

Above- and below-ground interactions in a leucaena/millet alley cropping system. I. Experimental design, instrumentation and diurnal trends¹

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ABSTRACT

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Leucaena (*Leucaena leucocephala* (Lam.) de Wit) and pearl millet (*Pennisetum glaucum* (L.) R.Br.) were grown together in an alley cropping system in a semi-arid area of India. The five treatments included sole millet (SM), sole leucaena (SL) planted in double rows to form hedges with an alley width of 2.8 m, and alley cropping treatments LM5, LM6 and LM6P with alley widths of 2.8, 3.3 and 3.3 m, respectively. Millet rows within the alleys were spaced at 47 cm, giving five rows in LM5 and six rows in both LM6 and LM6P. LM6P differed from LM6 in that a vertical polythene barrier separated the root systems of leucaena and millet to a depth of 50 cm.

Light interception, wind speed, saturation deficit and air, soil and leaf temperatures were monitored during the 1986 and 1987 rainy seasons in treatments SM, SL and LM5. This paper describes the experimental design and instrumentation and presents representative diurnal time courses illustrating the nature of the microclimatic changes associated with alley cropping. These indicate that alley cropping altered the microclimate experienced by millet to an extent which depended on its proximity to the hedge, hedge shape and the relative size of the two components.

The larger leucaena canopy in 1987 than in 1986 resulted in more substantial reductions in wind speed and incident light in the alleys of LM5 as compared with SM. Leaf and soil temperatures within the alleys tended to be warmer during the night and cooler during the day than in SM and temperature differences

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between rows within LM5 were related to the degree of shading by leucaena. Analysis of integrated data predicted little effect of the observed changes in saturation deficit on the productivity of millet, while thermal time analysis for 1987 suggested a 2–3 day delay in flowering for millet adjacent to the hedge as compared with sole millet.

INTRODUCTION

Tropical agroforestry systems have attracted much attention in recent years because of their perceived potential for the production of multiple products (food, fodder, fuel and timber). Moreover, they require low inputs and conserve natural resources. Alley cropping, a form of agroforestry developed in the humid tropics to replace shifting cultivation (Wilson and Kang, 1981; Kang et al., 1984), involves the intercropping of annual crops in alleys formed by hedgerows of perennial species. The perennial component may be leguminous and periodically lopped to provide green manure or mulch for the annual crop. Alley cropping retains the main advantages of shifting cultivation without the need for fallow periods and, while often treated as a low input system, has also proved successful under more intensive management (Ssekabembe, 1985).

In the Indian semi-arid tropics, a replacement for shifting cultivation is not needed, as around 80% of the available area is already under continuous cultivation (Kanwar, 1986). However, population growth is outstripping production, leading to the spread of farming into marginal lands, the felling of forests and land degradation. Thus, as in the humid tropics, alley cropping may have the potential to increase productivity and provide multiple products while conserving resources.

Maintenance of soil fertility and nutrient cycling in alley cropping systems relies on farmers returning lopped material to the soil (Kang et al., 1985). In India however Singh et al. (1989a) reported no consistent crop response to green mulching and identified fodder and timber as the preferred end-uses for loppings. This finding reflects the high value of fodder during the dry season and the availability of inexpensive inorganic fertilizer (Walker, 1987). It therefore appears that alley cropping can offer little to the maintenance or improvement of soil fertility in India. Research at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT, Hyderabad, India) has therefore concentrated on assessing the nature and extent of complementary interactions between trees and crops as a basis for improving productivity.

Conventional intercropping of two or more annual crops has been shown in many cases to be more productive than sole cropping and research at ICRISAT has analysed this 'intercropping advantage' in terms of resource capture and utilisation in space and time (Natarajan and Willey, 1980; Marshall and Willey, 1983). Willey et al. (1987) summarised the concepts of

species complementarity and indicated how these may be extended and applied to agroforestry systems. The main resources tapped by any cropping system are solar radiation, water and nutrients, which interact with the crop to determine its microclimate and ultimately its productivity. However, most agroforestry studies have concentrated on assessing whether trees affect the productivity of the annual component, with little analysis of the mechanisms by which observed changes come about (e.g. Singh et al., 1989a). A capacity for beneficial modification of microclimate has been attributed to trees by a number of workers (e.g. Huxley, 1983) and these modifications have already been studied for shelterbelt plantings (Guyot, 1989) and shade trees in coffee plantations (Barradas and Fanjul, 1986). Microclimatic studies in agroforestry systems containing annual crops are rare and have tended to concentrate on changes in light climate (e.g. Kang et al., 1985).

The aim of the present work was to quantify physical interactions in a leucaena/millet alley cropping system in order to determine the factors limiting productivity. This paper describes the experimental system and instrumentation and presents typical diurnal trends in microclimatic variables at the time of millet anthesis. The magnitude of treatment and row-to-row differences are discussed and an introduction is given to the forms of analysis used to integrate microclimatic variables over time. Subsequent papers describe the effects of microclimatic modification on the development and productivity of pearl millet and leucaena.

MANAGEMENT AND METHODS

Site

Pearl millet and leucaena were grown together in an alley cropping system at ICRISAT, Patancheru, Hyderabad, India (18° N, 78° E, altitude 545 m) which experiences three distinct seasons: the rainy season (June–October); the cool, post-rainy season (October–January); the hot summer season (February–May). During the period of study, annual rainfall was below the long term average of 780 mm in 1986 (712 mm), but above average in 1987 (879 mm). In both years, pearl millet cultivar BK560 was grown from late June to mid-September, when rainfall represented 58% and 38% of the annual rainfall, respectively. The soil was a shallow to medium depth Alfisol with a stony 'murram' layer at a depth of 15–70 cm.

Experimental design

The experimental design is shown in Fig. 1(a), with treatments identified as follows: SM, sole millet: 15 cm spacing within rows and 47 cm between rows; SL, sole leucaena: 25 cm spacing within rows with two rows 50 cm apart

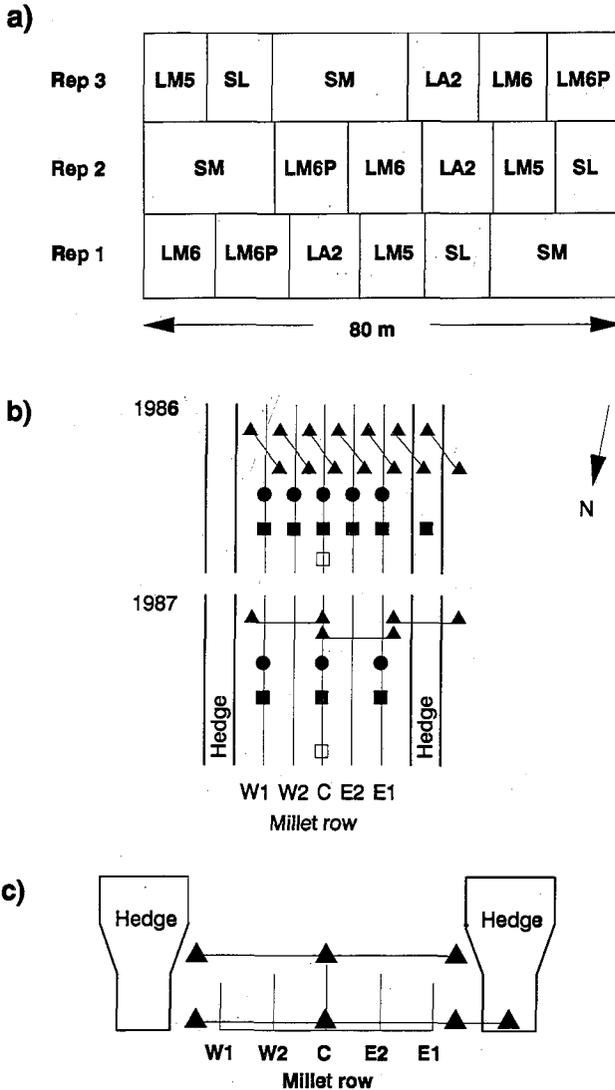


Fig. 1. (a) Experimental design, 1986 and 1987. SM, sole millet; SL, sole leucaena; LM5, alley cropping with five rows of millet; LM6, alley cropping with six rows of millet; LM6P, alley cropping with six rows of millet and polythene barrier between millet and leucaena roots. Plots marked LA2 were not used. (b) Instrumentation in the central alley of LM5: anemometer and psychrometer mast (\square); two leaf thermocouples (\bullet); soil thermocouple at a depth of 5 cm (\blacksquare); tube solarimeter (\blacktriangle). (c) Solarimeter positioning in LM5, 1987.

within hedges; alley width 2.82 m; LM5, alley cropping with five rows of millet spaced as in SM; hedges as in SL; LM6, alley cropping with six rows of millet, spacing as in SM, leucaena rows 60 cm apart within hedges; alley width 3.29 m; LM6P, alley cropping with six rows of millet as in LM6 but with a

vertical polythene barrier, 50 cm deep, separating millet and leucaena root systems.

Each plot contained three alleys in all alley cropping treatments and in sole leucaena. The experimental design was constrained by the pre-existing layout of leucaena hedgerows and the distribution of treatments was unavoidably semi-systematic. Residual variance was tested for a range of variables and plot residuals were found to be independent, allowing the experiment to be treated as a randomised complete block design.

Management

The leucaena hedgerows were planted in July 1985 into an existing millet crop which had been fertilised with $100 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5$ and $60 \text{ kg ha}^{-1} \text{ N}$. In mid-September 1985 the hedges were thinned and the remaining seedlings cut back to 25 cm in an attempt to improve the uniformity of the stand. The trees were therefore 11 months old at the beginning of the 1986 rainy season and had received 180 mm of rainfall during their establishment period. Details of millet and leucaena management during the experimental period (June 1986 to February 1988) are summarised in Table 1.

Root barriers

The polythene barriers in treatment LM6P were installed between 12 May and 10 June 1986, following a technique described by Willey and Reddy

TABLE 1

1986 and 1987 rainy seasons. Management of millet and leucaena

Date	Month	Days after sowing	Management
<i>1986</i>			
10-18	June		Leucaena lopped to a height of 70 cm
24	June	0	Millet sown
2	July	8	$20 \text{ kg ha}^{-1} \text{ N}$ applied to millet
17	July	23	$40 \text{ kg ha}^{-1} \text{ N}$ applied to millet
23	July	29	Leucaena lopped to a height of 70 cm
15	September	83	Millet harvest
18-23	September		Leucaena lopped to a height of 70 cm
<i>1987</i>			
8-12	June		Leucaena lopped to a height of 65 cm
29	June	0	Millet sown
7	July	8	$18 \text{ kg ha}^{-1} \text{ N}$ and $46 \text{ kg ha}^{-1} \text{ P}_2\text{O}_5$ applied to millet
30	July	31	$42 \text{ kg ha}^{-1} \text{ N}$ applied to millet
10-13	August	42-45	Leucaena side branches lopped
18	September	81	Millet harvested
24-7	September-October		Leucaena lopped to a height of 65 cm

(1981) for separating above- and below-ground interactions in intercropping systems. Trenches 50 cm deep and approximately 25 cm wide were dug by hand 20–25 cm from the base of the leucaena hedges. The trenches were 22 m long and there were six in each LM6P plot giving three alleys with root partitioning. A thick polythene sheet 60 cm deep was positioned against the face nearest the hedge, leaving 10 cm of the barrier above the soil surface. The soil from different layers was returned to the approximate depth from which it had come. At first the soil could not all be returned to the trenches, but after several heavy showers in early June, refilling was completed and no further slumping occurred.

INSTRUMENTATION

Light interception, wind speed, saturation deficit and air, leaf and soil temperatures were measured in both the 1986 and 1987 rainy seasons. In 1986 the emphasis was on comparing the microclimates experienced by millet in SM and LM5 and on establishing the variation in temperature and light interception across the alleys, with measurements being concentrated in Replicates 2 and 3. In 1987, temperatures and light interception were measured in all three replicates to allow statistical examination of relationships between microclimate and growth and development. In both years, wind speed and saturation deficit were measured only in Replicate 3 of SM, SL and LM5.

Light interception

Tube solarimeters (Green and Deuchar, 1985) were used to measure solar radiation above and below the tree and millet canopies. These were calibrated against a Kipp solarimeter before and after each season and periodically cleaned to remove dust. In 1986 total solar radiation was measured using two solarimeters, oriented as for the below-canopy tubes and mounted at a height of 3 m immediately south of the experimental area. Transmitted solar radiation was measured using seven solarimeters per plot in LM5 and SL, and one per plot in SM. In LM5, one tube was placed under each millet or leucaena row, oriented so that it spanned half the inter-row space on either side (Fig. 1(b)). Tubes under the millet and tree rows were respectively 100 and 110 cm long. In both cases the tubes were at an angle of approximately 27° to the row so as to span one complete row width. In SL the tubes were positioned as in LM5, while in SM one 100 cm long tube was positioned under a row in the centre of each replicate, again at an angle of 27°.

In 1987, all tubes were oriented at 90° to the crop rows so as to measure over the whole leucaena hedge width or 1.5 rows of millet. In LM5, two 120 cm solarimeters were positioned under the millet rows and one 100 cm tube under the hedge. A similar arrangement of tubes was used in SL, while

in SM one 100 cm tube was placed under the canopy spanning two rows. In LM5 two additional 120 cm tubes were used to measure solar radiation incident on the millet canopy (Fig. 1(c)); these were raised periodically as the millet grew.

As the systematic monitoring of spatial variation in light interception was less intensive in 1987 than in 1986, instantaneous measurements across individual alleys were made periodically using a travelling quantum sensor known as the 'mouse' (Matthews et al., 1987).

Wind speed

Cup anemometers (Met-One, USA) with a starting speed of 0.5 m s^{-1} were used to measure horizontal wind velocity above the trial and within treatments SM, LM5 and SL (Fig. 1(b)). In both 1986 and 1987 the reference anemometer was at a fixed height of 3 m above the ground in Replicate 3 of SM. In 1986 the anemometers within the treatments were initially located at a height of 40 cm and subsequently raised simultaneously and by the same amount in all treatments to keep them just above the millet canopy. This proved unsatisfactory because of the different rates of millet growth in the various treatments, and so in 1987 the anemometers were moved independently to keep them just above the millet canopy. The anemometer in SL was positioned at the same height as in LM5.

Saturation deficit

Aspirated psychrometers were positioned on the same masts and at the same heights as the anemometers to measure air temperature and air saturation vapour pressure deficit (*SD*, referred to below as saturation deficit). These were of the design described by Ong (1989) and consisted of wet and dry copper-constantan thermocouples shielded by a foil-coated plastic tube, ventilated at around 2.2 m s^{-1} by a 12 V fan (Micronel A-G, Switzerland) and with a large water reservoir to moisten the wick of the wet thermocouple.

Soil and leaf temperatures

Soil and leaf temperatures were measured using T-type (copper-constantan) thermocouples. Soil thermocouples (PR-T-24, Omega, Broughton Astley, UK) were installed at a depth of 5 cm, protected by a thin plastic sheath and sealed with Araldite adhesive to prevent leakage to earth in wet soil. Leaf thermocouples were of a finer gauge (76P/50, Comark, Rustington, UK) and were held in contact with the underside of millet leaves either by plastic paper-clips or by threading the thermocouple and its lead wire through the lamina itself. These thermocouples were always positioned about half-way along the youngest fully expanded leaf.

The location of leaf and soil thermocouples within LM5 is shown in Fig. 1(b). In SL, soil thermocouples were installed in positions corresponding to those in LM5, while in SM, leaf and soil thermocouples were located in one row per plot.

Logging

A Campbell 21X datalogger with three multiplexers (Campbell Scientific, Logan, UT) was used to monitor the output from all permanently installed instruments. The logger was programmed to scan all channels at 6 min intervals and calculate and store the hourly means from the ten measurements for each variable.

THEORY

Thermal time

Of all the environmental variables, temperature most strongly influences the rate of crop development from germination through to flowering and seed production. Many workers have used the concept of thermal time to describe the dependence of developmental rate on temperature (e.g. Gallagher (1979) for wheat; Ong and Monteith (1985) for pearl millet). In their analysis, the rate of development was expressed as the reciprocal of time (t) between the beginning and end of a specific development process (e.g. panicle initiation to anthesis). This rate has been found for many species and processes to be a linear function of temperature given by

$$1/t = (T - T_b)/\Theta_1 \quad T_b < T < T_o \quad (1)$$

where the temperature (T) experienced by the developing tissue exceeds the base temperature (T_b), below which no development occurs, but is less than the optimum temperature (T_o) above which increasing temperatures reduce the rate of development. The thermal duration (Θ_1) is the number of 'degree-days' ($^{\circ}\text{Cd}$) above T_b but below T_o necessary for completion of the developmental phase and can be determined when temperature is the only variable controlling development. Development may cease above a certain maximum temperature (T_m) and, when temperatures exceed T_o , Θ_2 may be defined as the number of degree-days below T_m but above T_o necessary for completion of the developmental phase.

When plants are exposed to other factors which might affect the rate of development, eqn. (1) may be solved for a variable Θ (thermal time) and used to determine whether the rate of a process is solely dependent on temperature, i.e. $\Theta = \Theta_1$. When hourly mean values are collected (\bar{T}), thermal time in degree-days, can be calculated for each hour from

$$\Theta = (\bar{T} - T_b)/24 \quad \text{for } T_b < \bar{T} < T_o \text{ and} \quad (2)$$

$$\Theta = (T_m - \bar{T})\Theta_1/24\Theta_2 \quad \text{for } T_o < \bar{T} < T_m \quad (3)$$

The ratio $\Theta_1 : \Theta_2$ is needed to convert thermal-time in degree-days below T_m into degree-days above T_o and is equivalent to $(T_o - T_b)/(T_m - T_o)$. The hourly values calculated from eqns. (2) and (3) may be accumulated to give the thermal time for a particular day or growth stage.

The vapour pressure deficit factor

Transpiration rate is highly dependent on the leaf to air vapour pressure deficit (D) and stomata have been found to respond to increasing D by reducing their conductance to both vapour and CO_2 flux (Fanjul and Jones, 1982). Monteith (1986) linked D and carbon assimilation using a relation developed from laboratory studies (El Sharkawy et al., 1984) in which net carbon exchange (N) is related to vapour pressure deficit by a linear relation whereby

$$N = N_m \cdot Z \quad (4)$$

where N_m is the maximum net carbon exchange and Z is a vapour pressure deficit factor, used as a measure of the reduction in assimilation caused by stomatal closure, defined as

$$Z = 1 \quad D < D_o$$

$$Z = 1 - (D - D_o)/(D_m - D_o) \quad D_o < D < D_m$$

$$Z = 0 \quad D > D_m$$

assuming that all other microclimatic factors, especially soil moisture, remain constant. D_o is the vapour pressure deficit above which the stomata start to close and D_m is the deficit at which net carbon exchange becomes zero. D may be calculated using SD , air and leaf temperature measurements and a daily Z factor calculated as the mean of 12 day-time values, although this involves the assumption that N_m is constant throughout the day.

RESULTS

1986

Millet reached 50% flowering 50–58 days after sowing (DAS) in 1986. Figure 2(a) shows the diurnal trends for incident solar radiation, air temperature and SD on 18 August (55 DAS), a relatively cool and humid day with 0.8 mm of rainfall and total incident radiation of 22 MJ m^{-2} . Wind speed measured at 1.3 m in SM, SL and LM5 (Fig. 2(b)) was 50% lower than that at 3 m throughout the day and much of the night. The millet was around 1.2 m tall in both SM and the central rows of LM5, while the leucaena was approxi-

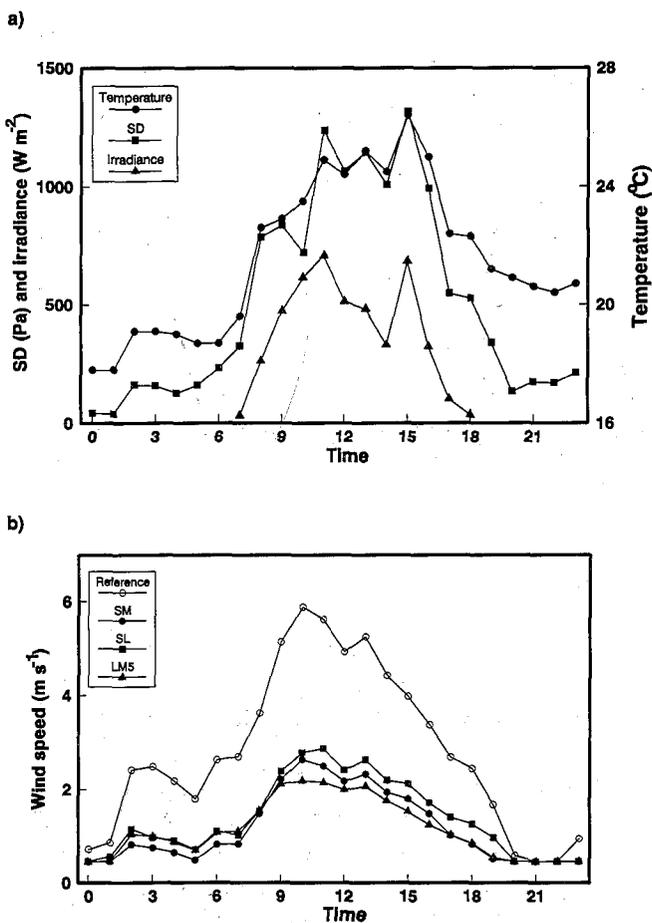


Fig. 2. Diurnal trends (Indian Standard Time) on 18 August 1986 (55 DAS) for: (a) air temperature, saturation vapour pressure deficit (*SD*) and irradiance; (b) wind speed at the reference height (3 m) and at crop height within treatments SM, SL, and LM5.

mately 1.5 m tall. Consequently, the hedges had very little effect on the wind speed experienced by millet in the alley crop at this time. During the day, wind speed consistently followed the ranking $SL > SM > LM5$.

As tree size and shape were similar in LM5 and SL, the light interception values for SL Rows E1, C and W1 (Fig. 3) provide a good estimate of the degree of shading experienced by millet at these row positions in LM5. Light interception in the centre of LM5 alleys was only slightly higher than in sole millet, whereas the values for SL Row C indicate that interception by leucaena was $< 20\%$ at this position for most of the day. The diurnal trends for SL Rows E1 and W1 show that land to the west of the hedge was more heavily shaded in the morning while that to the east was shaded in the afternoon.

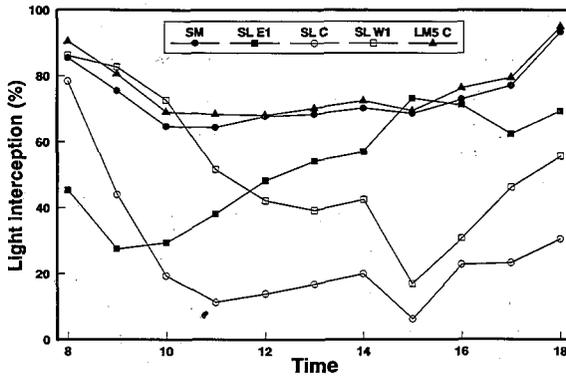


Fig. 3. Diurnal trends of light interception on 18 August 1986 (55 DAS) for treatments SM, SL and LM5. E1, W1 and C denote row positions to the east and west of the hedge and in the centre of the alley respectively (see Fig. 1(b)).

Differences in leaf temperature between rows and treatments were generally less than 1°C (Fig. 4(a)). Leaf to air temperature difference (Fig. 4(c)) never exceeded 1.5°C , but with the largest differential occurring in SM. Leaf temperature in LM5 was obviously moderated by the leucaena canopy, which would have reduced long-wave losses from the millet at night and short-wave gains during the day.

Soil temperature at a depth of 5 cm (Fig. 4(b)) differed much more between treatments and rows than leaf temperature, with the largest differences occurring during the day. Day-time temperatures were lowest in LM5 Rows E1 and W1 and, as with leaf temperature, soil temperature increased more slowly in Row W1 than in the other rows during the morning because of shading by the leucaena. During the night, soil temperatures in both treatments were $2\text{--}4^{\circ}\text{C}$ warmer than air and leaf temperatures (Fig. 4(c)) but during the day, the temperature differential was positive in SM (soil warmer than air) and negative in LM5 Row E1. This difference between SM and LM5 Row E may be attributed to a smaller quantity of transmitted radiation reaching the soil in the latter, but the wetter soil surface in LM5 Row E may also have contributed.

Table 2 shows the mean number of degree-days accumulated per day between panicle initiation and flowering (GS2) for sole millet and three rows in the alley cropping treatment LM5. All values in 1986 were similar, indicating that the influence of the cooler day-time temperatures in LM5 as compared with SM was offset by the warmer night-time temperatures. This analysis suggests that temperature differences between SM and LM5 were insufficient to affect the length of GS2.

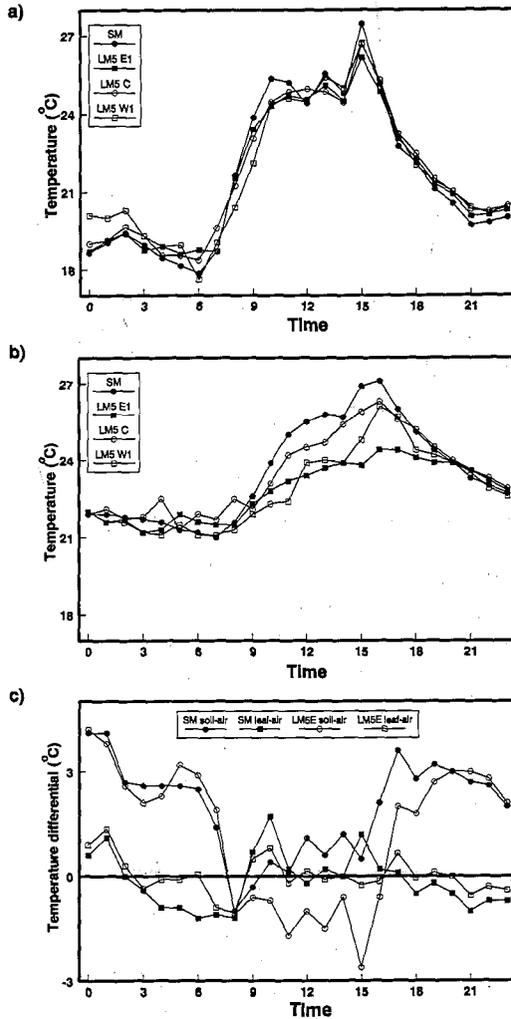


Fig. 4. Diurnal trends on 18 August 1986 (55 DAS) for: (a) leaf temperature in millet; (b) soil temperature at a depth of 5 cm in treatments SM and LM5 Rows E1, C and W1; (c) soil-air and leaf-air temperature differentials in treatments SM and LM5 Row E1 using air temperature at 3 m.

1987

In 1987 millet reached 50% flowering between 53–60 DAS. Figure 5(a) shows the diurnal trends for incident solar radiation, air temperature and *SD* at 3 m on 25 August (57 DAS), a cool cloudy day with total incident radiation of 13.6 MJ m^{-2} and 0.8 mm of rainfall. Air temperature rose slowly during the morning as irradiance increased, while saturation deficit followed a similar trend to that in air temperature.

TABLE 2

1986 and 1987 rainy seasons. Mean number of degree-days accumulated per day ($\theta^{\circ}\text{Cd day}^{-1}$) during growth stage two for millet in SM and LM5

Year	SM	LM5 Row E1	LM5 Row C	LM5 Row W1
1986	12.5	12.7	12.8	12.7
1987	12.9	11.9	12.3	12.1

Millet was approximately 1.2 m tall in both SM and the central row of LM5 at 55 DAS but was significantly shorter in rows adjacent to the hedges, being only 0.85 and 1.0 m in Rows E1 and W1. The leucaena hedges were 2.6 m high in all treatments, compared with 1.5 m in 1986, because of the less severe

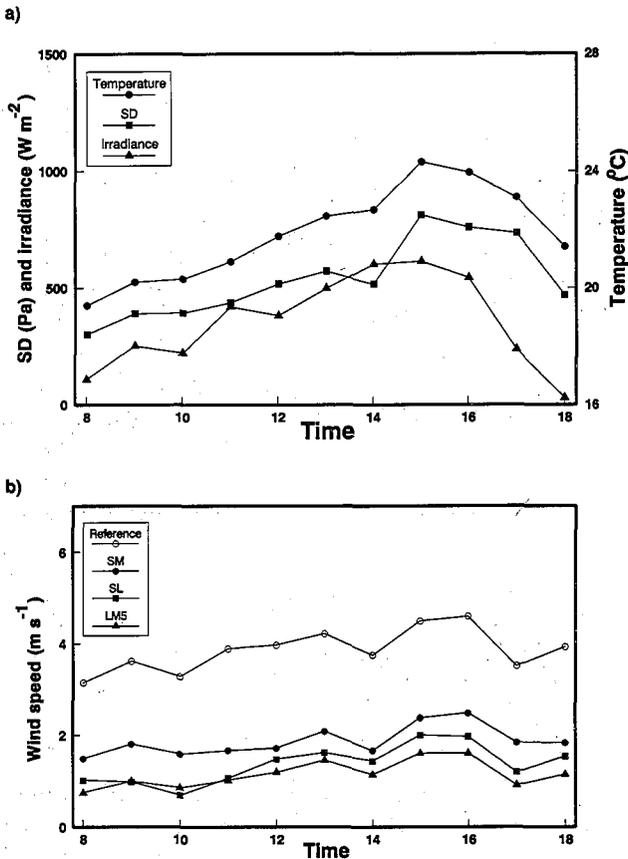


Fig. 5. Diurnal trends on 25 August 1987 (57 DAS) for: (a) air temperature, saturation vapour pressure deficit (SD) and irradiance; (b) wind speed at the reference height (3 m) and at crop height within treatments SM, SL and LM5.

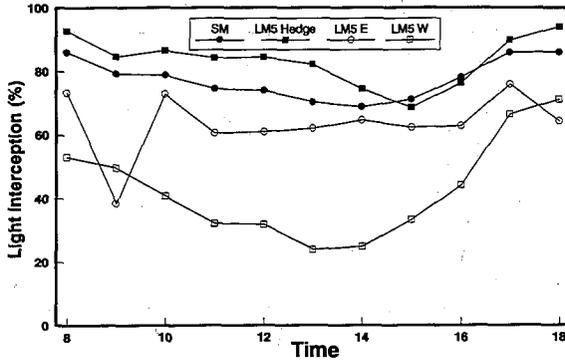


Fig. 6. Diurnal trends of light interception on 25 August 1987 (57 DAS) for treatments SM and LM5. Solarimeters in LM5 were positioned either under the hedge (LM5 hedge) or above the millet canopy to the east and west of the hedge (LM5 E and LM5 W).

lopping regime. Wind speed immediately above the millet in SM was consistently less than half the values at 3 m (Fig. 5(b)) and the differences in wind speed between sole millet and treatments SL and LM5 were larger than in 1986. Millet in LM5 experienced wind speeds $0.5\text{--}1.9\text{ m s}^{-1}$ lower than in the sole crop and the ranking of wind speed differed from 1986 as values in SL were lower than in sole millet. This may be partly attributable to the taller hedges in 1987, but may also reflect differences in wind direction on the 2 days.

Light interception by the sole millet ranged from 70–85% and was slightly lower than that intercepted by the hedges in LM5 (Fig. 6). The values for light interception by leucaena in the alley demonstrate the effects of hedge shape and orientation, as well as solar angle on the quantity of light reaching the millet canopy. The larger leucaena canopy in 1987 was asymmetric because the prevailing westerly winds caused regrowth shoots to extend further and lower over millet Rows E1 and E2 than over Rows W1 and W2. Light interception to the east of the hedge was thus greater than that to the west. Although the solarimeter data do not indicate the spatial variation in interception by the leucaena over individual millet rows, transects of photosynthetically active radiation interception at 52 DAS made using the 'mouse' showed that values for interception tended to be lower over Row W1 than over Row C except in the early morning. Interception was highest over Row E1 (data not presented).

Leaf temperature was generally higher in sole millet than in alley cropped millet and within LM5 temperatures were ranked in the order $W1 > C > E1$ (Fig. 7(a)). The higher temperatures in Row W1 than in Row C may be attributed to the differing degrees of shading by the hedge. The leaf to air temperature differential for Row E1 (which received most shading) was $< 0.5^\circ\text{C}$ except during the early morning, whereas leaf temperatures in SM were $1\text{--}1.5^\circ\text{C}$ warmer than air temperature for much of the day (Fig. 7(c)).

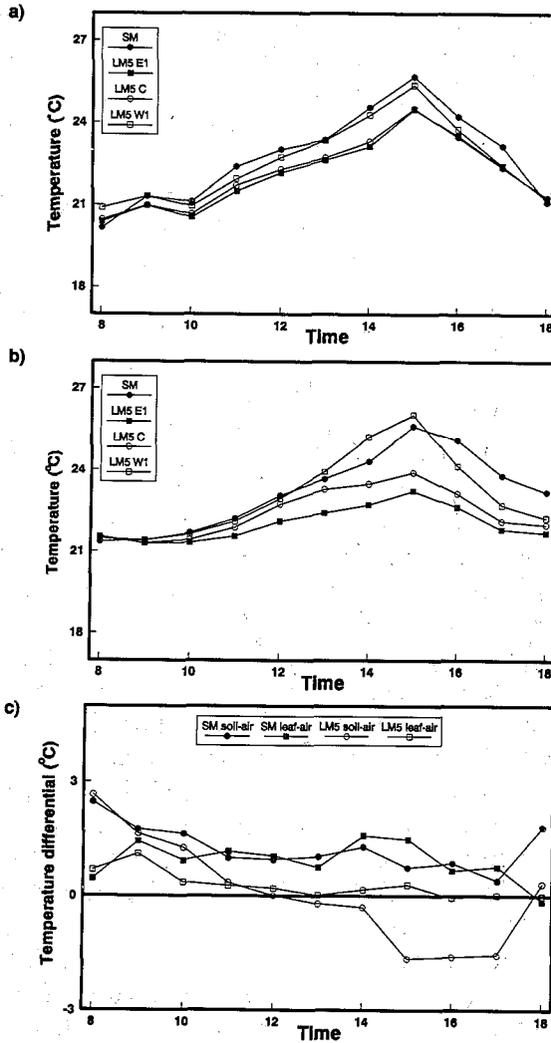


Fig. 7. Diurnal trends on 25 August 1987 (57 DAS) for: (a) leaf temperature in millet; (b) soil temperature at a depth of 5 cm in treatments SM and LM5 Rows E1, C and W1; (c) soil-air and leaf-air temperature differentials in treatments SM and LM5 Row E1 using air temperature at 3 m.

Soil temperature at 57 DAS differed much more between rows and treatments than leaf temperature (Fig. 7(b)), as was also found in 1986 (Fig. 4(b)). Although soil temperature varied by only 2°C under Row E1 in LM5 during the day, that under SM and LM5 Row W1 rose by almost 5°C between 09:00 and 15:00 h. Soil to air temperature differentials were also relatively large, with soil temperature in SM being 1–2°C above air temperature for most of the day. The mean number of degree-days accumulated per day during GS2

TABLE 3

1987 rainy season. Vapour pressure deficit factor for millet in SM and LM5

Days after sowing	SM	LM5 Row C
40	0.95	1.0
45	0.97	1.0
50	0.99	1.0
55	0.99	1.0
60	0.98	1.0
65	0.97	1.0

was significantly lower ($P < 0.05$) for LM5 Rows E1 and W1 than for sole millet (Table 2).

Table 3 shows 5-day means for the vapour pressure deficit factor around the time of millet flowering, calculated from eqn. (5) and taking D_o and D_m to be 1 kPa and 6 kPa, respectively, as determined by El-Sharkawy et al. (1984) for cassava. During this 30 day period there were frequent showers and mean daytime SD was only 0.5–0.7 kPa. The Z values reflect the fact that D never rose above 1 kPa in LM5 but frequently exceeded 1 kPa around midday in SM and may therefore have reduced assimilation rates by inducing partial stomatal closure.

DISCUSSION

The results presented here indicate that alley cropping alters the microclimate experienced by associated annual crops to an extent related to hedge shape and the relative heights of the two components. This is most clearly demonstrated by the effects of leucaena on wind speed and incident radiation levels within the alleys (Figs. 2, 3, 5 and 6).

The larger leucaena canopy in 1987 resulted in more substantial reductions in wind speed in the alleys of LM5 than in 1986. Predicting the consequences of such reductions in wind speed on crop growth and development is difficult, because the effects are usually indirect, arising through alteration of aerodynamic resistances and surface temperatures. Increases in crop yield in the lee of windbreaks have previously been attributed to reductions in mechanical damage and evapotranspiration, although the latter is dependent on water availability (Grace, 1977; Campbell, 1981). However, as crop yield is proportional to intercepted radiation when water is not limiting (Monteith, 1981), millet yield in LM5 would be expected to be reduced proportionately to the degree of shading by leucaena, as was indeed the case (Corlett et al., 1992). In a previous study, Lawson and Kang (1990) assessed the extent of shading by various hedgerow species in alley cropping systems with 2 and 4 m wide alleys and found that, even when regularly pruned to 0.6 m, the trees reduced light incident on associated annual crops by 10–80%. However, dry

matter production by maize and cowpea was not closely correlated with shading except when it exceeded 50% of full light, and no assessment was made of light interception by these crops. Light interception and dry matter accumulation by leucaena and millet in the present study are discussed in Corlett et al. (1992).

In addition to its direct effects on productivity, radiant energy load during the day appears to have been the most important factor determining leaf and soil temperatures in millet. In both seasons, shading affected soil temperature more than leaf temperature on the days presented, indicating that transpiration may have been more closely correlated with intercepted radiation than was evaporation from the soil surface. In 1986, daytime soil temperatures within treatment LM5 were ranked according to the degree of shading, as was also found by Matthews et al. (1991) in an intercropping system in which single sorghum rows imposed differential shading on three adjacent rows of groundnut.

Although the leucaena hedges were 140–180 cm taller than the millet at anthesis in 1987, the larger reductions in the quantity of light incident on the alley cropped millet did not result in increased differences in soil and leaf temperatures between SM and LM5 as compared with 1986. The higher leaf and soil temperatures in Row W1 relative to Row C may indicate that, although the quantity of solar radiation reaching both rows was similar, Row W1 was less able to moderate surface temperatures by sensible and latent heat losses.

Reductions in soil and leaf temperatures caused by shading will be most beneficial when these regularly exceed the optimum for associated annual crops. This is often the case at sowing in semi-arid environments where high soil temperatures may reduce germination and cause poor crop establishment (Khalifa and Ong, 1990). In the present study, temperatures were generally below T_0 and, assuming 380°Cd as the thermal duration of GS2 (Ong, 1983; for millet variety BK560), then in 1987 a 2–3 day delay in flowering would be expected in Rows W1 and E1 with respect to SM. Such a response might increase crop yield by extending canopy duration if other factors, particularly water availability, were favourable (Overseas Development Administration, 1987).

Reductions in wind speed may decrease SD and D , which may in turn reduce transpiration in crops which are well supplied with water and have high stomatal conductances (Campbell, 1981). However, the leaf to air vapour pressure deficit was not greatly altered by the hedgerows in the present study and since SD was generally less than 1 kPa there was little scope for any beneficial modification. Similarly, in an alley cropping system with hedges 5 m tall and alleys 10 m wide, Singh et al. (1989b) reported significant reductions in wind speed with little effect on SD . The vapour pressure deficit factor (Z), employed here to assess the effects of changing D on crop growth, has

previously been used for a pearl millet/groundnut intercrop by Ong et al. (1991), who also adopted the model of Monteith (1986) and the constants determined for cassava by El Sharkawy et al. (1984). Monteith (1990) has recently suggested a refinement to this form of analysis, but since the shape of the assimilation/ D curve has not been determined rigorously for millet, and stomatal response to SD is known to vary with irradiance (Black and Squire, 1979), the original model has been retained here to illustrate the possibility of predicting effects of changing D on productivity.

This paper has described an experimental system for monitoring microclimatic conditions in an alley cropping system, shown that alley cropping does cause microclimatic modification and has indicated how such modifications may be related to crop development and yield. The degree of modification was shown to vary with hedge size and shape, with changes in wind speed and particularly shading being likely to have more effect on crop growth than surface temperatures or saturation deficit.

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