited at lower SWC and in non-fertilized tea (Figure 1). Increase in SWC increased shoot growth, though the four fertilizer rate treatments showed

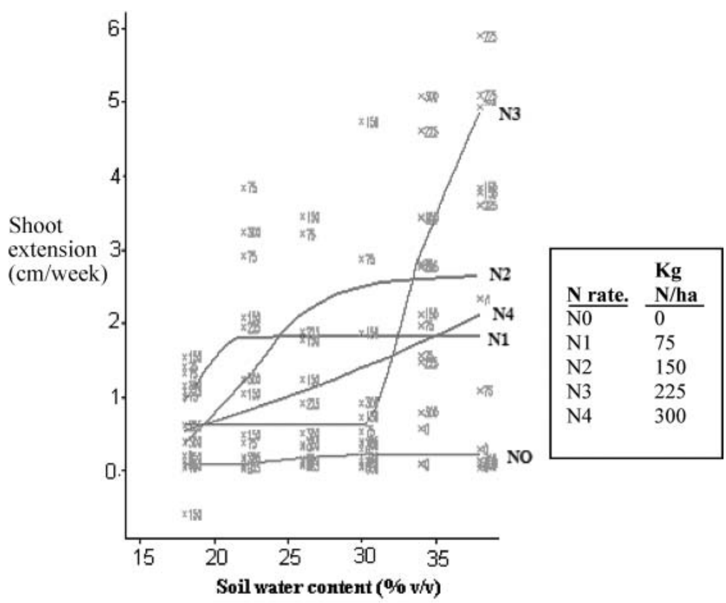

FIGURE 1 Shoot extension as mean of first 4 weeks of water treatment ($P < 0.001$, SE 1.24, $n = 90$, adjusted $r^2 = 35\%$).

TABLE 1 Response of tea to soil water content and N fertilizer supply rates

Soil water content and N treatments	Shoot extension† (cm/week)	Leaf expansion (cm^2/week)	Shoot/ root ratio (SRR)	LMR (cm^2/g)
Soil water content (SWC) % v/v				
18	0.44b*	3.93d	1.64ns	0.34a
22	0.86b	7.28bc	1.44ns	0.31ab
26	0.74b	6.90bcd	1.55ns	0.32ab
30	0.70b	5.70cd	1.55ns	0.29b
34	1.62a	10.62a	1.46ns	0.29b
38	1.83a	9.75ab	1.56ns	0.29b
N supply rate (kg ha^{-1})				
0	0.15b	1.55b	0.94c	0.22b
75	1.17a	7.96a	1.42b	0.31a
150	1.47a	10.29a	1.60b	0.33a
225	1.33a	8.72a	2.03a	0.34a
300	0.98a	8.06a	1.68b	0.33a
P values				
SWC	0.0006	< 0.0001	0.9175	0.0525
N rate	0.0007	< 0.0001	< 0.0001	< 0.0001
Interaction (SWC × N)	0.1165	0.4043	0.6269	0.3064

*$P \leq 0.05$. Means followed by same letter in the column are not significantly different, means separation by LSD;

†shoot growth, average of 6 weeks; ns—non significant; LMR is leaf-to-total mass ratio.

no significant differences on shoot growth (Table 1). The lowest fertilizer rate (75 kg N ha^{-1}) elicited the same rate of shoot growth as the highest (300 kg N ha^{-1}) though this was significantly different from the zero N treatment. Again, leaf growth of tea significantly increased with nitrogen fertilizer supply and with high SWC (Table 1). Though leaf growth declined with declining soil water deficit, that decline was linear with fertilizer rates above 150 kg N ha^{-1}, whereas both 0 and 75 kg N ha^{-1} gave a characteristic S-response curve (Figure 2).

Plant Water Relation

The shoot water potential as influenced by fertilizer rates exhibited wide variations at lower SWC but such differences were minimal at higher SWC. High amounts of fertilizer lowered plant water potential and this was more pronounced at lower SWC (Figure 3).

Dry Matter Partitioning

Shoot-to-root ratio (SRR) was not significantly influenced by the varying SWC regime but was increased by fertilizer supply (Table 1). Fertilizer supply increased foliage development over root biomass (Figure 4a). The leaf-to-total biomass ratio (LMR) was significantly influenced by both SWC

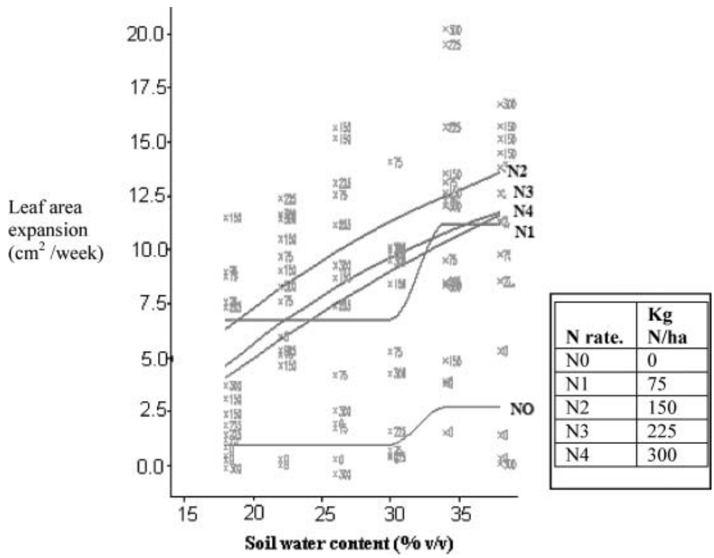

FIGURE 2 Influence of fertilizer and SWC on leaf expansion ($P < 0.001$, SE 4.36, $n = 90$, adjusted $r^2 =$ 40.53%).

and N supply. LMR was highest at 18% SWC and reduced at 30–38% SWC while it was significantly lower in non-fertilized tea. Though fertilizer increased LMR, there was no difference among different rates (Table 1 and Figure 4b).

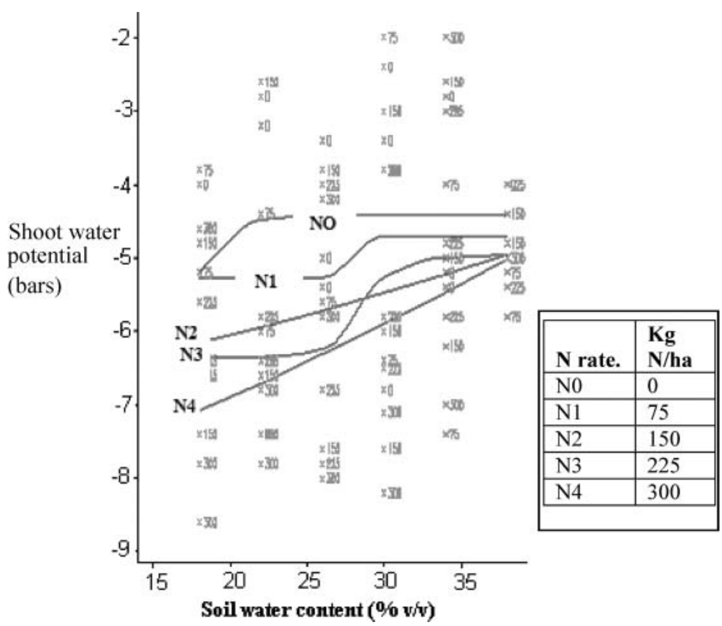

FIGURE 3 Shoot water potential of tea as influenced by fertilizer supply to tea and SWC. ($P < 0.001$, SE 1.77, $n = 90$, adjusted $r^2 = 63.7\%$).

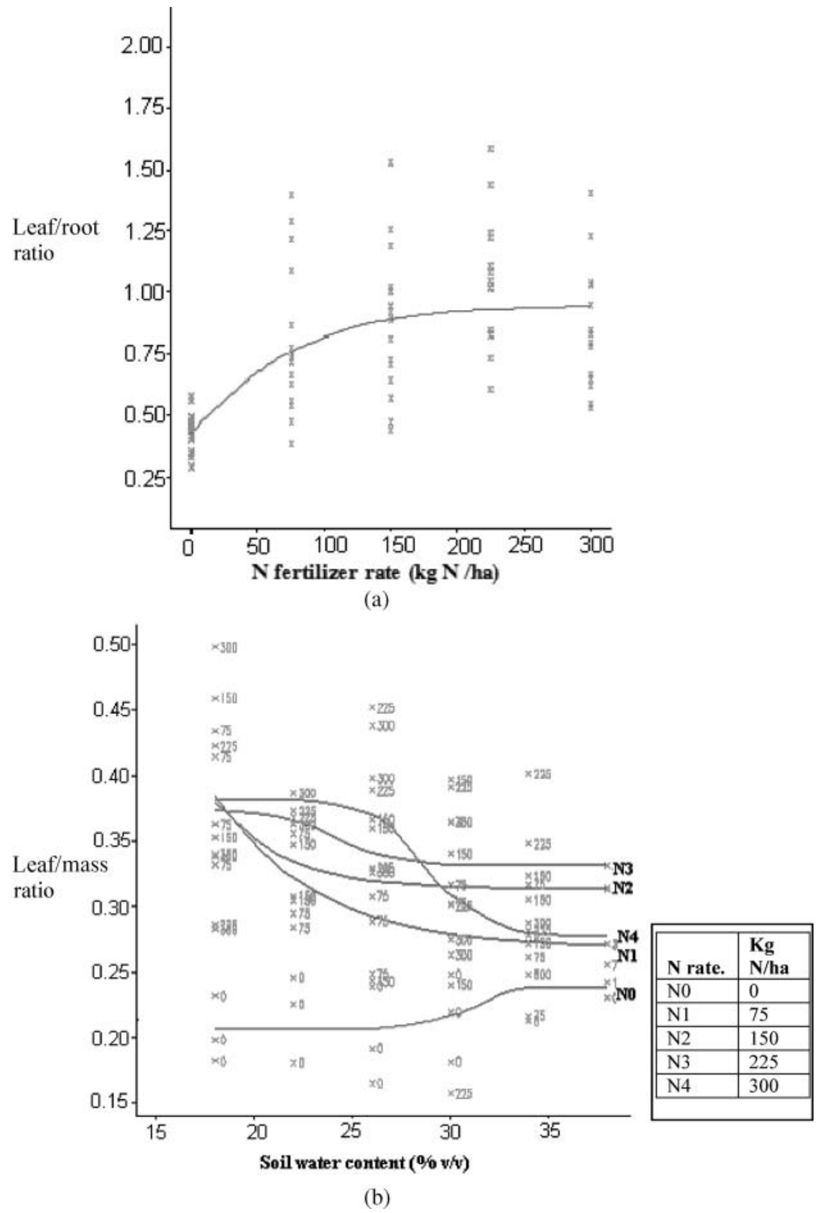

FIGURE 4 (a): Influence of fertilizer supply on leaf-to-root ratio in tea ($P < 0.001$, SE 0.33, $n = 90$, adjusted $r^2 = 72\%$), and (b) effect of soil water content and fertilizer on leaf-to-mass ratio ($P < 0.001$, SE 0.06, $n = 90$, adjusted $r^2 = 43.5\%$).

Influence of N Fertilizer and Drought on Shoot Density and Yield of Tea

Shoot Density and Yield

The dry period in tea growing areas of Kenya usually begins in November or December and its effect on tea can be observed a month later. Data in this

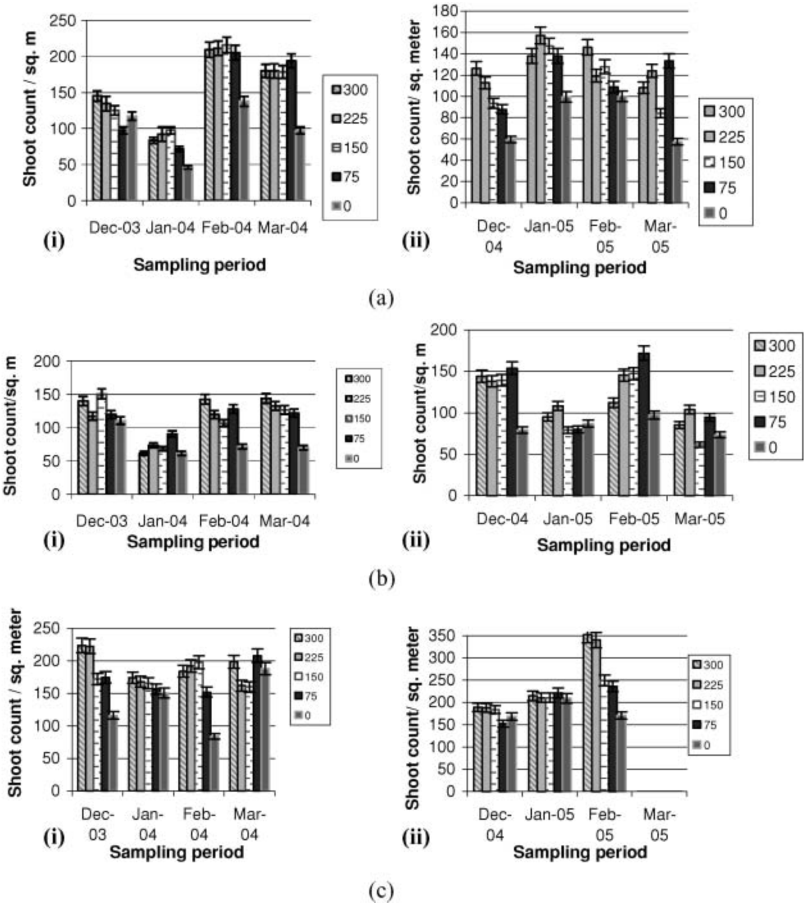

FIGURE 5 (a) Harvestable tea shoot density obtained from Changoi in 2003/04 (i) and in 2004/05 (ii) seasons, (b) harvestable tea shoot density obtained from Timbilil in 2003/04 (i) and in 2004/05 (ii) seasons, and (c) harvestable tea shoot density obtained from Karirana in 2003/04 (i) and in 2004/05 (ii) seasons.

experiment was collected between December and March in the 2003/04 and 2004/05 seasons. Harvestable shoots on tea bushes following drought varied with both location and year. Shoot density and leaf yield declined during the dry season with greater decline in the warm highlands than in the cool highlands (Figures 5 and 6). Though drought affected shoot density and yield in all fertilizer rates, greater reduction was observed in tea supplied with higher fertilizer rates. In some instances, tea with lower fertilizer rates performed better than those with higher rates (Figures 5b, 6b, and 6c).

Soil Water Content in Changoi and Timbilil Tea Estates during the December-March Season in 2004/05

The SWC in the field declined from about 30% to 20% v/v during the dry season (Figures 7a and 7b). The decline of SWC was more noticeable at

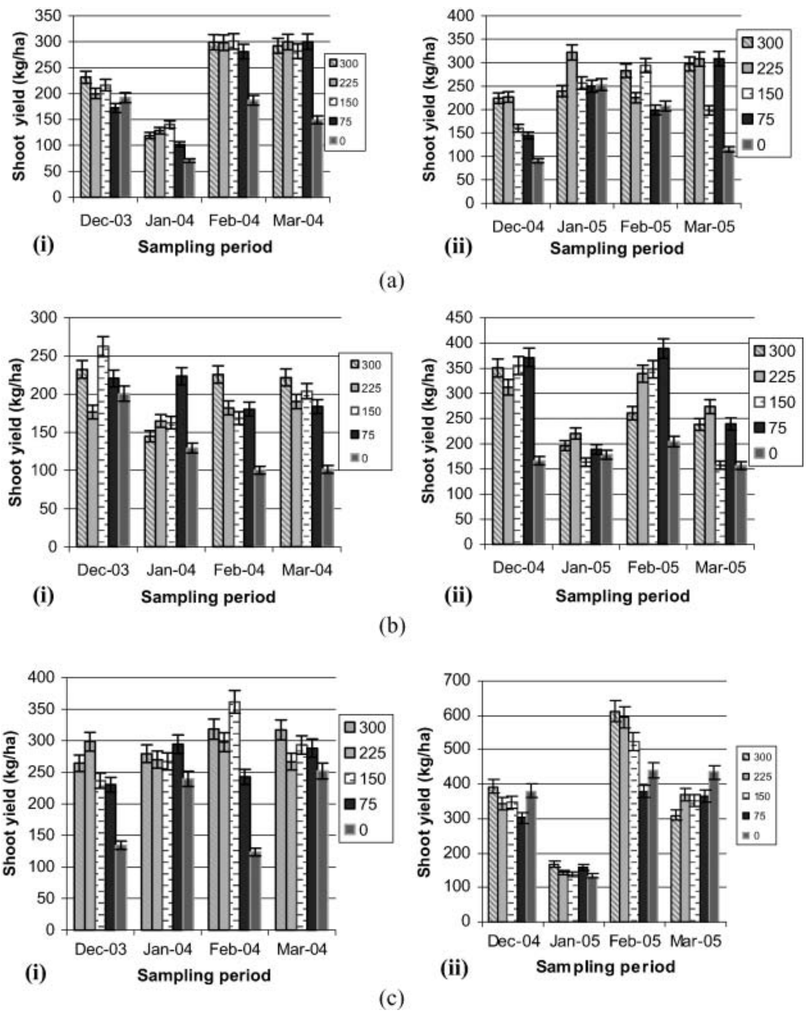

FIGURE 6 (a) Shoot yield obtained from Changoi in (i) 2003/04 and in 2004/05 (ii) seasons, (b) Shoot yield obtained from Timbilil in (i) 2003/04 and in 2004/05 (ii) seasons, and (c) Shoot yield obtained from Karirana in (i) 2003/04 and in 2004/05 (ii) seasons.

the upper 0–10 cm soil layer compared to the 25–35 cm depth. However, of greater significance was the change in SWC as influenced by fertilizer rates. Higher fertilizer rates, especially 300 kg N/ha consistently showed lower SWC compared to the lower or zero fertilizer rates at the three soil depth levels (Figures 7a and 7b). Among the two test sites, Timbilil experienced a greater SWC decline compared to Changoi.

DISCUSSION

The hypothesis in this study was that high rates of N fertilizer raise the optimal soil water requirement for tea and subsequently decrease tea

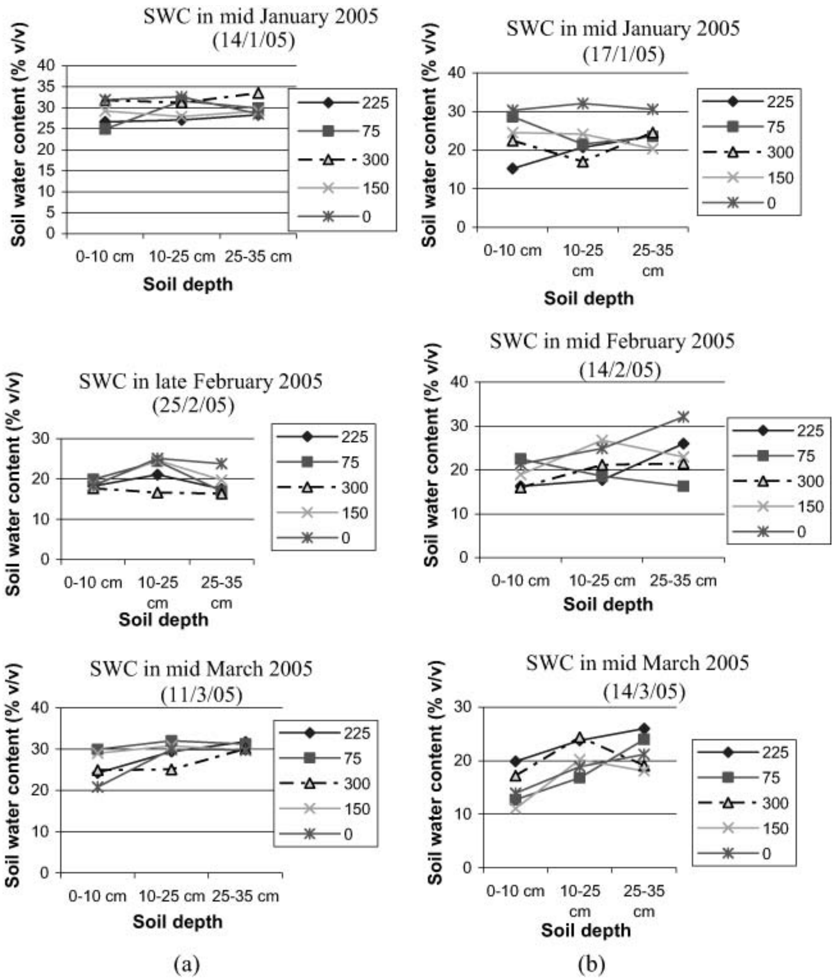

FIGURE 7 (a) Changes in soil water content in the tea experiment in Changoi during dry months, and (b) Changes in soil water content in the tea experiment in Timbilil during dry months.

productivity during drought. Results obtained provide strong evidence that though fertilizer improves performance of tea, application rates above 200 kg N ha^{-1} limits growth and yield of tea during drought periods. Under favorable SWC (20–34% SWC) the fertilizer supply increased shoot extension and leaf expansion (Figures 1 and 2). Drought reduced tea yields, and fertilizer rates in excess of 200 kg N ha^{-1} were shown to contribute to yield decline when compared to the lower N rates of 75–150 kg ha^{-1} (Figure 6).

Fertilizer increased the shoot-to-root ratio (SRR) and the leaf fraction, determined as leaf-to-total mass ratio (LMR) and leaf-to-root ratio (LRR) was notably increased under water stress. The response of unfertilized tea in our study agrees with the theory of "functional balance", which explains plant responses to the complexities of assimilate partitioning where shortage of an essential resource will necessitate the plant to invest in the structures responsible for the acquisition of that limiting resource (Davidson et al., 1969). Allocation of dry matter in the plant has been related to the ratio of total dry matter to shoots and roots as two major sinks within the plant. Shoots provide roots with carbohydrates while roots provide the shoots with mineral nutrients and water, thus shoot-to-root ratios are modulated as a plant response index to factors influencing carbon synthesis and nutrient acquisition (Davidson, 1969; Thornley, 1972; Hilbert, 1990; Dewar, 1993; Linker and Johnson-Rutzke, 2005). Uptake of N via roots is then assimilated and incorporated in proteins, enzymes, and structural molecules which include chlorophyll. Carbon skeletons are primarily synthesized by the leaves in the presence of PAR and carbon dioxide (CO_2) before being translocated to various sinks within the plant. Plants receiving an adequate supply of N with no limitation to water will have an increase in assimilates in the shoot for structural growth; therefore, SRR will increase (Andrews et al., 1999; Grechi et al., 2007). This probably explains why fertilizer improved SRR and LRR of tea. However, under water stress, plants are generally known to invest more dry matter in roots over shoot and gradually shift the allocation in favor of shoot when SWC become less limiting (Munns and Cramer, 1996) which conformed to fertilizer deprived tea in this study. Contrary to the expectation, N supplied tea grown in low soil moisture regime allocated larger proportion of dry matter to the shoot against roots (Figure 4a). The observed trend suggests strong significance of nutrient supply over water deficit as signal to partitioning of dry matter in tea. This may reflect limitation in root development caused by N fertilizer which corroborates work by Chamuah (1988) on tea and Arora and Mohan (2001) on wheat. Relatively high investment in shoot over roots by the plant at low SWC has therefore, negative implications on productivity and survival of tea plants.

The deliberate development of shoot over root and particularly LRR at low SWC in high N supply explains why fertilizer disadvantages tea during drought. A larger LRR will lead to canopy demand for water and mineral ions which cannot be sustained under water deficit conditions. This explains why tea supplied with higher fertilizer rates experienced greater decline in soil water content during drought (Figures 5 and 6) and this could be the major cause of yield reduction and plant deaths during drought.

Besides being a major organ for synthesis of assimilates, the plant leaf is the avenue through which tissue water is lost via transpiration and it would have been expected that the plants growing under low SWC conditions would have equally invested in roots to meet the expected water demand (Fernandez et al., 2002). Unfortunately, this was not the case in fertilized tea. The increase in LRR at lower soil water content meant an increase in water demand for both physiological functions and biochemical processes, through a relatively limited root system. Consequently, insufficient supply of water to the shoot canopy was expected which led to the observed decline in growth. These results agree with Nixon et al. (2001) who reported drought sensitivity of young tea with a shoot-to-root ratio of 2:1 compared to mature tea with a ratio of 1:1, showing vulnerability of tea to drought as a result of dry matter partitioning. Secondly, fertilized tea had increased shoot water potential signifying the increased suction force the plant had to exert so as to draw soil water. The influence of N fertilizer on shoot water potential was not clear but was similar to observations by Stirzaker and Passioura (1996), where plants in nutrient-flushed soil had difficulty extracting water, a condition that needs further investigation. Given the combined effect of increased leaf canopy with limited root system and reduced suction pressure of tea, N fertilizer plays a key role in growth decline and death of some plants in fertilized tea during droughty periods, a scenario commonly observed in tea fields. These results highlight the need to optimize N fertilizer supply to tea in relation to drought recurrence in tea zones to achieve consistent favorable leaf yield and to avoid plant deaths.

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REFERENCES

Andrews, M., J. I. Sprent, J. A. Raven, and P. E. Eady. 1999. Relationships between shoot to root ratio, growth and leaf soluble protein content of *Pisum sativum*, *Phaseolus vulgaris* and *Triticum aestivum* under different nutrient deficiencies. *Plant, Cell and Environment* 22: 949–958.

Arora, A., and J. Mohan. 2001. Expression of dwarfing genes under nitrogen and moisture stress in wheat (*Triticum spp.*): Dry matter partitioning, root growth, and leaf nitrogen. *Journal of Agronomy and Crop Science* 186: 111–118.

Burgess, P. J., and M. K. V. Carr. 1993. Responses of tea (*Camellia sinensis*) clones to drought. I. Yield, dry matter production and partitioning. *Aspects of Applied Biology* 34: 249–258.

Carr, M. K. V. 1971. The climatic requirements of tea plant: A review. *Experimental Agriculture* 8: 1–14.

Chamuah, G. S. 1988. The effect of nitrogen on root growth and nutrient uptake of young tea plants (*Camellia sinensis* L.) grown in sand culture. *Fertilizer Research* 16: 59–65.

Cheruiyot, E. K., L. M. Mumera, W. K. Ng'etich, A. Hassanali, and F. Wachira. 2007. Polyphenols as potential indicators for drought tolerance in tea (*Camellia sinensis* L.). *Bioscience, Biotechnology and Biochemistry* 71: 2190–2197.

Davidson, R. L. 1969. Effects of soil nutrients and moisture on root/shoot ratios in *Lolium perenne* L. and *Trifolium repens* L. *Annals of Botany* 33: 571–577.

Dewar, R. C. 1993. A root-shoot partitioning model based on carbon-nitrogen-water interactions and Munch phloem flow. *Functional Ecology* 7: 356–368.

Fernandez, R. J., M. Wang, and J. F. Reynolds. 2002. Do morphological changes mediate plant responses to water stress? A steady-state experiment with two C4 grasses. *New Phytologist* 155: 79–88.

Grechi, I., P. Vivin, G. Hilbert, S. Milin, T. Robert, and J. P. Gaudillere. 2007. Effect of light and nitrogen supply on internal C: N balance and control of root-to- shoot biomass allocation in grapevine. *Environmental and Experimental Botany* 59: 139–149.

Hilbert, D. W. 1990. Optimization of plant root: shoot ratios and internal nitrogen concentration. *Annals of Botany* 66: 91–99.

Jaetzold, R., and H. Schmidt. 1983. *Farm Management Hand Book of Kenya, Vol. II/B Central Kenya.* Nairobi: Ministry of Agriculture, Kenya in Cooperation with German Agricultural Team (GAT) of German Agency of Technical Cooperation (GTZ).

Linker, R., and C. Johnson-Rutzke. 2005. Modeling the effect of abrupt changes in nitrogen availability on lettuce growth, root-shoot partitioning, and nitrate concentration. *Agricultural Systems* 86: 166–189.

Munns, R., and G. R. Cramer. 1996. Is coordination of leaf and root growth mediated by abscisic acid? Opinion. *Plant and Soil* 185: 33–49.

Ng'etich, W. K. 1995. An evaluation of the responses of some tea clones to environment in Kenya. PhD Thesis, Silsoe College, Cranfield University, Bedford, UK.

Ng'etich, W. K. 1999. Effects of different applied nitrogen rates on yield and plant survival during periods of water stress. *Tea* 20: 61–65.

Ng'etich, W. K., and W. Stephens. 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.

Ng'etich, W. K., and F. N Wachira. 1992. Use of a non-destructive method of leaf area estimation in triploid and diploid tea plants (*Camellia sinensis*). *Tea* 13: 11–17.

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

Olyslaegers, I. N., J. Roebben, F. Kockelbergh, F. Vanassche, M. Laker, J. P. Verbelen, R Samson, R. Lemeur, and I. Impens. 2002. Morphological and physiological indicators of tolerance to atmospheric stress in two sensitive and two tolerant tea clones in South Africa. *Experimental Agriculture* 38: 397–410.

Owuor P. O. 1997. Fertilizer use in tea: The case of nitrogen. *Tea* 18: 132–143.

Owuor, P. O., M. Obanda, and J. K. Wanyoko. 1995. Quality response of low yielding tea to rates and splitting nitrogen fertilizer application in the eastern and western Kenya highlands. *Tea* 16: 124–128.

Owuor, P. O., J. K Wanyoko, C. O. Othieno, and Z. K. M'Imwere. 1994. High rates of nitrogen on tea at high altitudes: VI; Yield response to rates and splitting application of NPKS 25:5:5:5 fertilizer and economic analysis of the application to clonal tea in eastern Kenya highlands. *Tea* 15: 8–16.

Panda, R. K., W. Stephens, and R. Matthews. 2003. Modelling the influence of irrigation on the potential yield of tea (*Camellia sinensis*) in North-East India. *Experimental Agriculture* 39: 181–198.

Radin, J. W., and L. L. Parker. 1979. Water relations of cotton plants under nitrogen deficiency. *Plant Physiology* 64: 495–498.

Stephens, W., and M. K. V. Carr. 1989. A water stress index for tea (*Camellia sinensis*). *Experimental Agriculture* 25: 545–558.

Stirzaker, R. J., and J. B. Passioura. 1996. The water relations of the root-soil interface. *Plant, Cell and Environment* 19: 201–208.

Tea Research Foundation of Kenya. 1986. *Tea Growers' Handbook.* Nairobi: Tea Research Foundation of Kenya.

Thornley, J. H. M. 1972. A balanced quantitative model for root: Shoot ratios in vegetative plants. *Annals of Botany* 68: 211–264.

Wijeratne, M. A. 1996. Vulnerability of Sri Lanka tea production to global climate change. *Water, Air and Soil Pollution* 92: 87–94.

Younis, M. E., O. A. El-Shahaby, S. A. Abo-Hamed, and A. H. Ibrahim. 2000. Effects of water stress on growth, pigments, and $^{14}CO_2$ assimilation in three sorghum cultivars. *Journal of Agronomy and Crop Science* 185: 73–82.