Journal of Agricultural Science (2005), **143**, 395–405. © 2005 *Cambridge University Press*
doi:10.1017/S0021859605005563 *Printed in the United Kingdom*

Resource competition in contour hedgerow intercropping systems involving different shrub species with mature and young tea on sloping highlands in Sri Lanka

W. A. J. M. DE COSTA†* AND P. SURENTHRAN

Department of Crop Science, Faculty of Agriculture, University of Peradeniya, Peradeniya 20400, Sri Lanka

(*Revised MS received 18 June 2005*)

SUMMARY

Tea (*Camellia sinensis*) in Sri Lanka is grown predominantly on sloping highlands. Incorporating trees as hedgerows along contours is aimed at reducing erosion and improving soil fertility through addition of prunings as mulch. However, there could be significant competition for essential growth resources between the hedgerows and tea. The primary objective of this study was to determine the influence of six hedgerow species (*Calliandra calothyrsus*, *Senna* [*Cassia*] *spectabilis*, *Eupatorium inulifolium*, *Flemingia congesta*, *Gliricidia sepium* and *Tithonia diversifolia*) on mature (6-year-old) and young (6-month-old) tea. This study had three on-farm, long-term (from Nov 1998 to Dec 2002) field experiments. Experiment 1 had 12 treatment combinations with the six shrub species and two mulching treatments (i.e. hedgerow prunings added to the tea plot as a mulch, and unmulched) on mature tea plus a sole tea crop as control. The same was repeated on young tea in Experiment 2 to determine whether resource competition on young tea was greater than that on mature tea. Experiment 3 examined the effects of removing tree root competition on tea by cutting a 1-m deep trench between hedgerows and tea.

In all experiments, total tea yields of hedgerow intercrops, cumulated over the 50-month experimental period, were significantly lower (by 3–50%) than sole tea crops, thus indicating significant resource competition except in the case of mulched hedgerow systems involving *Eupatorium* and mature tea (18% yield increase). Removal of below-ground competition significantly increased tea yields by 11–19%. Addition of hedgerow prunings as a mulch significantly increased yields of both mature and young tea by 13–21%. Tea yields of hedgerow systems with *Calliandra*, *Flemingia* and *Eupatorium* showed greater yield reductions in young tea than in mature tea, but the opposite was shown with other hedgerow species. There was a significant negative linear relationship between tea yield and pruned biomass of hedgerows. Tea yields of all experiments showed significant negative correlations with several hedgerow characters, which are indicators of their competitive ability. These included hedgerow root density, canopy lateral spread, height and cross-section. In a majority of hedgerow systems, the available phosphorus content of topsoil (0–20 cm depth) was up to 51% lower compared to sole crops. It is concluded that incorporation of contour hedgerows in to an existing tea crop could result in significant resource competition with tea and thereby cause tea yield to decrease. However, there is scope for selection of hedgerow species that minimize competition through spatial and temporal complementarity with tea in resource capture.

INTRODUCTION

Tea (*Camellia sinensis* (L.) O. Kuntz) is one of the world's major beverages and is the main perennial crop grown in Sri Lanka. A major portion of tea in Sri Lanka is grown on sloping terrain in areas of high rainfall (>2500 mm/year) and is highly susceptible to

† To whom all correspondence should be addressed. Email: janendrad@yahoo.com

* Present address (until 20.12.05): Institut fur Pflanzenernaehrung, Interdisziplinares Forschungszentrum (IFZ), Justus-Liebig-Universitat, Heinrich-Buff-Ring 26-32, 35392 Giessen, Germany.

erosion. Export of soil nutrients as tea yield over a long period of time coupled with soil erosion has reduced soil fertility in most tea-growing regions (De Costa 1997; Anonymous 2002). Therefore, measures to reduce erosion and regenerate soil fertility have become essential pre-requisites to sustain high tea yields. Incorporation of shrub hedges along contours of sloping land among the existing tea rows has been proposed (Ekanayake 1994). The contour hedgerows are expected to form a biological barrier to trap eroding soil within the tea field (Wiersum 1984, 1991; Garrity 1996). In addition, frequent prunings of fast-growing shrub species, when added to the soil, are expected to improve the physical properties and nutrient status of the soil (Palm 1995; Sanchez *et al.* 1997; Palm *et al.* 2001; Smithson & Giller 2002).

Despite these potential benefits of contour hedgerows, there can be significant competition for essential growth resources such as light, water and nutrients (Ong 1991; Rao *et al.* 1998; De Costa & Chandrapala 2000*a, b*) between hedgerows and tea. As different tree species differ in the degree of resource competition exerted, selection of appropriate species for hedgerows is crucial for success. Therefore, the primary objective of the present study was to quantify the resource competition by a range of potential hedgerow species on tea.

Tea is a perennial crop, and so adverse effects of resource competition from hedgerow species could be expected to vary with the age of the tea crop. At the beginning of this study, it was hypothesized that if contour hedgerows exert significant resource competition any adverse effects would be felt to a greater extent on 'young' tea, which is just establishing its root system and foliage canopy. In contrast, establishing hedgerows on 'mature' tea which is already well-established in the field would enable the tea crop to be more competitive with the hedgerows in resource capture. Therefore, the second objective of this study was to compare contour hedgerow intercropping systems involving young tea (i.e. a 6-month-old tea crop in its first pruning cycle) with those involving mature tea (i.e. a 6-year-old tea crop in its third pruning cycle).

When contour hedgerows are established within a tea crop, hedgerow roots could grow both vertically and laterally into tea plots and compete with tea for below-ground resources (Huxley *et al.* 1989; Rao *et al.* 1991; Livesley *et al.* 2000; Odhiambo *et al.* 2000). Preventing the lateral spread of hedgerow roots into tea plots would reduce this competition. Hence, a third objective of this study was to quantify the effects of removing below-ground resource competition by hedgerows on tea by cutting a 1-m deep trench between hedgerows and the nearest tea row. Any adverse effects of resource competition by hedgerow species might be offset by positive effects brought about by adding their prunings to the soil. Therefore, a fourth objective was to determine the potential beneficial effects of adding hedgerow prunings on soil properties and productivity of young and mature tea.

MATERIALS AND METHODS

This study consisted of three long-term field experiments performed concurrently during a 50-month period from Nov 1998 to Dec 2002. This period represented one complete pruning cycle (i.e. 36 months from Nov 1998 to Oct 2001) of tea plus 10 months (from Mar to Dec 2002) in the subsequent pruning cycle and a 4-month re-growth period (Nov 2001 to Feb 2002) following pruning at the end of Oct 2001.

Climate and soil conditions during the experiment

All three experiments were carried out as on-farm experiments at Helbodde Estate, Pussellawa in the high elevation (945 m a.s.l.), humid zone of Sri Lanka. According to Panabokke (1996), this agro-ecological zone is classified as 'Up-country, wet zone (WU_2)'. The mean annual rainfall during the experimental period was 2938 mm/year with an average of 153 rainy days (i.e. days with above 5 mm of rainfall) per year and a potential evapotranspiration of 846 mm/year. The rainfall was well distributed throughout the year. Monthly rainfall below 100 mm for two consecutive months occurred only in February and March 2001. Hence, there was no prolonged drought during the experimental period. Mean minimum and maximum air temperatures at screen height (1·2 m above the soil surface) were 13·6 (standard deviation = 1·58) and 24·0 (S.D. 1·54) °C with a daily mean of 18·8 (0·70) °C. Mean relative humidity was 94 (S.D. 2·3) % and the daily mean incident solar radiation was 15·59 (S.D. 2·48) MJ/m^2 per day.

The soil was allocated to the great group Rhodudults (Panabokke 1996) and classified as Haplic Alisol (FAO/UNESCO system) and Typic Hapludult (USDA system) (Dassanayake & Hettiarachchi 1999). It was well-drained, dark yellowish-brown in colour, with a clay loam (40% sand, 25% silt and 35% clay) texture on the surface and loam to clay in subsoil. It had a weak subangular blocky structure on the surface and a moderate subangular blocky structure in subsoil. The bulk density ranged from 0·85–1·50 t/m^3 while top and subsoil pH ranged from 4·5–4·8 and 4·9–5·2 respectively. At the beginning of the experiment, average soil nutrient contents were: total nitrogen: 2·70 (S.D. 0·22) g/kg soil; available phosphorus: 25·8 (S.D. 3·1) mg/kg; exchangeable potassium: 0·215 (S.D. 0·037) mg/kg; organic matter: 51 (S.D. 4·1) g/kg soil. The experimental field had a slope of 30–35%.

Experiment 1 – Experimental treatments and design

The specific objectives of Expt 1 were to determine the effects of different hedgerow species and addition of hedgerow prunings as mulch on a 6-year-old (at the beginning of the experiment) tea crop which was in its third pruning cycle (i.e. mature tea). There were six hedgerow intercropping systems consisting of tea with the following shrub species: *Calliandra calothyrsus* Meissner; *Senna* [*Cassia*] *spectabilis* (DC.) H. Irwin & Barneby; *Eupatorium inulifolium* (R. M. King & H. Rob.) H. B. K.; *Flemingia congesta* Aiton F.; *Gliricidia sepium* (Jacq.) (Kunth.) Walp. and *Tithonia diversifolia* (Hemsl.) A. Gray. Hedgerow systems with each species had two mulching treatments. In the 'mulched' treatment, hedgerow prunings obtained at 4-month intervals were spread uniformly over the tea plot. In the 'unmulched' treatment, hedgerow prunings were not added to the tea plots. The treatment structure was a two-factor factorial with hedgerow species and mulching as the main factors with an additional control, which was tea sole cropped without contour hedgerows. The 13 treatments were laid out in a randomized complete block design with three blocks. Different blocks were laid along separate contours.

The contour hedgerows were established in 1992. Each hedgerow was made up of two closely planted rows with intra-row spacing of 0·50 m. The distance between two hedgerows varied between 8 and 9 m depending on the slope. Tea (clone TRI2023) was planted between hedgerows at a spacing of 1·22 m (along the slope) × 0·61 m (along the contour). The distance between hedgerows and the nearest tea row was 0·61 m. There were six tea rows between any pair of hedgerows. Each hedgerow intercrop plot (31·28 m along the slope × 10·98 m along the contour) had four hedgerows with tea growing in between. There was a 1-m deep trench around each plot to prevent lateral spread of roots between adjacent plots. An experimental plot of 9·76 m (along the contour) × 15·64 m (along the slope) was identified for measurements within each hedgerow intercrop plot. This consisted of the two middle hedgerows, the six tea rows in between them and three tea rows above and below them. In each block, the control plots were located 25 m away from the hedgerow intercrops in the respective contours in order to avoid the spread of hedgerow roots into sole tea plots.

Crop management

Tea was grown as a rainfed crop with pest and disease control and fertilizer application as recommended by the Tea Research Institute of Sri Lanka (Anonymous 1994). Accordingly, 220 kg N, 37 kg P and 110 kg K per ha per year were added in four equal splits at 3-month intervals. Tea was pruned to a height of 0·30 m at 3-year intervals. Hedgerows were pruned to a height of 0·45 m at 4-month intervals. At each pruning, all leaves and stems above this height were removed.

Measurements

Tea yield of each experimental plot was obtained by plucking 12 rows of tea bushes separately in pairs (i.e. six pairs of rows) at 6–7 day intervals using the same plucker. Out of the 18 bushes in each row, 16 were harvested. In the control treatment, 32 tea bushes (four rows of eight bushes each) were harvested from the middle of the plots. Tea yield was expressed as t DW/ha over the 50-month experimental period.

At each pruning of hedgerows, fresh biomass of leaf and stem prunings was obtained. To obtain the ratio of dry biomass to fresh biomass, 100 g subsamples were oven-dried to a constant weight at 80 °C. The dry biomass of prunings was obtained based on the above ratio. Periodic pruned biomass values obtained during the 50-month period were cumulated to compute total pruned biomass in t DW/ha.

In order to determine the degree of belowground competition exerted by different hedgerow species, their root growth was measured between October 2001 and February 2002 when the tea crop was pruned. A pit (60 cm deep and 60 cm wide) was cut along the hedgerow in each plot. The exposed vertical soil surface was divided into 15 cm × 15 cm grids and the number of cut root ends visible from the vertical soil surface was counted. The canopy growth of hedgerows was measured in terms of their lateral spread from the mid-point of hedgerow (i.e. half the hedgerow width) and canopy height. The canopy cross-section was estimated as hedgerow width × canopy height above 0·45 m (i.e. hedgerow pruning height) and taken to indicate the degree of aboveground competition by hedgerows. All measurements were made at 2, 3 and 4 months after pruning of hedgerows over five pruning cycles from September 1999 to March 2001.

Topsoil (0–20 cm) chemical properties in tea plots were measured in January, May and September in 2000 and 2001, which were the second and third years of the pruning cycle of tea. Soil samples were obtained 3 months after an application of chemical fertilizer, just before the next application. In each experimental plot, five soil samples each were obtained from between the two middle rows above and below the hedgerows. Total soil nitrogen was measured using a micro-Kjeldahl method. Available phosphorus was measured by the Bray method (Van Ranst *et al.* 1999) and exchangeable potassium was analysed by flame photometry after digestion with concentrated sulphuric acid.

Table 1. *Variation of total tea leaf yield (t DW/ha) of hedgerow intercropping systems and sole cropped tea with different tree species and mulching treatments in mature tea (Expt 1) and young tea (Expt 2) and with and without root competition (Expt 3) during the 50-month period from November 1998 to December 2002*

	Experiment 1		Experiment 2		Experiment 3	
Species	Mulched	Unmulched	Mulched	Unmulched	With root competition	Without root competition
Calliandra calothyrsus	7·2	6·3	5·9	5·0	4·2	4·8
Senna spectabilis	6·7	5·9	6·9	6·0	3·6	4·2
Eupatorium inulifolium	11·7	9·7	8·0	6·7	5·2	5·8
Flemingia congesta	7·4	6·4	5·3	4·5	5·1	5·9
Gliricidia sepium	6·9	5·8	6·5	5·6	3·1	3·7
Tithonia diversifolia	6·6	5·7	6·5	5·7	4·0	4·7
S.E.[1] (D.F. = 10)	0·52	0·39	0·34	0·26	0·41	0·49
Mean	7·7	6·6	6·5	5·6	4·2	4·8
S.E.[2] (D.F. = 22)	0·44		0·29		0·43	
Sole cropped tea (Control)	10·0		8·9		6·5	
S.E.[3] (D.F. = 12)	0·54		0·29		0·57	

Note: S.E.[1] – Standard error of means to compare tea yields under different hedgerow species.
S.E.[2] – Standard error of means to compare mean tea yields under mulched and unmulched conditions (in Expts 1 and 2) and with and without root competition (in Expt 3).
S.E.[3] – Standard error of means to compare mean tea yields in hedgerow intercrops with that in the sole tea crop.

Data analysis

Analysis of variance was used to determine the significance of treatment effects on tea yields and pruned biomass of hedgerows cumulated over the 50-month experimental period. The relationship between tea yield and pruned biomass of hedgerows was determined by linear regression. Correlations between tea yield and hedgerow characters indicating the degree of above- (i.e. canopy lateral spread, height and cross-section) and below-ground competition (i.e. total root number per m^2 counted on the vertical face of a soil pit) were examined by multiple correlation analysis. The forward selection procedure of multiple regression analysis (SAS 2000) was used to determine the contribution of different hedgerow properties to the observed variation of tea yields in hedgerow systems.

Experiment 2

The specific objective of Expt 2 was to determine the effects of different hedgerow species and addition of hedgerow prunings as mulch on a 6-month-old tea crop ('young tea') in which plucking had just begun. Hedgerows were planted at the time of establishing the tea crop in March–April, 1998. Experimental treatments, layout, crop management, measurements and data analysis were similar to those of Expt 1.

Experiment 3

The specific objective of Expt 3 was to quantify the effects of removing below-ground competition exerted by the six hedgerow species tested in Expts 1 and 2. Below-ground competition was eliminated by cutting a 1-m deep trench between the hedgerow and the nearest tea row on either side of the hedges. The experimental design had 12 treatment combinations comprising six hedgerow species and two trenching treatments (i.e. with and without a trench) laid out in a randomized complete block design with three blocks. This experiment was carried out on another part of the mature tea field used for Expt 1. Except for the trenching treatment, crop management, measurements and data analysis were similar to Expts 1 and 2.

RESULTS

Tea yield – Expt 1

Total dry weights of plucked tea-leaves during the 50-month measurement period in different hedgerow systems and sole cropped tea are given in Table 1. Different hedgerow species and mulching treatments had highly significant ($P < 0·0001$) effects on tea yields. There was no significant ($P < 0·05$) species × mulching interaction on tea yields. A majority of hedgerow systems showed significant reductions of tea yield in comparison to the sole crop control under both mulched and unmulched conditions. However, hedgerows of *Eupatorium inulifolium* had a significantly greater tea yield than the control under mulched conditions, but not when unmulched. The reductions in tea yield were 27–34% in mulched hedgerow systems and 3–43% when unmulched. In contrast,

Table 2. *Total dry weights and the proportion of leaf dry weight in total dry weight of prunings in different hedgerow species in the three experiments during the 50-month period from November 1998 to December 2002*

Species	Experiment 1		Experiment 2		Experiment 3	
	Total dry weight (t/ha)	Proportion of leaf DW	Total dry weight (t/ha)	Proportion of leaf DW	Total dry weight (t/ha)	Proportion of leaf DW
Calliandra calothyrsus	16·7	0·52	15·0	0·61	21·3	0·55
Senna spectabilis	14·2	0·56	24·0	0·48	15·4	0·55
Eupatorium inulifolium	9·3	0·42	13·3	0·42	7·9	0·45
Flemingia congesta	14·1	0·60	12·5	0·57	14·2	0·49
Gliricidia sepium	10·1	0·61	5·9	0·58	10·6	0·54
Tithonia diversifolia	15·1	0·42	9·9	0·29	25·0	0·57
S.E. (D.F.=10)	1·90		2·07		2·95	

Note: S.E. is the standard error of means for comparisons between different hedgerow species.

tea yield increased by 18% when mulched with *Eupatorium*. Mulching significantly increased tea yields (compared to unmulched) in all hedgerow systems. The highest tea yield response to mulching (+21%) was with *Eupatorium*, while yield increases with other species was 13–19%.

Tea yield – Expt 2

As in Expt 1, young tea yields (Table 1) were also significantly affected by different hedgerow species ($P<0·0001$) and mulching treatments ($P<0·0001$). However, the tree species × mulching interaction was not significant at $P=0·05$. In contrast to mature tea, young tea under all hedgerow species, including *Eupatorium*, had significantly lower yields than sole cropped tea, under both mulched and unmulched conditions. Under mulched conditions, the yield reductions ranged from 11% under *Eupatorium* to 40% under *Flemingia*. The corresponding range of yield reductions under unmulched conditions was from 24% under *Eupatorium* to 50% under *Flemingia*. Mulching increased the tea yield in all hedgerow systems in both young and mature tea. Yield increases under different hedgerow species ranged from 14% under *Tithonia* to 20% under *Flemingia*. Except with *Senna*, absolute yields of young tea in hedgerow systems as well as in the control, were lower in Expt 2 than the corresponding yields of mature tea in Expt 1. When percentage yield reductions (based on data in Table 1) below the control in corresponding hedgerow systems involving young and mature tea were compared, three hedgerow systems showed greater percentage yield reductions in young tea. These were the hedgerow systems involving *Flemingia*, *Calliandra* and *Eupatorium*. The rest showed greater percentage yield reductions in mature tea.

Tea yield – Expt 3

Removal of root competition by cutting a 1-m deep trench between hedgerows and tea bushes significantly ($P<0·001$) increased tea yields under all hedgerow species (Table 1). Yield increases ranged from 11% under *Eupatorium* to 19% under *Gliricidia*. When averaged across different hedgerow species, the mean yield increase due to removal of root competition was 15%. All tea crops growing under hedgerows, both with and without root competition, had significantly lower yields than the sole crop control. When root competition was present, yield reductions ranged from 20% under *Eupatorium* to 52% under *Gliricidia*. In contrast, when root competition was removed, yield reductions ranged from 10% under *Flemingia* to 43% under *Gliricidia*. There was no significant trenching × hedgerow species interaction effect on tea yields.

Biomass of hedgerow prunings and its relationship to tea yield

Total biomass of prunings differed significantly ($P<0·01$) between hedgerow species in all three experiments (Table 2). *Tithonia* and *Calliandra* produced significantly more, and *Eupatorium* and *Gliricidia* significantly less pruned biomass. Partitioning of pruned biomass between leaf and stem biomass varied between species (and experiments). While *Gliricidia* and *Calliandra* consistently had a greater proportion of leaf biomass, *Eupatorium* had a greater proportion of stem biomass in its prunings. In all three experiments, significant negative relationships were observed between mean tea yield and pruned biomass of hedgerows (Table 3).

Table 3. *Linear relationships between mean tea yield (Y, t DW/ha) and pruned biomass of hedgerows (BM) in three experiments containing hedgerow intercropping systems involving tea and different hedgerow species in sloping highlands of Sri Lanka*

Experiment	Linear relationship	R^2
1	Y = 10·40–0·25 BM	0·53
2	Y = 7·45–0·09 BM	0·24
3	Y = 5·84–0·08 BM	0·35

Note: Mean tea yields of mulched and unmulched treatments in Experiments 1 and 2 and mean tea yields of trenched and untrenched treatments in Experiment 3 were used in the regressions.

Root growth of hedgerows and its depth distribution

The total number of roots (N_R) counted on the vertical face of a soil pit along hedgerows showed significant ($P<0·05$) variation between different shrub species in all experiments (Table 3). *Tithonia* showed significantly more roots and *Gliricidia* significantly fewer roots in all experiments. The distribution of total root densities in different soil depth layers varied significantly between species (Table 4). *Eupatorium* consistently had a lower proportion of its root system in the top soil layer (0–15 cm) and a higher proportion in the middle soil layers (15–45 cm). In contrast, *Tithonia* consistently had a higher proportion of its root system in the topsoil.

Canopy growth of hedgerows

Canopy lateral spread (S), height (H) and the cross-section (A) showed significant ($P<0·05$) variation between different hedgerow species in all experiments (Table 5). *Gliricidia* had the lowest S, H and A values in all experiments while consistently higher values were shown by *Calliandra*. In the two experiments involving mature tea (Expts 1 and 3), the highest S, H and A were shown by *Tithonia*, whereas *Senna* had the highest values in the experiment involving young tea. It could be noted that *Flemingia* canopies had consistently low S, H and A.

Correlations between tea yield and hedgerow characters

In all experiments, significant negative correlations were observed between tea yield and the hedgerow characters (Table 6). These included canopy lateral spread, height and cross-section area, which indicated the degree of above-ground competition, and the total number of roots per m² of vertical wall of a soil pit, which indicated below-ground competition. Multiple regression analysis showed that a substantial portion of tea yield variation (total $R^2>0·75$) in hedgerow systems could be explained by variation of the above hedgerow characters. In Expt 1, the respective contributions to tea yield variation as indicated by partial R^2 were 0·53 by pruned biomass of hedgerows, 0·11 by canopy height and 0·11 by the total root number per m². Canopy height (partial $R^2=0·59$) and canopy cross-section (partial $R^2=0·17$) had the highest contributions to tea yield variation in Expt 2. In Expt 3, variations of canopy lateral spread (partial $R^2=0·37$), total root number per m² (partial $R^2=0·24$), pruned biomass of hedgerows (partial $R^2=0·19$) and canopy cross-section (partial $R^2=0·14$) were responsible for tea yield variation.

Soil chemical properties

Although the topsoil N, P and K concentrations showed a gradual increase with time, measurements at different times during the experimental period (i.e. three times each in the 2nd and 3rd years of the pruning cycle) were pooled because they did not show significant ($P<0·05$) variation between times of measurement. The interaction effects between hedgerow species and mulching treatments (Expts 1 and 2) or removal of root competition (Expt 3) were not significant ($P=0·05$). Therefore, the two main effects are examined separately (Tables 7 and 8). Topsoil N in the majority of hedgerow systems of all three experiments was not significantly ($P=0·05$) different from that of the sole crop control (Table 7). Some hedgerow systems showed significantly greater N in the topsoil than the control (e.g. *Tithonia* in Expt 1, *Flemingia* in Expts 2 and 3) and only one (i.e. *Tithonia* in Expt 3) showed significantly lower soil N than the control. In contrast, most hedgerow systems in all experiments showed significantly lower available P in the topsoil than the control. There were none that showed significantly greater P than the control. The response of available K in the topsoil was inconsistent in the three experiments. None of the hedgerow systems in any experiment showed significantly greater soil K than the control.

All three nutrients showed significant increases due to addition of prunings as mulch (Table 8). Soil N increased by 21% and 38% respectively in Expts 1 and 2, while the corresponding increases for P were 33% and 41%. Although removal of root competition increased soil N and P slightly (i.e. by 2% and 5% respectively), these increases were not statistically significant at $P=0·05$. However, removal of root competition significantly increased soil-available K.

DISCUSSION

Results of all three long-term experiments of this study confirmed the initial hypothesis that hedgerows

https://doi.org/10.1017/S0021859605005563 Published online by Cambridge University Press

Table 4. *Root density and its distribution at different soil depths as counted on the vertical wall of a soil pit along hedgerows of different tree species used in contour hedgerow intercrops with tea*

	Experiment 1		Experiment 2		Experiment 3	
Species	Total root density (no./m²)‡	Depth distribution†	Total root density (no./m²)	Depth distribution	Total root density (no./m²)	Depth distribution
Calliandra calothyrsus	209	0·42:0·25:0·20:0·13	206	0·42:0·24:0·22:0·12	263	0·27:0·27:0·26:0·20
Senna spectabilis	232	0·38:0·27:0·21:0·14	184	0·30:0·26:0·26:0·18	156	0·37:0·24:0·23:0·16
Eupatorium inulifolium	240	0·29:0·34:0·25:0·12	242	0·32:0·28:0·24:0·16	248	0·28:0·35:0·23:0·14
Flemingia congesta	223	0·36:0·30:0·21:0·13	202	0·38:0·27:0·19:0·16	181	0·26:0·27:0·28:0·19
Gliricidia sepium	196	0·27:0·27:0·27:0·19	169	0·42:0·27:0·20:0·11	158	0·27:0·23:0·28:0·22
Tithonia diversifolia	316	0·33:0·27:0·20:0·20	261	0·37:0·28:0·18:0·17	254	0·33:0·30:0·21:0·16
S.E. (D.F. = 12)	14·0		13·1		19·4	

Note: ‡ Number of roots counted per m² of vertical face of a soil pit.
† Proportions of the total root density distributed in four depth layers as 0–15 cm; 15–30 cm; 30–45 cm; 45–60 cm.
S.E. is the standard error of means for comparisons between different hedgerow species.

Table 5. *Maximum lateral canopy spread* (*S*), *canopy height* (*H*) *and cross-sectional area above pruning height* (*A*) *of different contour hedgerow species in the sloping highlands of Sri Lanka*

	Experiment 1			Experiment 2			Experiment 3		
Species	S (m)	H (m)	A (m²)	S (m)	H (m)	A (m²)	S (m)	H (m)	A (m²)
Calliandra calothyrsus	1·33	1·54	3·21	1·16	1·38	2·44	1·09	1·40	2·26
Senna spectabilis	1·12	1·59	2·63	1·37	1·53	3·17	1·09	1·46	2·33
Eupatorium inulifolium	0·97	1·36	1·80	1·10	1·42	2·29	0·99	1·10	1·41
Flemingia congesta	0·73	1·48	1·59	0·68	1·46	1·48	0·66	1·35	1·21
Gliricidia sepium	0·96	1·10	1·42	0·69	0·96	0·74	0·76	0·88	0·79
Tithonia diversifolia	1·51	1·75	4·39	0·94	1·27	1·60	1·70	1·87	5·41
S.E. (D.F. = 82)	0·242	0·289	1·206	0·195	0·275	0·841	0·232	0·260	1·246

Note: Each value is a mean of measurements over five pruning cycles in three replicate plots, each containing two hedgerows. Measurements were made just before pruning. Canopy lateral spread was defined as half the canopy width. Canopy cross-sectional area above pruning height for a 10-m length of each hedgerow was calculated as the product between height above 0·45 m and twice the lateral spread. S.E. is the standard error of means for comparisons between different hedgerow species.

exerted significant competition on both mature and young tea and thereby caused significant yield reductions. Such yield reductions have also been observed in hedgerow intercropping systems involving a range of crops (Huxley *et al.* 1989 with maize; Rao *et al.* 1991 with groundnut; Corlett *et al.* 1992 with pearl millet; Rao *et al.* 1992 with sorghum; De Costa & Chandrapala, 2000*a* with mung bean). The significant negative relationships observed between tea yield and hedgerow biomass production showed that fast-growing tree species were not suitable as hedgerow species with tea in this agroecological zone. Similar results have been obtained by Broadhead *et al.* (2003) for maize and *Phaseolus vulgaris* growing with rows of tree species differing in their leaf phenology.

It was hypothesized at the beginning of the experiment that young tea, which was just establishing its root system and foliage canopy, would be more susceptible to resource competition from hedgerows than mature tea, which already had well-established root and shoot systems for resource capture. However, results over the 50-month period of the present

https://doi.org/10.1017/S0021859605005563 Published online by Cambridge University Press

Table 6. *Linear correlation coefficients between hedgerow characters and tea yield in hedgerow intercropping systems involving tea and different tree species*

	Linear correlation coefficient with tea yield in hedgerow intercrops				
Experiment	Pruned biomass of hedgerows	Total number of hedgerow roots/m² of vertical face of a soil pit	Canopy lateral spread of hedgerows	Canopy height of hedgerows	Canopy cross-sectional area of hedgerows
1	−0·726	−0·520	−0·605	−0·589	−0·594
2	−0·494	−0·699	−0·537	−0·769	−0·438
3	−0·594	−0·430	−0·610	−0·572	−0·407

Note: All values are significant at $P<0{\cdot}05$.

Table 7. *Variation of total nitrogen, available phosphorus and exchangeable potassium in the top soil* (*0–20 cm depth*) *of hedgerow intercropping systems involving different tree species and mature tea* (*Expt 1*)*, young tea* (*Expt 2*) *and with and without root competition* (*Expt 3*)

	Experiment 1			Experiment 2			Experiment 3		
Species	Total N (g/kg)	Av. P (mg/kg)	Exch. K (mg/kg)	Total N (g/kg)	Av. P (mg/kg)	Exch. K (mg/kg)	Total N (g/kg)	Av. P (mg/kg)	Exch. K (mg/kg)
Calliandra calothyrsus	2·82	37·3	0·210	3·82	33·5	0·215	3·03	34·1	0·055
Cassia spectabilis	2·88	21·5	0·153	2·92	15·6	0·172	3·76	22·0	0·108
Eupatorium inulifolium	2·99	41·5	0·286	2·04	28·4	0·143	2·97	37·9	0·137
Flemingia congesta	2·79	28·8	0·122	3·56	19·6	0·236	3·33	32·1	0·047
Gliricidia sepium	2·84	26·1	0·144	2·53	22·0	0·213	2·67	24·2	0·103
Tithonia diversifolia	3·37	49·5	0·236	2·39	15·6	0·137	2·51	40·6	0·085
Control	3·06	43·8	0·230	2·37	27·9	0·188	3·06	43·8	0·230
S.E. (D.F. = 46)	0·502	7·26	0·0979	0·592	6·22	0·1047	0·454	3·82	0·0563

Note: The values are means of pooled measurements taken from the up-slope and down-slope sides of the hedgerows and mulched and unmulched treatments (in Expts 1 and 2) or with- and without root competition (in Expt 3). S.E. is the standard error of means for comparisons between different hedgerow species.

experiments only partially supported this initial hypothesis. Only hedgerows of *Calliandra*, *Flemingia* and *Eupatorium* showed greater yield reductions of young tea (relative to the control) than these species with mature tea (Table 1). One plausible explanation for the above observation is that the different hedgerow species have different phonologies and dynamics of resource capture, as do young and mature tea. This is supported by the lower yield reductions observed in young tea growing with *Gliricidia* and *Tithonia*, both of which had substantially less pruned biomass during the early stages (i.e. in Expt 2) than during the latter stages (i.e. in Expt 1) (Table 2). This temporal separation of resource capture probably played an important role in determining the degree of competition exerted by a given hedgerow species on tea at different phenological stages (Broadhead *et al*. 2003). Ong *et al*. (1999) have also shown for several tree species, including *Gliricidia* and *Senna*, that resource competition could vary substantially with tree age. The other hedgerow species under which young tea showed a lower yield reduction was *Senna*. Although *Senna* had a greater pruned biomass in Expt 2 (in contrast to *Gliricidia* and *Tithonia*), it also had a lower total root density (Table 4) and cross-sectional area (Table 5) in Expt 2 than in Expt 1.

Table 8. *Effects of mulching* (*in Experiments 1 and 2*) *or removal of root competition* (*in Experiment 3*) *on total nitrogen, available phosphorus and exchangeable potassium in the top soil* (*0–20 cm depth*) *of hedgerow intercropping systems involving different tree species*

	Experiment 1			Experiment 2			Experiment 3		
Species	Total N (g/kg)	Av. P (mg/kg)	Exch. K (mg/kg)	Total N (g/kg)	Av. P (mg/kg)	Exch. K (mg/kg)	Total N (g/kg)	Av. P (mg/kg)	Exch. K (mg/kg)
With mulch/root competition	3·23	39·0	0·249	3·34	26·3	0·238	3·02	31·0	0·060
Without mulch/root competition	2·67	29·3	0·134	2·42	18·7	0·133	3·08	32·6	0·119
S.E. (D.F. = 46)	0·290	4·19	0·0565	0·341	3·59	0·0604	0·262	2·21	0·0325

Note: The values are means of pooled measurements taken from the up-slope and down-slope sides of the hedgerows and intercrops of tea with different hedgerow species. S.E. is the standard error of means for comparisons between different mulching (in Experiments 1 and 2) or root competition (in Experiment 3) treatments.

The significant negative correlations between tea yield and various hedgerow characters (Table 6) clearly showed that tree-crop competition was present for both above-ground and below-ground resources. The overall tea yield reductions observed in hedgerow intercrops with different shrub species resulted from a combined effect of above- and below-ground competition. For example, the highest yield reduction in mature tea was observed in hedgerow systems with *Tithonia*, which had the highest root density (Table 4) and cross-sectional area (Table 5) among the hedgerow species. The lowest yield reductions of mature tea in hedgerow systems were obtained with *Eupatorium* (Table 1), which showed the lowest pruned biomass of hedgerows and the lowest proportion of the root system present in the top soil layer. The tea crop (which is propagated from immature stem cuttings) has a major portion of its root system in the top soil layers (De Costa, unpublished). Cannell *et al.* (1996) noted that ‘incorporation of trees in a crop would only be beneficial if the trees are able to capture resources that are not used by the crop’; the performance of tea under *Eupatorium* agrees with this.

The observation of significant tea yield increases in all hedgerow systems upon removal of root competition further demonstrated significant competition for below-ground resources in this system. Similar yield increases following removal of root competition have been reported by Singh *et al.* (1989), Rao *et al.* (1991) and Corlett *et al.* (1992). A comparatively higher yield increase (i.e. 17%) has been shown upon removal of root competition in the hedgerow system with *Tithonia* (Table 1), which had a higher root density (Table 4). However, the proportional yield increases did not exactly correlate with measured root densities in all hedgerow systems. Cutting a 1-m deep trench between hedgerows and the nearest tea row could be recommended as a management option to minimize root competition from hedgerows in commercial tea plantations.

The results of Expts 1 and 2 clearly showed that despite the significant resource competition exerted by contour hedgerows, addition of hedgerow prunings to the tea plots as mulch significantly increased tea yields (Table 1). The prunings provided essential nutrients upon decomposition (De Costa & Atapattu 2001) and also significantly improved soil physical properties such as cation exchange capacity, bulk density and organic matter content (data not shown). Similar responses have been shown by Kang *et al.* (1981, 1985) and Yamoah *et al.* (1986). The magnitude of yield increase varied for different hedgerow species primarily because of the variation in amount and quality (as determined by chemical composition) of prunings. In a previous study, De Costa & Atapattu (2001) showed that prunings of the six species used for contour hedgerows in the present study varied significantly in chemical composition and in rates and patterns of decomposition and nutrient release. However, a direct relationship between the amount of pruned biomass (Table 2) and tea yield response to mulching (Table 1) was not observed in the present study. It is interesting that the highest yield response to mulching in Expt 1 (Table 1) was shown in the hedgerow system with *Eupatorium*, which had the lowest pruned biomass during the 50-month experimental period (Table 2).

While the correlations between tea yield variation and hedgerow characters provided clear evidence of significant resource competition, variation of soil chemical properties did not provide such clear evidence, except in the case of available P (Table 7). De Costa & Atapattu (2001) demonstrated that hedgerow prunings provided substantial portions of the recommended N and K fertilizer requirements of tea, but provided only a very small portion of the P requirement.

In these hedgerow systems, the negative effects of resource competition exceeded the positive effects of mulching. This was true for both mature and young tea. However, this situation might be reversed with time if continuous addition of prunings causes a long-term improvement of the soil physical and chemical fertility status. This is exemplified by the mulched hedgerow intercrop with *Eupatorium* and mature tea, which was the only treatment to show a significant yield improvement over the control (Table 1). Thus, contour hedgerow intercropping may contribute to sustainable tea production on the sloping highlands of Sri Lanka. However, as shown in the present study, proper selection of hedgerow species is crucial to its success.

The authors thank the National Science Foundation in Sri Lanka for financial support (Research grant no. RG/97/AG/03), Messrs. K. B. Attanayake, G. Wijesooriya and N. Perera (Department of Crop Science, University of Peradeniya), and staff at Helbodde Estate, Pussellawa, Sri Lanka for help in the field and laboratory work.

REFERENCES

Anonymous (1994). *Fertilizer Recommendations for Mature Tea*. TRI Circular No. **F10**. Talawakelle, Sri Lanka: Tea Research Institute of Sri Lanka.

Anonymous (2002). *Annual Research Review – 2001*. Talawakelle, Sri Lanka: Tea Research Institute of Sri Lanka.

Broadhead, J. S., Black, C. R. & Ong, C. K. (2003). Tree leafing phenology and crop productivity in semi-arid agroforestry systems in Kenya. *Agroforestry Systems* **58**, 137–148.

Cannell, M. G. R., Van Noordwijk, M. & Ong, C. K. (1996). The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. *Agroforestry Systems* **34**, 27–31.

Corlett, J. E., Black, C. R., Ong, C. K. & Monteith, J. L. (1992). Above and below-ground interactions in a *Leucaena*/millet alley cropping system. II. Light interception and dry matter production. *Agricultural and Forest Meteorology* **60**, 73–91.

Dassanayake, A. R. & Hettiarachchi, L. S. K. (1999). Soils of the up country wet zone. In *Soils of the Wet Zone of Sri Lanka: Morphology, Characterization and Classification* (Eds R. B. Mapa, S. Somasiri & S. Nagarajah), pp. 122–137. Peradeniya, Sri Lanka: Soil Science Society of Sri Lanka.

De Costa, W. A. J. M. (1997). Sloping agricultural land technology (SALT) – an option for improving soil fertility in tea plantations. *MPTS News* **6**, 1–2.

De Costa, W. A. J. M. & Atapattu, A. M. L. K. (2001). Decomposition and nutrient loss from prunings of different contour hedgerow species in tea plantations in the sloping highlands of Sri Lanka. *Agroforestry Systems* **51**, 201–211.

De Costa, W. A. J. M. & Chandrapala, A. G. (2000*a*). Effects of different tree species on growth and yield on mung bean (*Vigna radiata* (L.) Wilczek) grown in hedgerow intercropping systems in Sri Lanka. *Journal of Agronomy and Crop Science* **184**, 43–48.

De Costa, W. A. J. M. & Chandrapala, A. G. (2000*b*). Environmental interactions between different tree species and mung bean (*Vigna radiata* (L.) *Wilczek*) in hedgerow intercropping systems in Sri Lanka. *Journal of Agronomy and Crop Science* **184**, 145–152.

Ekanayake, P. B. (1994). Application of sloping agricultural land technology (SALT) in tea plantations. *Tea Bulletin* **14**, 3–17.

Garrity, D. P. (1996). Tree–soil–crop interactions on slopes. In *Tree–Crop Interactions: A Physiological Approach* (Eds C. K. Ong & P. A. Huxley), pp. 299–318. Wallingford, UK: CAB International.

Huxley, P. A., Akunda, E., Pinney, A., Darnhofer, T. & Gatama, D. (1989). Tree-crop interface investigations: preliminary results with *Cassia siamea* and maize. In *Meteorology and Agroforestry* (Eds W. S. Reifsnyder & T. O. Darnhofer), pp. 361–370. Nairobi, Kenya: ICRAF.

Kang, B. T., Wilson, G. F. & Sipkens, L. (1981). Alley cropping maize (*Zea mays* L.) and leucaena (*Leucaena leucocephala* Lam) in southern Nigeria. *Plant and Soil* **63**, 165–179.

Kang, B. T., Grimme, H. & Lawson, T. L. (1985). Alley cropping sequentially cropped maize and cowpea with *Leucaena* on a sandy soil in southern Nigeria. *Plant and Soil* **85**, 267–277.

Livesley, S. J., Gregory, P. J. & Buresh, R. J. (2000). Competition in tree row agroforestry systems. 1. Distribution and dynamics of fine root length and biomass. *Plant and Soil* **227**, 149–161.

Odhiambo, H. A., Ong, C. K., Wilson, J., Deans, J. D., Broadhead, J. S. & Black, C. R. (2000). Tree-crop interactions for below-ground resources in drylands: root structure and function. *Annals of the Arid Zone* **38**, 221–238.

Ong, C. K. (1991). Interactions of light, water and nutrients in agroforestry systems. In *Biophysical Research for Asian Agroforestry* (Eds M. E. Avery, M. G. R. Cannell & C. K. Ong), pp. 107–124. New Delhi, India: Winrock International/Oxford & IBH.

Ong, C. K., Deans, J. D., Wilson, J., Mutua, J., Khan, A. A. H. & Lawson, E. M. (1999). Exploring below-ground complementarity in agroforestry using sapflow and root fractal techniques. *Agroforestry Systems* **44**, 87–103.

Palm, C. A. (1995). Contribution of agroforestry trees to nutrient requirements of intercropped plants. *Agroforestry Systems* **30**, 105–124.

Palm, C. A., Giller, K. E., Mafongaya, P. L. & Swift, M. J. (2001). Management of organic matter in the tropics: translating theory into practice. *Nutrient Cycling in Agroecosystems* **61**, 63–75.

Panabokke, C. R. (1996). *Soils and Agro-ecological Environments of Sri Lanka*. Colombo, Sri Lanka: Natural Resources, Energy and Science Authority of Sri Lanka.

RAO, M. R., SHARMA, M. M. & ONG, C. K. (1991). A tree-crop interface design and its use for evaluating the potential of hedgerow intercropping. *Agroforestry Systems* **13**, 143–158.

RAO, M. R., ONG, C. K., PATHAK, P. & SHARMA, M. M. (1992). Productivity of annual cropping and agroforestry systems on a shallow alfisol in semi-arid India. *Agroforestry Systems* **15**, 51–64.

RAO, M. R., NAIR, P. K. R. & ONG, C. K. (1998). Biophysical interactions in tropical agroforestry systems. *Agroforestry Systems* **38**, 3–50.

SAS INSTITUTE (2002). *Sas User Guide: Statistics*. North Carolina, USA: SAS Institute.

SANCHEZ, P. A., BURESH, R. J. & LEAKEY, R. J. (1997). Trees, soils and food security. *Philosophical Transactions of the Royal Society of London B* **352**, 949–961.

SINGH, R. P., ONG, C. K. & SAHARAN, N. (1989). Above and below ground interactions in alley-cropping in semi-arid India. *Agroforestry Systems* **9**, 259–274.

SMITHSON, P. C. & GILLER, K. E. (2002). Appropriate farm management practices for alleviating N and P deficiencies in low-nutrient status soils of the tropics. *Plant and Soil* **245**, 169–180.

VAN RANST, E., VERLOO, M., DEMEYER, A. & PAUWELS, J. M. (1999). *Manual for the Soil Chemistry and Fertility Laboratory: Analytical Methods for Soils and Plants, Equipment and Management of Consumables*. Gent, Belgium: International Training Centre for Post-Graduate Soil Scientists.

WIERSUM, K. F. (1984). Surface erosion under various tropical agroforestry systems. In *Proceedings of the Symposium on Effects of Forest Land Use on Erosion and Slope Stability* (Eds C. L. O'Loughlin & A. J. Pearce), pp. 231–239. Honolulu, Hawaii: Environment and Policy Institute, East-West Centre.

WIERSUM, K. F. (1991). Soil erosion and conservation in agroforestry systems. In *Biophysical Research for Asian Agroforestry* (Eds M. E. Avery, M. G. R. Cannell & C. K. Ong), pp. 209–230. New Delhi, India: Winrock International/Oxford & IBH.

YAMOAH, C. F., AGBOOLA, A. A., WILSON, G. F. & MULONGOY, K. (1986). Soil properties as affected by the use of leguminous shrubs for alley cropping with maize. *Agriculture, Ecosystems and Environment* **18**, 167–177.