Pre-print copy of paper published: Burgess PJ & Carr MKV (1996). Responses of young tea (Camellia sinensis) clones to drought and temperature. I. Yield and yield distribution. Experimental Agriculture 32: 357-372.

RESPONSES OF YOUNG TEA (*CAMELLIA SINENSIS*) CLONES TO DROUGHT AND TEMPERATURE. I. YIELD AND YIELD DISTRIBUTION

By PAUL J. BURGESS[1,2] *and* M.K.V. CARR[2]
[1] *Ngwazi Tea Research Unit, c/o P.O. Box 4955, Dar-es-Salaam, Tanzania.*
[2] *Department of Water Management, Silsoe College, Cranfield University, Silsoe, Bedford, MK45 4DT, U.K.*

SUMMARY

The yield responses to drought and temperature of six contrasting tea clones were studied in a line-source irrigation experiment in Southern Tanzania. The selected clones, all commercially and/or scientifically important in eastern Africa, embrace a range of morphological and physiological types. The bushes were planted in August 1988 and differential drought treatments were imposed for 16 and 13 weeks towards the end of the dry seasons in 1990 and 1991 respectively. The resulting soil water deficits were successfully simulated using a water balance model. Under well-watered conditions Clone S15/10 (from Kenya) gave the highest yield of dry tea reaching 5600 kg ha^{-1} in the fourth year after planting (1991/92) compared to 3640-4420 kg ha^{-1} for the other five clones. During the cool season Clone SFS150 (from Malawi) yielded more than Clones 1, 207, 6/8 and K35. Although annual yields decreased curvi-linearly as the maximum soil water deficit increased, single values for the drought sensitivity of each clone could be derived by using stress time as an index of drought. On this basis Clones S15/10 and 207 were identified as being the most sensitive to drought; Clones SFS150 and 1 were drought resistant. The reasons for these differences in yield responses and the importance of determining drought sensitivity over an appropriate time period are discussed.

INTRODUCTION

The tea crop is normally harvested at intervals of one to three weeks when the tender shoots comprising two or three unfurled leaves and a terminal bud are removed. The annual yield depends on the shoot population density, the duration of the shoot replacement cycle, and the fresh mass and dry matter content of the harvested shoots. In turn, these yield components are affected by the weather, specifically the soil water deficit (SWD), temperature and the vapour pressure deficit (VPD) of the air (Carr and Stephens, 1992; Tanton, 1982).

Although most new tea areas are planted with clones that have shown above average yield and/or quality in field trials, the ranking of these clones in terms of yield can vary between individual locations because they respond differently to the environment

---

[2] Address for correspondence:: Cranfield University, Cranfield, Bedfordshire, MK43 0AL (P.Burgess@cranfield.ac.uk)

(Wickramaratne, 1981). Attempts are now being made to quantify these responses and there is already clear evidence that the base temperature for shoot extension varies between cultivars (Stephens and Carr, 1990). Clonal differences in responses to drought have also been demonstrated by Carr (1977) and Othieno (1978) in Kenya, and by Nyirenda (1988) in Malawi, but these have not always been quantified in relation to the soil water deficit.

This paper, part of a series of three, reports the results from a clone x drought experiment, established in the Southern Highlands of Tanzania. The objectives of the experiment were to quantify the yields of six contrasting clones to various levels of water stress and to identify and quantify those attributes which determine the yield potential of a clone and its responses to drought and temperature.

METHODOLOGY

Site and climate

Ngwazi Tea Research Unit (8°32'S, 35°10'E, altitude 1840 m), in the Mufindi District of the Southern Highlands of Tanzania, lies 20 km north-west of a traditional tea growing area that follows the ridge of the Uzungwe escarpment. The year can be divided into three main seasons on the basis of rainfall and temperature. Over 95% of the 800-1100 mm annual rainfall occurs during a warm-wet season from the end of November until May, when the monthly mean air temperature (T_{mean}) ranges from 16 to 19°C. The remaining dry season can be split in half: a cool season from June to August when T_{mean} is 13-16°C, and a warm period from September to November when T_{mean} increases from 16 to 19°C. Daily short-wave solar radiation is lowest between May and August (14-18 MJ m^{-2}) and highest in October (23 MJ m^{-2}). The evaporation rate increases during the dry season from approximately 3 mm d^{-1} between June and August to 5 mm d^{-1} in October. The highest mean monthly mid-afternoon VPD, which also occurs in October, is only 1.5 kPa. Because this is below the limit at which the shoot growth of well watered tea is reduced (Tanton, 1982; Carr *et al.*, 1987), the yields of tea during the dry season in Mufindi are influenced principally by the soil water deficit.

A gently sloping (< 3%) area previously used intermittently for maize production, adjacent to Lake Ngwazi and to an area of mature tea, was selected for the experimental site. The pH (in water) of the soil at a depth of 0.6 m was about 5.2 which is within the range considered optimal for tea (Othieno, 1992). The soil, a Xanthic ferralsol, has the particle size distribution of a sandy clay to a depth of 0.15 m and that of a clay below. Despite the high proportion of clay the soil is friable because of the low effective cation exchange capacity (< 16 mmol 100g^{-1} of clay). The volumetric water content at a matric potential of -10 kPa increases from 250 mm m^{-1} in the top 0.15 m to 330 mm m^{-1} at a depth of 1.8 m. The available water content in the top 2 m of soil, held between this upper limit and the permanent wilting point corresponding to a matric potential of -1500 kPa, is in the range 110-122 mm m^{-1}.

Choice of clones

Six clones were chosen for their commercial and/or scientific importance in Kenya, Malawi and Tanzania, and because they showed contrasting morphological and physiological traits. The clones included those with small leaves, such as 1 and 207 (China-type), those of intermediate-leaf size such as 6/8, and large-leaf cultivars like SFS150, S15/10 and K35 (Assam-type).

Clones 1 and 207 were selected in Mufindi, Tanzania. Although Clone 1 can produce high yields under experimental conditions due to a large shoot population density (Stephens and Carr, 1990), the small and fibrous shoots can be difficult to harvest by hand.

Clone 1 has a high base temperature for shoot extension (Stephens and Carr, 1990) and is also considered to be drought resistant (Carr, 1971). Clone 207 is easier to harvest than Clone 1, and has been widely planted in Southern Tanzania because it is easy to establish.

Clone 6/8 is a high quality clone from Kenya, which is now grown throughout East Africa. In Kenya it is considered drought susceptible (Othieno, 1978) but this attribute has been less evident in Southern Tanzania (Stephens and Carr, 1991a, 1991b).

Clone SFS150, originally selected by the Tea Research Foundation of Central Africa in Malawi, is considered to be drought resistant and recovers quickly from pruning (Nyirenda and Grice, 1989). It has a low base temperature for shoot extension (Cannell *et al.* 1990), and in Malawi it is used as a control to compare the yield of new clones. Clone S15/10 was selected by the African Highlands Produce Company Ltd in Kericho, Kenya, where it has recently produced an annual commercial yield of made tea exceeding 10,000 kg ha^{-1} (Oyamo, 1992), which is claimed to be a world record. Clone K35, which is widely grown in Southern Tanzania, was originally identified in Kericho by Brooke Bond Kenya Ltd.

Experimental design

Each of the six clones was planted, as 12-18 month old transplants, at a spacing of 1.2 x 0.8 m within a line-source design (Hanks *et al.*, 1976) in August 1988. The experiment comprised four replicate blocks, two on each side of a centrally-placed sprinkler lateral, containing six 24 x 6.4 m plots (running perpendicular to the lateral) which were randomly allocated to each clone. There was a single guard row around each plot. These main plots were then split into six contiguous drought treatment sub-plots (3.6 x 4.8 m with 18 plants) labelled from I_5 (full irrigation) closest to the lateral to I_0 (most drought stressed) at the extreme sides of the experiment. Possible effects of a fertility gradient across the experiment were removed in the analysis of yield data by allowing for covariance with distance across the experiment (Morgan and Carr, 1988). Young plants which died were immediately replaced with healthy transplants of the same clone.

The experiment was mulched with Napier grass (*Pennisetum pupureum*) at planting and in April 1989, and with Guatemala grass (*Tripsacum laxum*) in October 1990. In order to bring the tea into production as early as possible, young branches were 'pegged' horizontally between April and October 1989. At planting, nitrogen (N), phosphate (P_2O_5) and potash (K_2O) were applied at rates of 33, 68 and 79 kg ha^{-1} respectively; this was followed by another three applications during the first year (August 1988 to July 1989) totalling 74, 26 and 26 kg ha^{-1}. In the second and third years (1989/90; 1990/91) there were three applications (all as $N:P_2O_5:K_2O$ 20:10:10) totalling 135:67:67 kg ha^{-1} in year two and 350:175:175 kg ha^{-1} in year three. In the fourth year, a total of 300:150:150 kg ha^{-1} was applied in two applications (July and January) to the irrigated tea, or as a single application to the unirrigated tea after the start of the rains. These rates were intended to minimise any nutrient deficiency and were based on the recommendations from the Tea Research Foundation of Kenya (TRFK, 1986) and the results of an adjacent fertiliser experiment (Stephens and Carr, 1991a).

Drought treatments

To minimise the number of plant deaths during the initial years of the experiment, drought treatments were only applied from 9 October to 27 November 1989 (7 weeks), from 27 July to 18 November 1990 (16 weeks), and from 18 July to 20 October 1991 (13 weeks). At all other times during the dry season, the experiment was irrigated uniformly.

Irrigation was scheduled so that the soil profile in the fully irrigated (I_5) sub-plots was rewetted to field capacity before the soil water deficit (SWD) exceeded a value likely to reduce yield. The critical SWD for the dry season yield of mature Clone 6/8 at Ngwazi is between 40 and 100 mm, corresponding to a depletion of about 12-30% of the ‘extractable’ water (330 mm) within a 5.5 m deep rooting zone (Stephens and Carr, 1990). Using this as a guide and taking into account the rooting depth of the young tea as well as practical constraints on the availability of equipment, during 1990 and 1991 irrigation was applied when the estimated SWD reached 45 mm.

For the purposes of irrigation scheduling, the SWD on day i was calculated using a simple soil water balance (Equation 1).

$$SWD_i = SWD_{i-1} - R_i - I_i + D_i + ET_i \qquad (1)$$

where R_i is the rainfall, I_i is the irrigation, D_i is the instantaneous drainage and ET_i is the crop evapotranspiration all calculated daily in mm. A value of I_i for each watering treatment was measured using catch-cans spaced symmetrically across the experiment. Any rainfall or irrigation received when the soil profile was at field capacity (SWD = 0) was assumed to drain instantly and movement of surface water between treatments was prevented by micro-catchments excavated between the bushes. The value of ET_i was taken to equal the daily evaporation (E_{pan}; mm) from a screened 1.85 m square x 0.6 m deep evaporation pan which accurately models the water loss from tea with full crop cover (Stephens and Carr, 1991a). Because the experiment was irrigated at frequent intervals, any overestimation of transpiration due to incomplete crop cover during 1990 was assumed to be offset by evaporation from the soil surface and by slow drainage.

The differential watering treatments were imposed using 22 sprinklers spaced at 6 m intervals to provide uniform application rates parallel to the single central lateral. Two types of sprinklers (Bauer B90Z, with 7 and 3.5 mm nozzles, and Wright Rain Lancer with 5.1 and 3.2 mm nozzles) with different watering patterns were exchanged halfway through each irrigation in order to obtain the required distribution perpendicular to the lateral. Both sets were operated at a constant pressure of 340-380 kPa. During the imposition of the differential drought treatments, the irrigation sub-plots received between 0 and 481 mm in 1990, and 0 and 374 mm in 1991 (Table 1).

Table 1. *Rainfall and irrigation water (mm) applied to each drought/irrigation treatment* (I_5 *to* I_0) *during the periods of differential drought in 1990 and 1991.*

	Rainfall	Drought treatment					
		I_5	I_4	I_3	I_2	I_1	I_0
Season							
27 July - 18 Nov. 1990	11	481	401	256	70	9	0
18 July - 20 Oct. 1991	1	374	328	185	55	12	0

Soil water balance

A water balance model, based on that used by Stephens and Carr (1991b), was used to estimate the daily SWD within each drought treatment during 1990 and 1991. This model used the same values of rainfall and irrigation that were used for irrigation scheduling (Equation 1), but ET_i was partitioned into transpiration, soil evaporation and slow drainage. At field capacity, the ‘extractable’ water available to a mature tea plant with roots extending to a depth of 5.5 m is about 330 mm at this site (Stephens and Carr, 1991b). The distribution of this water within the soil profile was then used to determine the quantity of water available to young tea plants with different rooting depths. In this way, the estimate of ‘extractable’ water increased from 114 mm, when the maximum root depth was 1.5 m in November 1990 (Burgess and Carr, 1996a), to 157 mm to a depth of 2.2 m in November 1991. The daily transpiration rate was then assumed to equal E_{pan} adjusted for crop cover (see below) until 18% of the ‘extractable’ water was removed (Stephens and Carr, 1991a), beyond which point the rate declined linearly to zero at 100% depletion.

The potential water lost by evaporation from the soil surface and slow percolation was determined from four uncultivated sites next to the experiment. Using water release curves and water content measurements, made with a Wallingford neutron probe (Didcot Instruments Ltd.) which was calibrated at a site adjacent to the experiment (Stephens and Carr, 1991b), a zero-flux plane was identified at 0.4 m. Water losses above and below this depth were therefore assumed to be caused by soil evaporation and slow drainage respectively. Soil evaporation declined from 1.0 mm d^{-1} at ‘field capacity’ to zero when the SWD within the top 0.4 m reached about 40 mm. Slow drainage was related to the SWD between 0.4 m and the maximum rooting depth, declining linearly from 2.4 mm d^{-1} when the soil was at ‘field capacity’ to zero when the SWD reached 83 mm. These values for evaporation and slow drainage were then adjusted for the proportion of the ground not covered by the crop.

The model was validated by using the neutron probe to measure the soil water content around 40 mm diameter access holes in selected treatments. Although each hole was augered by hand to a depth of 2 m, a shortage of aluminium tubing meant that it was only possible to line the top 0.45 m of each hole. Below this depth, soil which fell from the sides could block the hole and for this reason, readings from 16 holes in 1990 and 32 in 1991 were excluded from subsequent data analysis. The soil water content was measured at 0.15-0.20 m increments to depths of 1.7 (1990) or 1.9 m (1991) in four replicates of the fully irrigated (I_5), partially irrigated (I_2 and I_3) and unirrigated (I_0) sub-plots of Clones 1, 6/8, SFS150 and S15/10 (a total of 64 holes), one to two days before and two to three days after each irrigation. The SWD within each treatment was then calculated as the difference between the measured water content and a mean ‘field capacity’ water content which was measured before the start of the dry season.

Yield and crop cover measurements

Shoots extending more than 0.45 m from ground level were removed in early November 1989, 15 months after planting, to produce a level surface on each bush. All the shoots with two or more unfurled leaves above this surface were then harvested one month later and subsequently at intervals varying from 13 days in the warm season to 24 days during the cool season. The total fresh mass of the shoots from each sub-plot was weighed at each harvest and the corresponding dry mass was estimated using a conversion factor derived from a regression analysis of the dry matter content of leaf samples taken from each clone with the mean air temperature recorded over the preceding two months (Burgess, 1992).

Crop cover was measured using a 1.2 x 0.8 m frame, corresponding to the bush spacing and containing a grid of 96 squares measuring 0.1 x 0.1 m, which was supported immediately above selected bushes. The proportion of each square (0-25, 25-75 or 75-100%) which included leaf, when examined individually from overhead, was recorded to provide an estimate of the proportion of the ground covered by the crop. Two or three bushes were examined in each of the four replicates of selected drought treatments of each clone on a monthly basis.

Sensitivity to drought

Drought sensitivity was first examined by relating annual yields to the maximum soil water deficits calculated using the model. However previous work has shown that if the decline in yield as the SWD increases is curved, a linear relation can be obtained by relating the yields to a stress time index (Stephens and Carr, 1989). To derive a similar function, each drought treatment in this experiment was defined in terms of stress time (mm d); an accumulated measure of the time and the extent that the soil water deficit was greater than a critical deficit beyond which yields declined. Values of stress time for each drought treatment and season were calculated using critical deficits ranging from 0 to 100 mm. The most appropriate value for the critical deficit (± 5 mm) in each season was taken as that which resulted in the best linear relation between the mean yield of the six clones and the corresponding stress time.

RESULTS

Soil water deficit model

During 1990 and 1991, the values of the SWD estimated with the model (SWD_{model}) were similar to those calculated from the neutron probe measurements (SWD_{NP}) in the selected sub-plots (Figure 1; Equations 2 and 3). It was therefore possible to use the model to estimate daily values of SWD within each of the treatments.

$$1990\ SWD_{model} = 0.99\ (\pm 0.04)\ .SWD_{NP} - 3\ (\pm 2.7) \qquad (n=50, R^2 = 0.92) \qquad (2)$$

$$1991\ SWD_{model} = 1.00\ (\pm 0.06)\ .SWD_{NP} + 9\ (\pm 3.9) \qquad (n=45, R^2 = 0.86) \qquad (3)$$

The neutron probe measurements were not sufficiently precise to identify possible differences in the soil water deficit between clonal plots. The model also indicated that such differences would be minimal because changes in transpiration were masked by corresponding variations in soil evaporation and slow drainage. A single maximum SWD could therefore be calculated for each drought treatment in each season. Thus in 1990, maximum values of the SWD reached 45 and 117 mm within the fully irrigated (I_5) and most drought stressed (I_0) treatments respectively (Figure 1). In 1991 the corresponding values were 47 and 145 mm.

Yield development of fully irrigated tea

The dry mass of tea harvested from fully irrigated Clone S15/10 increased from 680 kg ha^{-1} in the year ending 31 May 1990 (during which harvesting began), to 3590 kg ha^{-1} and then 5650 kg ha^{-1} for the corresponding periods in 1990/91 and 1991/92 (Table 2). During each of these years Clone S15/10 yielded substantially more (28-75%) than the other five clones all of which gave similar yields except for Clones 6/8 and K35 which yielded less than Clone 207 in the year ending 31 May 1990 and Clone K35 which yielded less than Clone 1 in 1991/92.

The yield development of fully irrigated Clone S15/10 was associated with an increase in the crop cover from 19% in September 1989, 13 months after planting, to 51, 95 and 96% in May 1990, 1991 and 1992 respectively (Figure 2a). There were also differences between clones in the rates of increase in crop cover, for example in November 1990 the crop covers of Clones 1 and S15/10 (74-77%) exceeded those of Clones 6/8, 207 and K35 (50-58%). This is despite the fact that all of the bushes were brought into bearing by ‘pegging’, a technique which is likely to minimise differences between the clones. By April 1992, 44 months after planting, the crop cover of each of the fully irrigated clones had exceeded 90%.

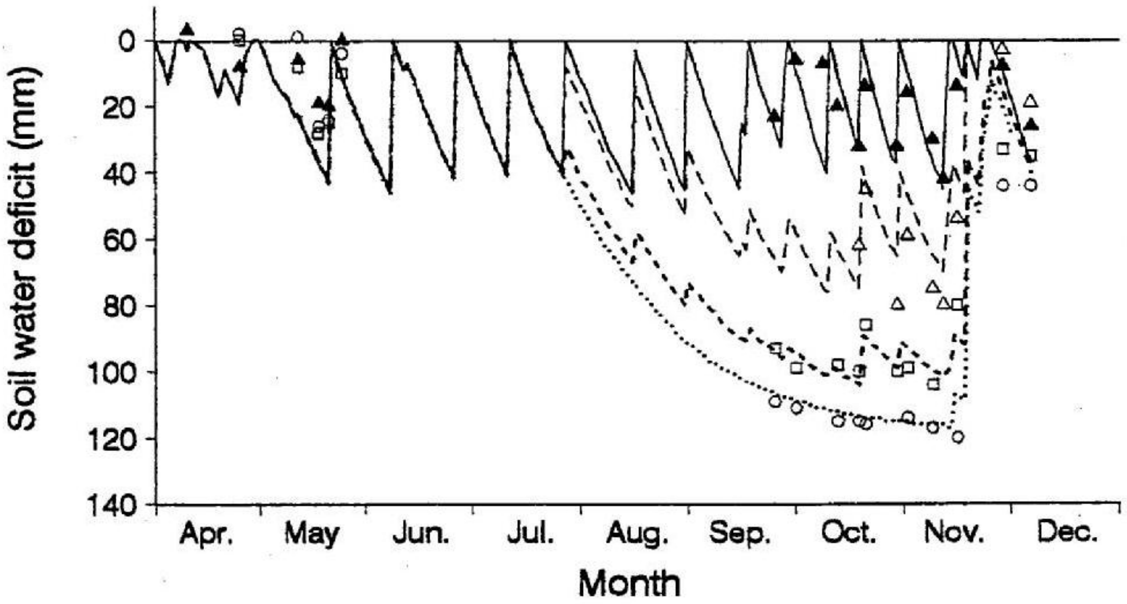

Figure 1. Predicted changes in the actual soil water deficit within each of four drought treatments during the 1990 dry season using the soil water balance model: fully irrigated I_5 : ———— , partially irrigated I_3 : — — — , I_2 : - - - -, and unirrigated I_0: ···········. The symbols indicate the soil water deficit measured using a neutron probe moisture meter I_5 : ▲ , I_3 :△, I_2: □ , I_0: O.

Seasonal yield distribution of fully irrigated tea

Yields from all the clones were reduced during each cool season from June to August as rates of shoot growth and crop canopy development were constrained by low temperatures, but there were differences between clones in crop yield distribution. For example Clone SFS150 yielded more than Clone 1 during the cool season in 1991, but less than Clone 1 during the succeeding warm weather between December 1991 and May 1992 (Table 2; Figure 2b). The seasonal yield distribution from Clone SFS150 was therefore more uniform than that from Clone 1.

Table 2. *Seasonal yields of dried tea (kg ha^{-1}) for each of six fully irrigated (I_5) clones from 1 December 1989 to 31 May 1992.*

	Yields by season and year								
	Warm wet	Cool dry	Warm dry	Warm wet	Annual total	Cool dry	Warm dry	Warm wet	Annual total
	Dec.89- May 90	Jun.90- Aug.90	Sep.90- Nov.90	Dec.90- May 91	Jun.90- May 91	Jun.91- Aug.91	Sep.91- Nov. 91	Dec.91- May 92	Jun.91- May 92
Clone									
S15/10	680	280	800	2510	3590	390	1630	3630	5650
1	540	170	470	1840	2480	200	1130	3090	4420
207	600	220	450	1860	2530	280	940	2680	3900
SFS150	510	330	560	1610	2510	430	1030	2350	3810
6/8	400	220	560	1540	2320	300	1170	2230	3690
K35	390	180	380	1530	2090	250	910	2490	3640
mean	520	230	540	1820	2590	310	1140	2740	4190
sed (n=4)	59	26	31	137	166	46	73	172	235

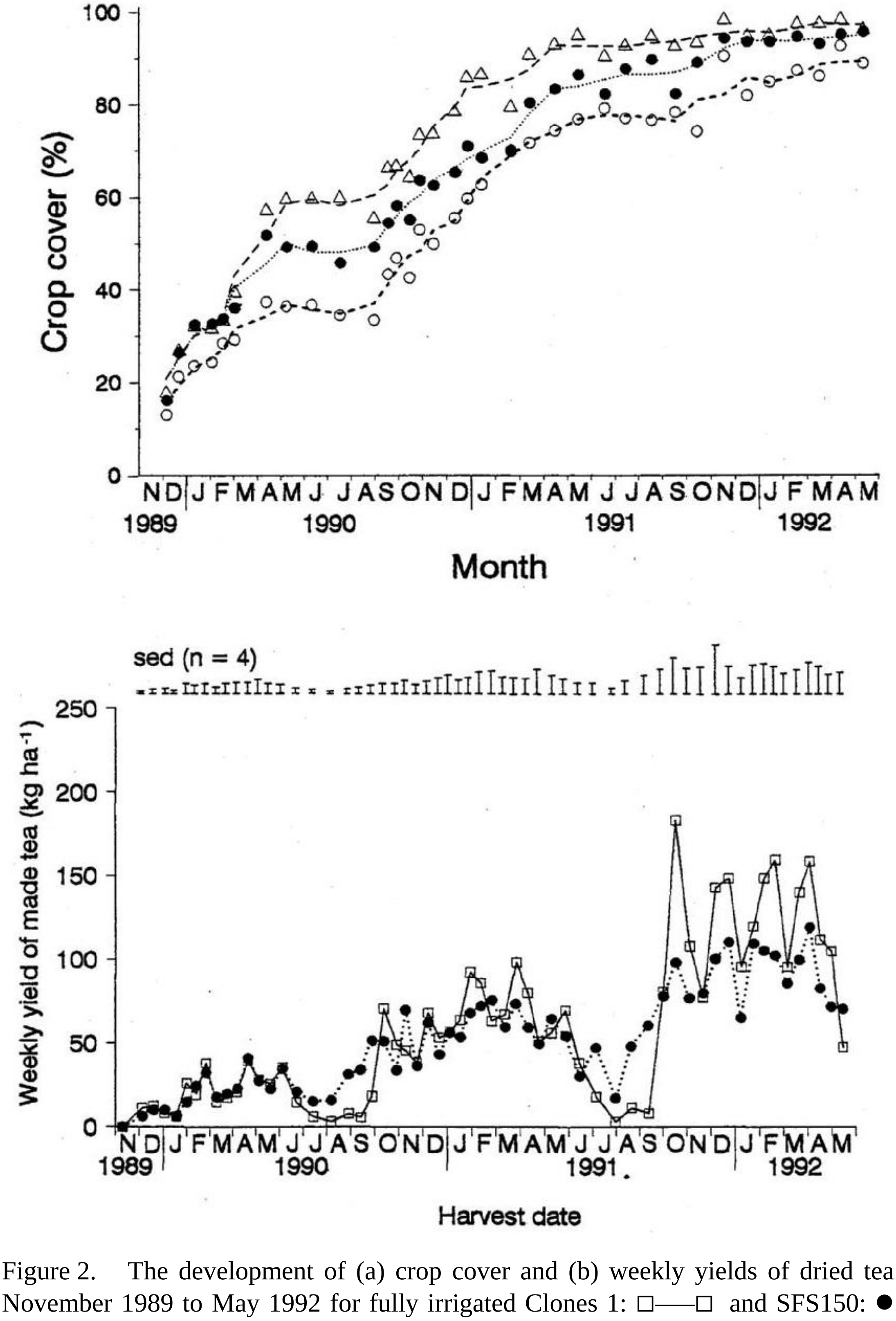

Figure 2. The development of (a) crop cover and (b) weekly yields of dried tea from November 1989 to May 1992 for fully irrigated Clones 1: □——□ and SFS150: ●······●. The crop cover figure also includes values for fully irrigated Clones S15/10: △---△, and 6/8: O- -O ; the lines were drawn using a rolling average.

Annual yields and drought

The responses of the annual yields to drought varied with clone in 1990/91 and 1991/92. Although the yields from Clone S15/10 were substantially larger than those from the other clones under well watered conditions, they were similar to those from Clones 1 and SFS150 within the most drought stressed treatments (Figures 3a and 3b). Because the relations between the annual yields and the maximum SWD appeared to be curvi-linear, the yields in each year were also examined in relation to the stress time summed above a derived value for the critical SWD during each of the two dry seasons. Using the mean annual yields for all six clones, these were estimated to be 70 mm in 1990/91 (R^2=0.99) and 90 mm in 1991/92 (R^2=0.99). The drought sensitivity of each clone (K_d: kg ha^{-1} mm^{-1} d^{-1}) was then defined by the slope of the linear relation between the annual yields of each clone and the corresponding stress time for each drought treatment. The ranking of the clones in terms of K_d was consistent between the two years: Clones S15/10 and 207 were the most sensitive to drought; Clones 1 and SFS150 were the least sensitive (Table 3).

Table 3. *Sensitivity of annual yields to drought (kg ha^{-1} mm^{-1} d^{-1}): the slope (K_d) of the linear relation between the annual yields from 1 June to 31 May for each of six clones and the corresponding drought stress time (mm d) summed above critical deficits of 70 mm in 1990/91 and 90 mm in 1991/92.*

		Sensitivity of annual yields to drought: K_d	
		1990/91	1991/92
Clone	S15/10	-0.68	-1.28
	207	-0.50	-0.95
	6/8	-0.40	-0.88
	K35	-0.39	-0.84
	1	- 0.36	-0.75
	SFS150	-0.37	-0.67
sed (n=4)		0.048	0.093

The apparent drought sensitivity of Clone 207 can be partly explained by the observation that infection by the fungus *Phomopsis theae* (Petch) caused the defoliation and death of 19% of the unirrigated plants between November 1990 and May 1991. By contrast less than 6% of plants of the other clones were affected. The drought resistance shown by unirrigated plants of Clones 1 and SFS150, between June 1990 and May 1991, was partly related to the capacity of these bushes to maintain a greater crop cover (47-48%) than corresponding plants of Clones 6/8, 207 and K35 (21-25%) at the end of the dry season in November 1990 (Table 4).

Dry season yields and drought

There were also clonal differences in the effects of drought on yields during the dry season. For example whereas yields from Clone S15/10 under well watered conditions were substantially larger than those from the other five clones, under droughted conditions they were similar to those from Clones 1, 207, 6/8 and K35. In the 1990 dry season, yields from unirrigated Clone S15/10 were even below those from Clone SFS150 (Figures 3c and 3d).

The dry season yields of each clone were also examined in relation to stress time and using the mean yields of all six clones, the derived critical soil water deficits were 40 mm in 1990 (R^2=0.98) and 50 mm in 1991 (R^2=0.99). These are less than those obtained from an examination of the annual yields. Although Clone S15/10 was again shown to be particularly drought sensitive (Table 5), this analysis failed to confirm the drought sensitivity of Clone 207 or the drought resistance of Clone 1 that were apparent with the annual yields.

Table 4. *Effects of drought on the crop cover (%) of each of six clones on 15 November 1990, 15 months after field planting.*

		Crop cover	
		Fully irrigated (I_5)	Droughted (I_0)
Clone	1	77	48
	S15/10	74	39
	SFS150	63	47
	207	58	25
	6/8	50	25
	K35	50	21
	Mean	62	34

Standard error of difference between:

clone x drought treatments (same clone) = 5.8 (n=8)
clone x drought treatments (same drought treatment) = 5.9 (n=8)
drought treatments = 2.8 (n=48)

Table 5. *Sensitivity of dry season yields to drought (kg ha^{-1} mm^{-1} d^{-1}): the slope (K_d) of the linear relation between the dry season yields from 1 June to 30 November for each of six clones and the corresponding drought stress time (mm d) summed above critical deficits of 40 mm in 1990 and 50 mm in 1991.*

		Sensitivity of dry season yields to drought: K_d	
		1990	1991
Clone	S15/10	-0.13	-0.25
	6/8	-0.09	-0.19
	1	-0.07	-0.19
	207	-0.08	-0.15
	SFS150	- 0.08	-0.15
	K35	-0.06	-0.15
sed (n=4)		0.008	0.017

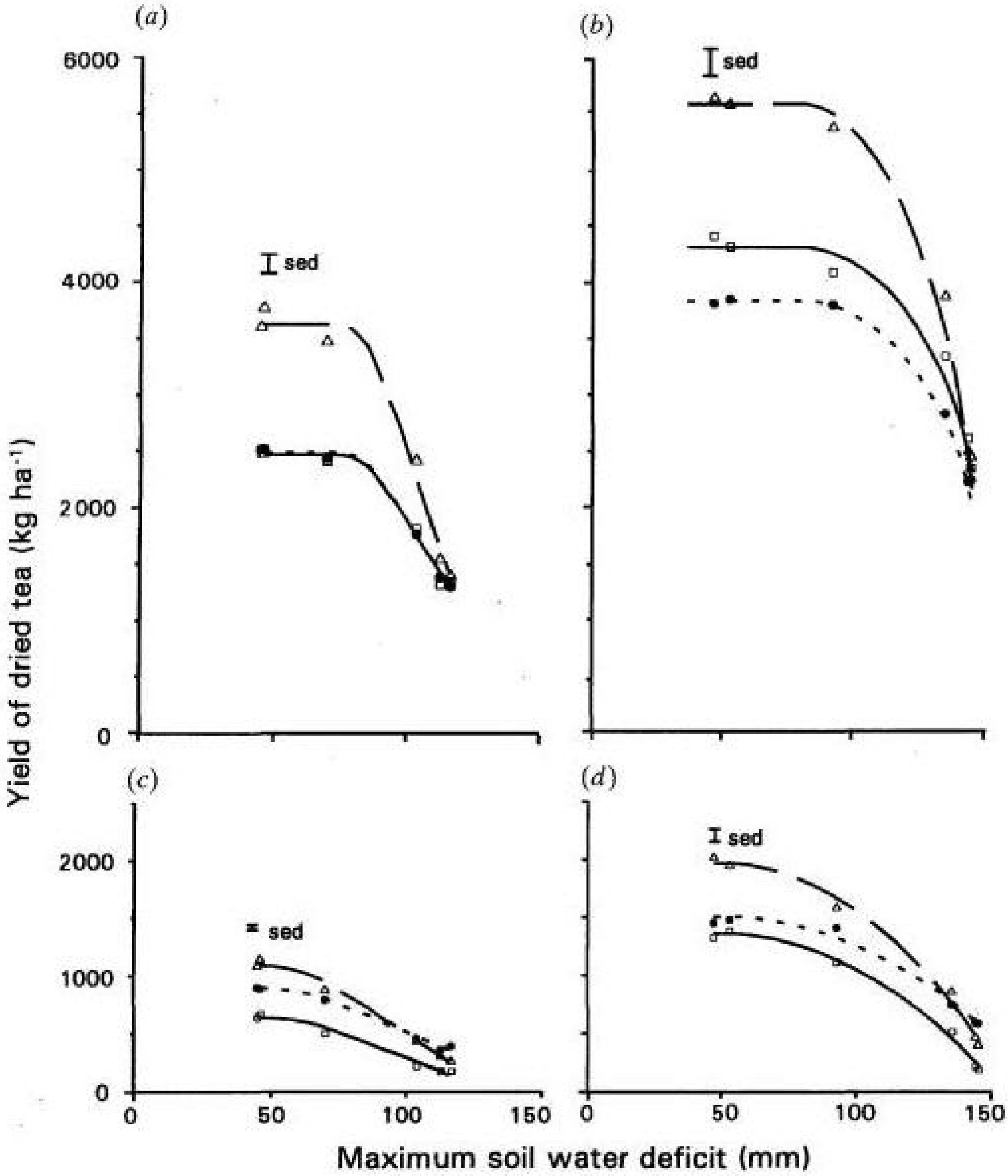

Figure 3. Relations between the yield of dried tea and the corresponding maximum soil water deficit for the annual periods from (a) June 1990 to May 1991, (b) June 1991 and May 1992, and the dry seasons from (c) June to November 1990 and (d) June to November 1991 for each of three clones: S15/10: △---△, 1: □——□, and SFS150: ●⋯⋯● (n = 4). The lines were drawn using the derived linear relations between the yields of each clone and stress time.

DISCUSSION

This study has highlighted the large annual yields that can be obtained from irrigated tea during the first four years after planting and the exceptional performance of Clone S15/10. There were also differences between clones in the seasonal yield distribution reflecting in part their relative sensitivities to low temperatures. The clones also differed in their responses to drought, although care is needed to specify an appropriate time period for the analysis. Each of these issues is discussed with specific reference to clonal selection. Firstly, though, the precision of the estimation of the actual soil water deficit is considered.

Soil water deficit

The soil water balance model provided a good description of the changes in SWD over a range of crop covers (50-90%) and maximum rooting depths (1.5-2.2 m). The model is also known to provide a good description of changes in SWD for young tea during the first year after planting (Burgess, 1992) and for mature tea with full crop cover and a maximum rooting depth of 5.5 m (Stephens and Carr, 1991b). It can therefore be used with some confidence to estimate the SWD for young and mature tea grown at this site with and without irrigation.

Further refinement of the model is limited by the precision of the neutron probe calibration, the repeatability of the field measurements and the definition of ‘field capacity’. The slope of the calibration curve relating the neutron probe readings to the volumetric water content had a standard error equivalent to 11 mm for each 100 mm of water extraction ($n = 21$). This is similar to values of between 6 and 17 mm per 100 mm ($n > 19$) reported for clay soils in the United States (Amoozegar *et al.*, 1989). The standard errors of the daily mean water content within each drought treatment ranged from 8 to 18 mm ($n = 16$). Such variations could be caused by differences in the chemical composition of the soil across the experiment or, more likely, by spatial differences in infiltration within the sub-plots. Differences in the gradual erosion of soil from the sides of the unlined holes could also have increased the variation in the calculated water content between replicates (Amoozegar *et al.*, 1989). For this reason the use of partially lined holes is not recommended. Lastly the SWD depends upon the determination of the water content at ‘field capacity’. In this experiment this was measured 24 hours after rain which had fully saturated the soil, and mean values to a depth of 1.9 m ranged from 490 to 516 mm.

Annual yields from fully irrigated clones

During the fourth year after planting (1991/92) the yield of dried tea from one clone, labelled S15/10, reached 5650 kg ha^{-1} compared with a mean of 3890 kg ha^{-1} from the other five clones. These values are greater than the 3000-3500 kg ha^{-1} currently obtained on the best commercial estates in Southern Tanzania from partially irrigated mature seedling and clonal tea with full ground cover. The large yields obtained in this experiment at commercial plant densities were possible through rapid establishment of crop cover by pegging, prevention of drought stress by irrigation and the removal of a high proportion of harvestable shoots by tightly controlled plucking. The real possibility of achieving such high yields from young tea has important commercial implications which are currently being examined by tea growers in the region.

One reason for the large initial yields from Clone S15/10 was its capacity to establish crop cover more quickly than four of the other clones. However the yield advantage of Clone S15/10 continued into 1992 even as the other clones approached full crop cover. In an accompanying paper, it is shown how the high yields of Clone S15/10 are associated with a greater partitioning of dry matter to leaves and less to large structural roots than the other five clones (Burgess and Carr, 1996a).

Seasonal yield distribution

There were also clonal differences in the seasonal distribution of yield. Although fully irrigated Clone SFS150 yielded more than Clone 1 during the cool-dry season, the ranking was reversed during the warm-wet season. Such differences can be caused by clonal differences in the 'base temperature' and 'thermal extension rate' for shoot growth. For example subsequent analyses have shown that Clone SFS150, selected in the seasonal climate of Southern Malawi, has a lower base temperature for shoot extension than Clones 1, 207 and K35 (Burgess and Carr, 1996b). This means that it is better able to maintain shoot growth during the winter months when the mean air temperature (13-15°C) is close to the base temperature for shoot extension. It also means that Clone SFS150 should be suitable for planting at high altitudes.

Clonal selection

By separating annual yield responses in terms of a) maximum yield and b) drought sensitivity, it is possible to identify those clones that give the highest yields for specified levels of drought stress. Where the crop was kept well watered, the yields from Clone S15/10 were 28-62% greater than those from the other five clones during the first four years after planting. Although it was unable to maintain this yield advantage when droughted, Clone S15/10 still produced yields higher than, or similar to, those from other clones at each of the drought levels examined in this experiment. Growers are therefore advised to grow a clone like S15/10, where partial irrigation can be provided or where the maximum actual SWD remains below 120-145 mm during the third and fourth years after planting. If the drought stress is greater than this, then yields from drought resistant Clones 1 and SFS150 could exceed those of Clone S15/10. However in practice Clone 1, although drought resistant, is of little commercial interest because the small fibrous shoots are difficult to harvest by hand and the quality of the processed tea is mediocre. Nevertheless it may be suitable as a root-stock for drought resistant composite plants. By contrast Clone SFS150 is of direct commercial interest (although of low inherent quality) and the results presented here suggest that it should be more widely grown by smallholders in Southern Tanzania who do not have the financial resources to provide irrigation. Clone SFS150 also has the advantage of relatively large yields during the cool season.

Comparison of annual and dry season responses

In each year the critical SWD for annual yield was substantially larger than that for the dry season alone. Although mild drought can reduce dry season yields by restricting the growth rate of shoots, these shoots can still contribute to yields in the subsequent wet season. Such compensation in growth and yields following the relief of drought stress has also been observed by Carr (1974). A grower must therefore balance the benefits obtained from a more even crop distribution by maintaining a small soil water deficit against the costs incurred by applying more water during the dry season.

The sensitivity to drought shown by the yields of Clone 207 on an annual basis was not apparent from an analysis of dry season yields alone. This is because the susceptibility of unirrigated Clone 207 to infection by the fungal disease *Phomopsis theae*, which is aggravated by drought (Shanmuganathan and Rodrigo, 1967), was only observed after the alleviation of stress. Similarly the benefits of the droughted plants of Clones 1 and SFS150 being able to maintain a greater crop cover than the other clones at the end of the dry season, only became fully apparent during the subsequent wet weather as increased interception of solar radiation led to greater dry matter production and larger yields. For this reason Clones 1 and SFS150 appeared to be more drought resistant when assessed on an annual, rather than a dry season basis. Both these examples highlight the importance of studying differences in the yield sensitivity to drought of perennial crops, such as tea, over an appropriate time period.

This experiment is continuing and the relations described above will be determined again for the same clones when they are mature. The quality and total value of the processed tea is also being measured.

Acknowledgements. This work was initiated whilst the senior author was supported by Associate Professional Officer Scheme run by the UK Overseas Development Administration. Afterwards the research was supported entirely by the tea industry: Brooke Bond Tanzania Ltd, the Tanzania Tea Authority, Mufindi Tea Company and the Tanganyika Wattle Company. The project is managed by the International Centre for Plantation Studies, Silsoe College, Cranfield University. Julio Lugusi, Badan Sanga and the late Gallus Myinga gave excellent technical support. Colin Congdon (Brooke Bond Tanzania Ltd) provided inspiration and essential logistical help. Dr Robin Matthews made helpful comments on the manuscript.

REFERENCES

Amoozegar, A., Martin, K.C., Hoover, M.T. (1989). Effects of access hole properties on soil water content determination by neutron thermalization. *Soil Science Society of America Journal* 53: 330-335.

Burgess, P.J. (1992). *Responses of tea clones to drought in Southern Tanzania*. PhD Thesis Silsoe College (Cranfield Institute of Technology) pp.254.

Burgess, P.J. & Carr, M.K.V. (1996a). Responses of young tea clones (*Camellia sinensis*) to drought and temperature. II. Dry matter production and partitioning. (In press).

Burgess, P.J. & Carr, M.K.V. (1996b). Responses of young tea clones (*Camellia sinensis*) to drought and temperature. III. Shoot extension and development. (Submitted).

Cannell, M.G.R., Harvey, F.J., Smith, R.I. & Deans, J.D. (1990). *Genetic improvement of tea.* Final report to the Overseas Development Administration February 1987-January 1990. Institute of Terrestrial Ecology, pp.85.

Carr, M.K.V. (1971). The internal status of the tea plant (*Camellia sinensis*): some results illustrating the use of the pressure chamber technique. *Agricultural Meteorology* 9: 447-460.

Carr, M.K.V. (1974). Irrigating seedling tea in Southern Tanzania: effects on total yields, distribution of yield and water use. *Journal of Agricultural Science,* Cambridge 83:363-378.

Carr, M.K.V. (1977). Changes in the water status of tea clones during dry weather in Kenya. *Journal of Agricultural Science,* Cambridge 89:297-307.

Carr, M.K.V. & Stephens, W. (1992). Climate, weather and the yield of tea. In : *Tea: Cultivation to consumption,* 87-135 (Eds K.C. Willson and M.N. Clifford). Chapman and Hall, London.

Carr, M.K.V., Dale, M.O. and Stephens, W. (1987). Yield distribution in irrigated tea (*Camellia sinensis*) at two sites in Eastern Africa. *Experimental Agriculture* 23: 75-85.

Hanks, R.J., Keller, J., Rasmussen, V.P. & Wilson, G.D. (1976). Line source sprinkler for continuous variable irrigation-crop production studies. *Soil Science Society of America Journal* 40: 426-429.

Morgan, D.D.V. & Carr, M.K.V. (1988). Analysing line source irrigation experiments. *Experimental Agriculture* 24: 169-176.

Nyirenda, H.E. (1988). Performance of new clones. *Tea Research Foundation of Central Africa Quarterly Newsletter* 91: 4-11.

Nyirenda, H.E. & Grice, W.J. (1989). TRF(CA) recommended clones. In *Tea Planter's Handbook.* Malawi: Tea Research Foundation of Central Africa.

Othieno, C.O. (1978). Supplementary irrigation of young clonal tea in Kenya. I: survival, growth and yield. *Experimental Agriculture* 14: 229-238.

Othieno, C.O. (1992). Soils. In Tea: Cultivation to Consumption, 137-172. (Eds. K.C. Willson and M.N. Clifford) London: Chapman & Hall.

Oyamo, J. (1992). The golden clone in a golden field. *Tea* 13: 1

Shanmuganathan, N. & Rodrigo, W.R.F. (1967). Studies on collar and branch canker of young tea (*Phomopsis theae* Petch). II - Influence of soil moisture on the disease. *Tea Quarterly* 38: 320-330.

Stephens, William & Carr, M.K.V. (1989). A water stress index for tea (*Camellia sinensis* L.) *Experimental Agriculture* 25: 545-558.

Stephens, William & Carr, M.K.V. (1990). Seasonal and clonal differences in shoot extension rates and numbers in tea (*Camellia sinensis*). *Experimental Agriculture* 26: 83-98.

Stephens, William & Carr, M.K.V. (1991a). Responses of tea (*Camellia sinensis*) to irrigation and fertiliser. I. Yield. *Experimental Agriculture* 27: 177-191.

Stephens, William & Carr, M.K.V. (1991b). Responses of tea (*Camellia sinensis*) to irrigation and fertiliser. II. Water use. *Experimental Agriculture* 27: 193-210.

Tanton, T.W. (1982). Environmental factors affecting the yield of tea (Camellia sinensis). II: Effects of soil temperature, day length, and dry air. *Experimental Agriculture* 18: 47-52.

Tea Research Foundation of Kenya. (1986). *Tea Growers Handbook 4th Edition.* The Tea Board of Kenya, pp.249.

Wickramaratne, M. Rupa T. (1981). Genotype-environment interactions in tea (*Camellia sinensis* L.) and their implications in tea breeding and selection. *Journal of Agricultural Science,* Cambridge 96: 471-478.