Expl Agric. (2001), volume 37, pp. 361–372
Printed in Great Britain

RESPONSES OF TEA TO ENVIRONMENT IN KENYA. 3. YIELD AND YIELD DISTRIBUTION

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(*Accepted 30 January 2001*)

SUMMARY

In an experiment on genotype × environment interactions in tea (*Camellia sinensis*), yield differed between the genotypes at all sites. The highest yield in the third year after planting was 3760 kg ha^{-1} for clone S15/10 at site 4 (1800 m altitude), while the lowest was 1610 kg ha^{-1} for clone 6/8 at site 1 (2200 m). The dry matter contents of harvested shoots from each clone ranged from 0.24 for clone TN14-3 down to 0.19 for clone S15/10. Yield response to soil water deficits was more pronounced at site 4, where larger deficits were observed. Hail damage affected the yield of two sites and a temperature influence on recovery was evident.

INTRODUCTION

The main climatic variables influencing the yield of tea (*Camellia sinensis*) are temperature, the saturation deficit of the air and, through their influence on plant and soil water deficits, rainfall and evapotranspiration (Carr, 1972; Stephens *et al*., 1992). In Kenya, annual yield reductions of 200 kg ha^{-1} have been observed in commercial fields for every 100 m rise in altitude, mainly due to associated temperature differences (Othieno *et al*., 1992). Other climatic variables such as wind stress (Carr, 1985) and low soil temperatures (Othieno, 1982) have also been reported to reduce tea yields. Hail is the least predictable climatic variable, causing damage and losses to the tea industry during most of the year (Carr and Stephens, 1992; Othieno *et al*., 1992). Most storms occur between May and October causing losses of about 10 to 20% annually (Mwakha, 1983; Stephens *et al*., 1992).

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

The majority of research reporting the effects of weather on tea yields in Africa has been carried out at single sites, (Othieno *et al.*, 1992; Stephens and Carr, 1989, 1991; Burgess, 1992; Carr and Stephens, 1992). Large differences in environments may occur, however, over small distances (Ng'etich *et al.*, 1995b) and there is a need, therefore, to evaluate tea clones of the same age at different sites.

Earlier papers in this series have reported on large differences and interactions in total dry matter (DM) production, partitioning and yields of four clones at four sites across the tea-growing area of Kericho in Kenya (Ng'etich & Stephens, 2001a; b). This paper examines the seasonal and annual yield distributions and the effects on these yields of the main environmental factors at each site.

METHODOLOGY

Site details

The soils and weather at the four sites used in this study have been described in a paper in this series (Ng'etich and Stephens, 2001a) and elsewhere (Ng'etich *et al.*, 1995a; b). Four tea clones of commercial and scientific importance in East Africa were used in this experiment. These clones were planted at four sites namely; Timbilil (2200 m asl), Kipketer (2060 m asl), Kaproret (1900 m asl) and Changoi (1800 m asl), numbered sites 1, 2, 3 and 4 respectively for ease of reference.

Yield measurement

It is important that yields obtained in the experiment should be comparable with those from similarly aged tea on estates. The harvest interval, therefore, was based on practice by neighbouring tea estates so that at sites 1 and 2 a 14-day interval was used, while at sites 3 and 4 a 12-day interval was imposed. These intervals were kept constant throughout the year because annual temperature variations are only slight. Shoots were harvested by hand and pluckers were instructed to select only those with two leaves and a bud protruding above the canopy.

The tea was brought into bearing by continuous tipping (removing all shoots protruding beyond a predetermined height above ground level (Ng'etich *et al.*, 1995a). They were first tipped to 0.25 m in January 1992 and thereafter at 0.3, 0.4 and twice at 0.45 m height above the ground. The first conventional harvest was done in December 1992.

Shoot dry mass:fresh mass ratio.

The Tea Research Foundation of Kenya (TRFK) traditionally has used a constant factor of 0.225 (Anon., 1998) to convert from green leaf mass to 'made tea' normally considered to have a moisture content of 3%. This factor, however, has been shown to vary with clone and soil moisture content (Burgess, 1992), with fertilizer (Cloughley *et al*, 1983) and with nutritional status (Stephens and Carr, 1993). At each harvest in this study, samples of harvested shoots were weighed

Table 1. Mean clonal shoot dry mass: fresh mass ratios during December 1992 to June 1994. The shoot dry mass: fresh mass ratio used for routine calculations by the Tea Research Foundation of Kenya (TRFK) is also shown (Anon., 1998).

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

fresh then oven dried for 24–36 h at 85–90 °C and their dry mass determined. The clonal mean ratios between dry and fresh shoot mass (Table 1) at each site were used to convert green leaf tea yields to made tea.

Hail damage assessment

Hail damage to the experimental plots was recorded during the period May 1992 to June 1994. Normal estate practice was used to estimate the loss in crop as the difference between the actual yield and the average yields of the last two harvests prior to the hailstorm (Othieno *et al.*, 1992). The tea bushes were deemed to have recovered when the yield reached or exceeded the average yield of two harvests preceding the hail event.

RESULTS

Annual yields

The environmental effects on clonal yield are reported from July 1993 to June 1994, during the third year after planting (Table 2). All four clones yielded most at site 4 and least at site 1. There were significant interactions between the clones and the sites, which were reported earlier (Ng'etich and Stephens, 2001a). Of the four clones planted, clone S15/10 yielded most and clone 6/8 the least, though the yield of the latter was not significantly different from that of clone TN14-3. The difference in annual yield between clones S15/10 and 6/8 increased from 730 kg ha^{-1} at site 1 up to 1210 kg ha^{-1} at site 4.

Regression analysis of yield against environmental variables identified tempera-

Table 2. Mean annual yields of made tea (kg ha^{-1}) for four clones at four sites in Kericho, Kenya: July 1993 to June 1994.

	S15/10	BB35	6/8	TN14-3	Mean	*s.e.* sites
Site 1	2340	1910	1610	1740	1900	
Site 2	2380	2200	1790	1910	2070	
Site 3	2230	2110	2090	1970	2100	
Site 4	3760	2980	2550	2730	3000	
Mean	2680	2300	2010	2090		
s.e.		66.7				66.7

s.e. interactions = 133.3: n=4

ture as the environmental variable most closely correlated with these yield differences. When site 3 was excluded from the analysis (because of atypical soil conditions), the mean annual yield increase with temperature was 326 kg ha^{-1} a^{-1} °C^{-1} ($r^2 = 99.9\%$). For individual clones the response varied from 275 kg ha^{-1} a^{-1} °C^{-1} for clone 6/8 up to 441 kg ha^{-1} a^{-1} °C^{-1} for clone S15/10.

Fitting a linear response to temperature across the three sites unaffected by soil conditions enabled an estimate to be made of yield losses experienced at site 3. These ranged from 1100 kg ha^{-1} a^{-1} (50%) for S15/10 to only 192 kg ha^{-1} a^{-1} (10%) for clone 6/8.

Seasonal yields.

There was considerable variation in clonal yields both within and between seasons (Fig. 1). Prior to December 1993, there was a general upward trend in weekly yields as the crop cover increased. Maximum weekly yields were 220 kg ha^{-1} at Site 4 and just over 100 kg ha^{-1} at Site 1. The yield variations at each site followed a similar seasonal pattern.

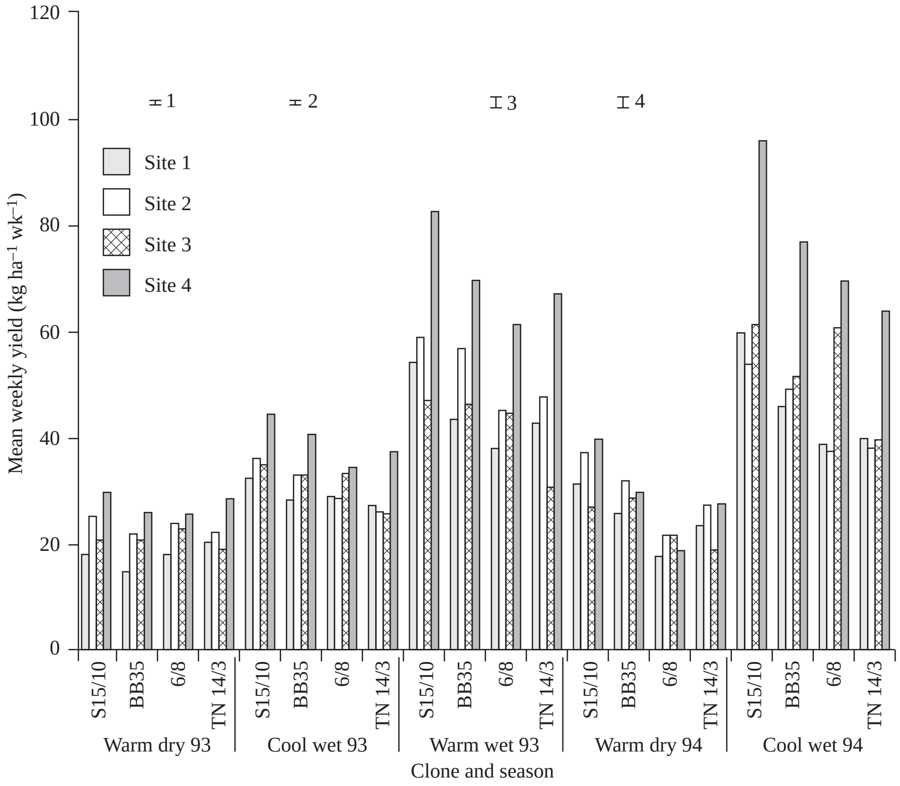

Figure 1. Variation in seasonal yield of four clones at four sites expressed as weekly yields. The *s.e.* bars are for (1) seasons; (2) clones and sites; (3) interactions of seasons and clones, and seasons and sites; and (4) interactions for clones and sites.

The period of this study was divided into seasons as described in Ng'etich *et al.* (1995b) and Stephens *et al.* (1992). April to August is a cool wet season, giving way to a warm wet season from September to mid-November. December to March is normally a warm dry season where potential soil water deficits can reach 400 mm. There were significant differences between clones during each of the seasons. Clone S15/10 consistently had the highest yield and the lowest-yielding clone was either clone 6/8 or TN14-3. The greatest yields were at site 4, while site 2 produced more than sites 3 and 1.

Interactions between seasons, clones and sites were significant. During the period December 1992 to March 1993, tea at site 4 yielded more than the other sites. Yields were least at site 3 but were not significantly different from those at site 1. There were significant differences, however, between sites 2 and 1. Only yields at site 4 were higher than at the other sites during the cool wet period May to August 1993. Differences between sites 1 and 3 were not significant during the short warm wet season (September to November 1993). During the dry season of December 1993 to March 1994, the yields at site 3 were lower than at the other sites. These periods were characterized by low soil moisture and high temperatures (Ng'etich *et al.*, 1995b).

The seasonal yield responses to temperature and other environmental variables were further investigated using multiple regression. During the warm dry season of December 1992 to March 1993, clonal responses to mean air temperature across the sites were not linear. There was a trend in yield increase with rise in air temperature, however. The addition of saturation deficit (SD), and soil water deficit (SWD) in a stepwise regression analysis improved the explanation of the variance. It showed that during the periods of water stress, the response to temperature is complicated by the presence of soil water deficits and dry air. Only during the cool wet season in April to June 1994 was there a significant response to temperature alone, with a mean increase in yield of 8 kg ha^{-1} week^{-1} $^{\circ}\mathrm{C}^{-1}$. Though not significant, the slope of response to temperature was steeper during the cool wet season when compared with either the warm dry or warm wet season.

During the warm dry seasons from December 1992 to March 1993 and December 1993 to March 1994, the percentage of variation accounted for by the relation with temperature was significantly improved by the addition of both maximum soil water deficits and mean afternoon saturation deficits in a stepwise regression. The responses of both clones BB35 and 6/8 were not significant, however, even with the inclusion of SWD or SD. These clones yielded more at site 2 than any other site during the period December 1993 to March 1994. During the warm wet season from September to November 1993, though there appeared to be no response to temperature, removal of site 3 improved the linear relationships with air temperature, giving a slope of 11.7 kg ha^{-1} week^{-1} $^{\circ}\mathrm{C}^{-1}$. There were differences in clonal responses, ranging from 10.9 (clone 6/8) to 13.2 kg ha^{-1} week^{-1} $^{\circ}\mathrm{C}^{-1}$ (clone S15/10).

Figure 2 shows the effects of SWD on yield at the two extreme sites (sites 1 and

4). At Site 1 (Fig. 2a), the critical SWD appeared to be about 30 mm, with no apparent clonal differences in yield at lower SWDs. Above this SWD, there was a linear decrease in yield of about 1.1 kg ha^{-1} week^{-1}(mm SWD)$^{-1}$. At site 4 (Fig. 2b), significantly linear relationships between dry season yield and soil water deficit were found and there was no evidence of a critical deficit. The yield loss varied between clones from 0.8 (clone 6/8) to 1.49 kg ha^{-1} week^{-1} (mm SWD)$^{-1}$ (clone BB35).

Hail damage

Severe hail damage was recorded at sites 2 and 4 towards the end of April 1994. Figure 3 shows the relative yield loss as a proportion of the previous four weeks' harvest. At site 4, the yield was reduced by 75% for five weeks following the damage, after which there was a period of rapid recovery during the next two weeks. At site 2, the yield reduction was over 80% for seven weeks after the hail damage, and recovery was only starting to show in week eight. The yield loss presented for these two sites may not be due entirely to hail damage since the event occurred at a period after the start of the rains when temperatures were falling.

DISCUSSION

Annual yields

Annual yields, three years after planting at site 4 (2550–3760 kg ha^{-1}), are similar to those reported by Burgess (1992) for irrigated clones S15/10, BB35 and 6/8 in their third year, in the southern highlands of Tanzania. At sites 1, 2 and 3, however, yields were lower (Table 2). In the experiment reported by Burgess (1992), the higher temperatures, irrigation and the use of pegging in bringing to bearing may all have contributed to larger yields. No attempt was made in this study to irrigate the tea even though at some of the sites (3 and 4) maximum actual SWDs exceeded 100 mm (Ng'etich *et al.*, 1995b). The ranking of clones BB35 and 6/8 differed from that reported by Burgess (1992). In this study, clone BB35 yielded more at each site and season than did clone 6/8. The reasons for these differences in ranking between the two tea growing areas are not clear but seem to suggest that clone BB35 is more suited to Kericho.

The yields reported here are still only about one third of the 10 995 kg ha^{-1} for sixteen-year-old clone S15/10 growing near Site 3 (Oyamo, 1992). There is considerable potential for greater yields, therefore, related largely to the development of the bush with time and the associated increases in harvest index that have been observed elsewhere (Burgess, 1994).

Seasonal yields

Clonal differences in seasonal yields were similar to those reported for young tea in Tanzania (Burgess, 1992). Clone S15/10 nearly always yielded more than the other clones at each site. There were, however, seasonal differences in ranking between clones BB35, 6/8 and TN14-3. That the lowest yield during the warm

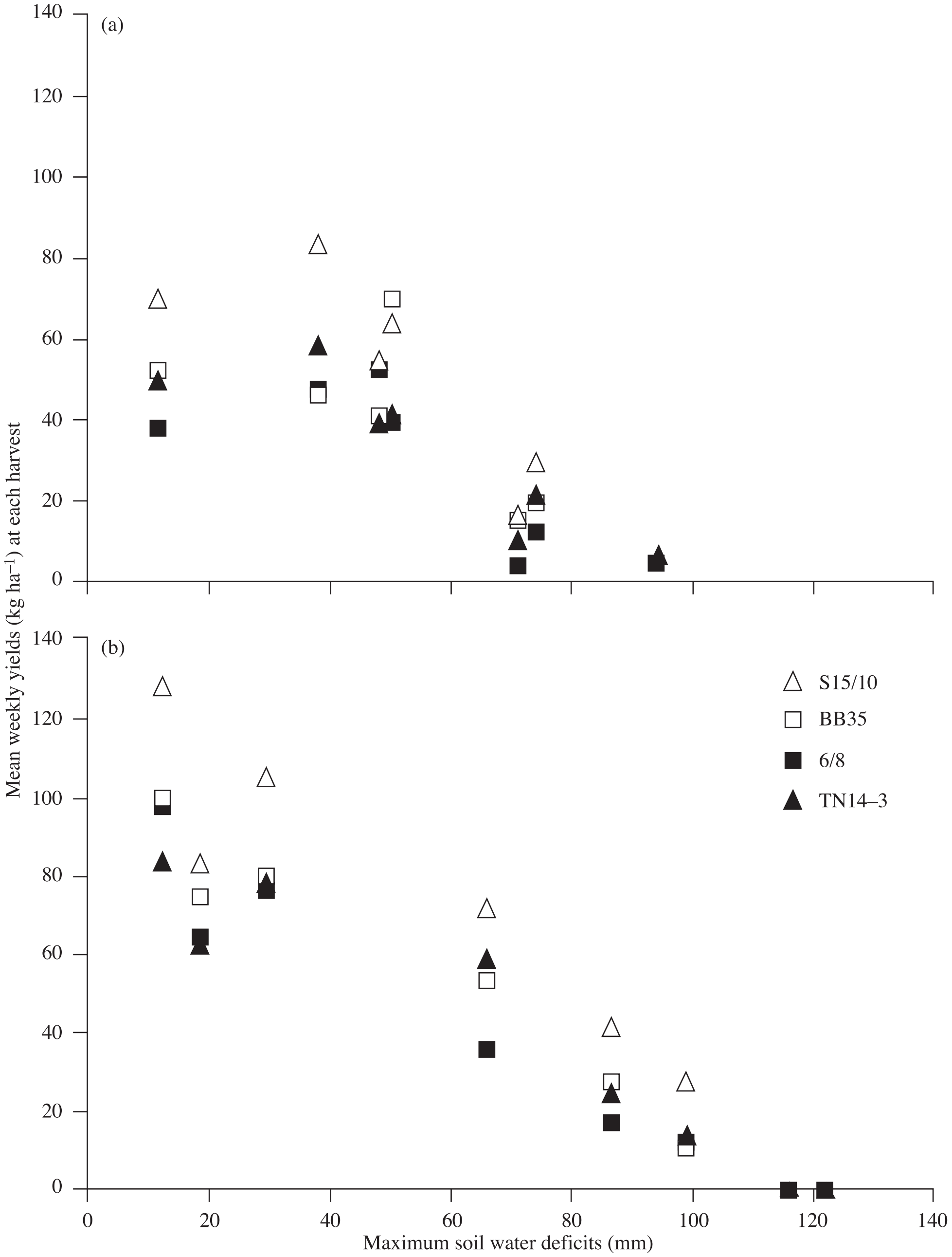

Figure 2. Relationships between dry season yield of four clones and soil water deficits during December 1993 to March 1994 at a) site 1 and b) site 4.

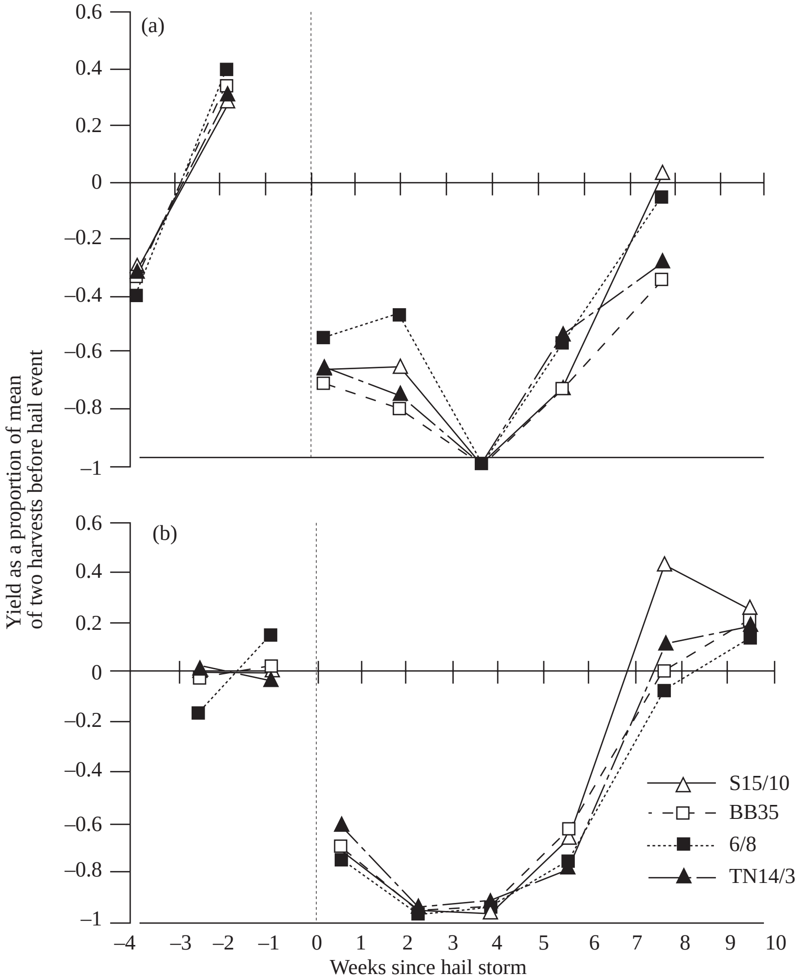

Figure 3. Yield at each harvest as a proportion of mean yield of two harvests before the hail storm during April – June 1994 at a) site 2 and b) Site 4.

dry season was that of clone 6/8 may be due to its sensitivity to SWDs (Othieno, 1978).

Responses to temperature in annual yield

When site 3 (where soil physical and chemical conditions limited yield) was excluded from the analysis there was a linear yield response to temperature of between 275 (6/8) and 441 kg ha^{-1} a^{-1} $°C^{-1}$ (S15/10) in all clones. These responses are greater than those reported for seedling tea on estates in Kericho (Othieno *et al.*, 1992) perhaps because there were still differences in ground cover and, therefore, light interception as the tea was only three years old. As the canopy closes at the higher sites the response to temperature may be reduced.

This might also explain why clone TN14-3 showed a greater response than that observed by other authors (Obaga *et al.*, 1988; Wachira *et al.*, 1990; Squire *et al.*, 1993).

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

Responses to temperature in seasonal yields

Kericho is regarded traditionally as an area with a very even yield distribution. In this experiment, however, there were large within-season fluctuations in yield. In addition, though there were seasonal responses to air temperature, these were confounded by the changes in soil water and air saturation deficits. Higher temperatures were associated usually with larger water deficits in both soil and air (Ng'etich *et al.*, 1995b). As Othieno *et al.* (1992) suggest, annual responses to temperature can be expected, therefore, to be modified by water stress when this becomes the major limiting factor during the dry season.

Yield response to water stress

The lack of a significantly linear yield response to SWD at site 1 may have been due to the relatively shorter period of stress compared with site 4. Some rains during January and late February shortened the period of stress. The rate of yield loss, however, was lower than the values reported by Burgess (1992) and Stephens and Carr (1991). For site 4, the yield losses with increasing SWDs were slightly greater than those reported by Stephens and Carr (1991).

One explanation for this variation in the response to SWD may be that the effect of temperature at the high altitudes, as at site 1, means that the unstressed yield is smaller. In addition, the dry air during the dry seasons in Kericho (mean afternoon air SD > 2.3kPa; Ng'etich *et al.*, 1995b) compared with southern Tanzania (maximum of 1.8 kPa; Stephens and Carr, 1991), could have restricted yields. This would have resulted in larger response slopes (rate of relative yield loss with SWD above critical deficits). The annual yield losses due to water stress were estimated at 14% for site 1, rising to 20% at site 4. Since there was no control of soil water content in this study, it was difficult to arrive at more accurate conclusions with respect to the water use at Kericho.

Other factors limiting yields

Though the reduction in yield at both sites 2 and 4 occurred after severe hail damage, there might be other factors that are equally important during this period. The hail damage occurred after a peak in yield following plant recovery from stress (SWD), hence the reduction in yield after the hail event could have been confounded by the beginning of an intra-seasonal yield cycle initiated by the earlier water stress (Fordham and Palmer-Jones, 1977). Temperatures were also falling during this period after the start of the rains, though only slightly.

At seven weeks after the hail damage occurred the yields at both sites 2 and 4 reached levels greater than the average for the two harvests preceding the storm. This could, in part, be due to compensatory effects after a stress but, as the tea was in its third year, yields could still be expected to be on the increase.

The occasional hail damage, mostly with negligible yield losses, also may have induced changes in partitioning to shoots. This in turn affects relationships with temperature. The estimates of yield loss due to hail should be considered, therefore, to be the upper limit for the severity of the storms recorded. The results presented here, however, are comparable with those reported for seedling tea at site 1 in Kericho (Othieno *et al.*, 1992) and indicate that, probably, estimates of 10–20% annual yield loss due to hail are reasonably accurate.

The other major limit to yield appeared to be the soil conditions at site 3. The tea growing area in Kericho is dotted with 'hut-sites', such as site 3, which are characterized by high pH and compact soil. Little work has been carried out to quantify the likely yield reductions in these areas, nor has the total area under hut sites been quantified. It is interesting to note, however, that yields were 190 to 1100 kg ha^{-1} below those expected on the basis of temperature alone, indicating that it may be worthwhile investigating methods of rehabilitating these sites.

The low yield at Site 3 is correlated with the less-extensive ground cover which may have been due to reductions in the shoot:root ratio (Ng'etich and Stephens, 2001b) caused by compaction and high pH (Ng'etich *et al.*, 1995a). In annual crops such as barley, shoot extension is severely reduced by soil compaction (Goss and Russell, 1980). In willow grown as short-rotation coppice in the UK, however, compaction imposed after the crop had established did not cause any long-term reductions in biomass production and yield as the roots were able to develop into uncompacted soil (Souch *et al.*, 2000). Thus, good agricultural practice of subsoiling to alleviate compaction before planting is probably the key to mitigating the adverse effects on yield.

Proportional contribution to yield

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

$$Y = S_o.f_s.\varepsilon_s.HI \qquad (1)$$

Since radiation in the tropics is high, the local variations may not be significant in influencing yield directly and, for a closed tea canopy, f_s will be large and uniform (Squire, 1985), though this is not the case for young tea. While there was only a difference of 12% in incident solar radiation between sites 1 and 4 (Ng'etich *et al.* 1995b), a difference of 21% in ground cover and up to 65% in HI (Ng'etich and Stephens, 2001b) were the main contributors to yield differences. Squire (1985) proposed that yield improvements in tea would come from an increase in either RUE or HI. Results from this study suggest that RUE varies little with temperature (Ng'etich and Stephens, 2001b). This means that yield differences between sites are due mainly to HI and ground cover. In mature tea, however, ground cover is at maximum (95–99%) and, therefore, any variation in yield will be mainly due to differences in HI. Indeed the recently reported high yield of clone S15/10 at site 3 could only be possible with HI of about 37%. While this may seem high for tea, the reports from Tanzania of 24% (Burgess, 1994) for clone 6/8 yielding 6 t ha^{-1} suggests this may not be unreasonable.

Acknowledgements. The authors wish to thank the African Highlands Produce Co. Ltd and George Williamson (Kenya) Ltd for providing sites for this experiment; the British Council for funding the study and the staff of the Crop Environment and Physiology department of the TRFK for assistance in collecting the data. This paper is published with the permission of the Director of the Tea Research Foundation of Kenya.

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