Journal of Environmental Sciences Vol.13, No.3, pp.291—298, 2001

ISSN 1001—0742
CN11—2629/X

Article ID: 1001-0742(2001)03-0291-08 **CLC number**: Q14 **Document code**: A

Understanding yields in alley cropping maize (*Zea mays* L.) and *Cassia siamea* Lam. under semi-arid conditions in Machakos, Eastern Kenya

D.N. Mungai[1], C.J. Stigter[2*], C.L. Coulson[3], J.K. Ng'Ang'A[4], G.W.S. Netondo[5], G.O. Umaya[6]

(1, 3, 4, 5, 6. TTMI-Project, University of Nairobi, P.O. Box 30197, Nairobi, Kenya; 1. Department of Geography, 3, 5, 6. Department of Botany, 4. Department of Meteorology; 2. TTMI-Project, Department of Environmental Sciences, C.T. de Wit Graduate School of Production Ecology and Resource Conservation, Wageningen University, Duivendaal 2, 6701 AP Wageningen, The Netherlands. E-mail: Kees.Stigter@User.METAIR.WAU.NL)

Abstract: Six seasons of experiments in Machakos, Kenya, revealed that above about 150 mm of rainfall, maize yields per row in alley cropped "replacement" agroforestry (AF) plots, of *Cassia siamea* Lam. and maize (*Zea mays*, cv. Katumani Composite B), may be expected to exceed those in the control (sole maize) plots. Such yields were insufficient to compensate for the area "lost" to the hedgerows. Below about 150 mm the control plots may be expected to perform better. This result was due to competition for water. Greater association of the fine roots of *Cassia* and *maize* was observed in the middle of the alleys than near the hedgerows. Photosynthetic consequences of shading were insignificant relative to other factors. In the alleys, reductions of soil temperature due to shade in the western and eastern maize rows were higher than in the middle row. Soil moisture extraction was higher in the AF than in the control plots. In the AF plots, moisture extraction was greater under the central maize rows than under those nearest the *Cassia*. Yield patterns followed such soil temperature and soil moisture patterns. Maize transpiration and photosynthetic rates were significantly higher in the control than in the AF plots during a below-average rainy season but not during above-average rainy seasons. It is concluded that alley cropping under semi-arid conditions should be approached differently from the system worked on. It must at least provide strong physical protection of crops and/or soils and have a strong economic incentive to be of interest to the farmers.

Key words: alley cropping; *Cassia siamea*; competition; Kenya; maize yields; microclimate; mulching; semi-arid conditions

Introduction

Only about 20% of Kenya's total land area has high potential for agricultural production, the rest being arid or semi-arid. The annual population growth rate in Kenya of close to 4% is one of the highest in the world (e.g. United Nations Development Programme, 1990). This situation has led to shortages of arable land, leading to considerable human migration from high potential areas to the drier, medium and even low potential areas. While increased settlement and exploitation of semi-arid areas may provide a temporary livelihood for small-scale farmers, several agricultural production constraints limit their capacity to maintain or increase subsistence food production with sustainable cropping systems. A diagnosis and design exercise carried out in the Machakos area of Eastern Kenya showed that the major problems facing farmers were (1) food insecurity due to extremely variable weather conditions and soil nutrient deficiencies; (2) a lack of adequate animal fodder, and (3) an acute shortage of fuelwood (Hoekstra, 1984).

Alley cropping has been proposed as an alternative to shifting cultivation and as a viable low external-input technology for sustainable land management, particularly in tropical farming situations (Kang, 1990). In alley cropping, hedgerows are periodically pruned to reduce competition with the associated crops, as well as providing green manure and mulch. Several alley cropping studies, largely in the humid tropics, have demonstrated the potential benefits of incorporating woody species into farming systems (Kang, 1990; Ong, 1994; Breman, 1995).

The results from one of the earliest alley cropping experiments in the semi-arid Machakos district (Arap, 1986) recorded yield differences for maize between agroforestry and control plots and between rows within agroforestry plots for which interpretation remained difficult, speculative and incomplete (Mungai, 1991). The results suggested that a more detailed knowledge of the microclimatic influences of alley cropping under semi-arid conditions was necessary to obtain a better understanding of the reasons underlying the observed within- and between-treatment yield differences. However, apart from a few case studies (Corlett, 1992), no quantitative microclimatic approaches have been reported in the literature in the context of alley cropping under semi-arid conditions. The need for rigorous quantification of agroforestry systems, including below-ground interactions, has only recently been emphasized (Ong, 1994).

* Correspongding author

The present study was undertaken to investigate the micro-climatic and competitive effects of *Cassia siamea* hedgerows (Fig. 1) and the mulching effects by its prunings on the growth and yield of Katumani Composite B maize under semi-arid conditions and assess the potential of this alley cropping combination (Mungai, 1991). This required a new research approach (Mungai, 1996) and an unusual quantitative approach (Stigter, 1989; Mungai, 1997; 2000). Some yield results were submitted to this journal in the context of explaining phenotypic nutrient up-take differences observed after sowing a hybrid variety during the short rains of 1988 (Mungai, 2001).

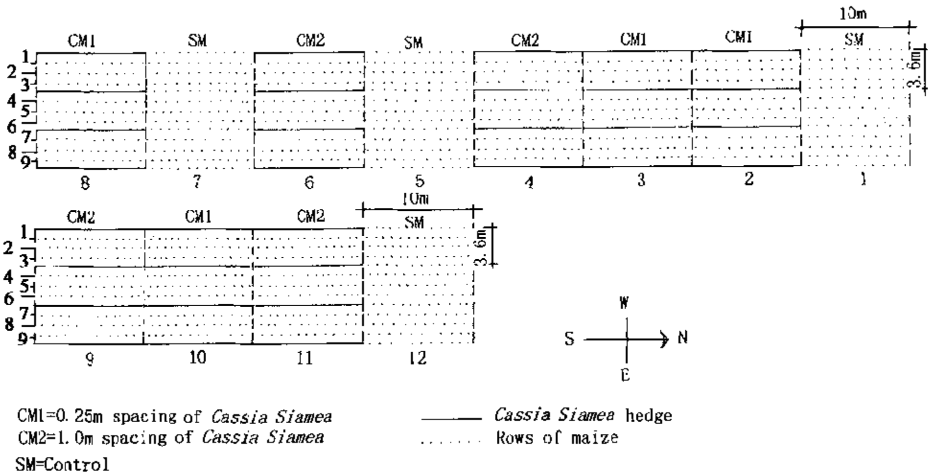

Fig. 1 Layout of the alley cropping experiment

The only results of this research that we did not yet publish were the long term yield data and their interpretation from the seasonal rainfall and the results of occasional and long term microclimatic and plant physiological measurements as well as data on plant length and root density. We published the summary interpretation of these yield results, that was already made in Mungai (1991), by showing Fig. 2 in a book on preliminary project results (Mungai, 1995), that had limited distribution. Because of the absence of statistical significance, due to the limited number of data that could be compared (only four of the six seasons of data), these data were never officially published.

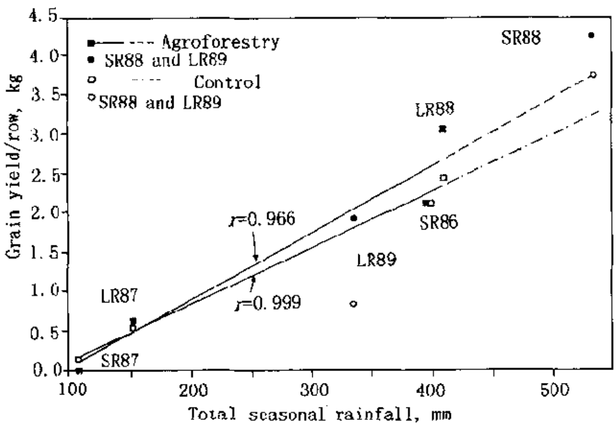

Fig. 2 Influence of seasonal rainfall on maize grain yield. Data for the short rains of 1988 (SR88) and long rains of 1989 (LR89) are shown for comparison, but were not used in the regression due to the influence of the hybrid maize variety sown in SR88. The broken lines are therefore extrapolations

However, recently Mathuva *et al*. (Mathuva, 1998) published results on Leucaena leucocephala hedgerows added to (instead of replacing) maize under the same climatic conditions. They used our method of interpretation, be it not graphically but in a tabular form, on a larger set of data. Even more recently, data collected by Kinama, Ong and Stigter (unpubl.), using the same approach, pointed towards comparable yield results for alley cropping systems with the *Cassia siamea* added to maize as well as cowpea. This paved the road for also making our earliest results more widely known, because the method that we developed in the early nineties (Mungai, 1991) was apparently a useful, be it limited, interpretation approach for the seasonal yields.

1 Materials and methods

1.1 Experimental site

Already twice this site has been described in this journal (Umaya, 1999; Mungai, 2001, where Fig.1 gives the lay out). The study was conducted over six growing seasons with contrasting rainfall, extending from the short rains of 1986 to the long rains of 1989. Details may be found in Mungai (Mungai, 1991).

1.2 Experimental design

The experimental design and treatment combinations were established under the Dryland Agroforestry Research Project (Arap, 1986). The field layout may be found in Mungai *et al*. (Mungai, 2001), in this journal. The experimental layout was a completely randomised design with each treatment occurring four times. Within each plot except the sole maize control, four *Cassia* hedges were established in November 1983 at a between-row spacing of 3.6m and within-row spacings of 0.25 m in treatment S1 and 1m in treatment S2. Three rows of maize were planted parallel to the hedgerows in each alley, at a spacing of 90 × 30 cm. In the sole maize control plots, an additional row of maize replaced each hedgerow. The present study was carried out in treatment S1 (here described as AF), as this was expected to give the strongest interaction effects, and the control. The problem of tree roots invading control plots was discussed in Mungai *et al*. (Mungai, 2001).

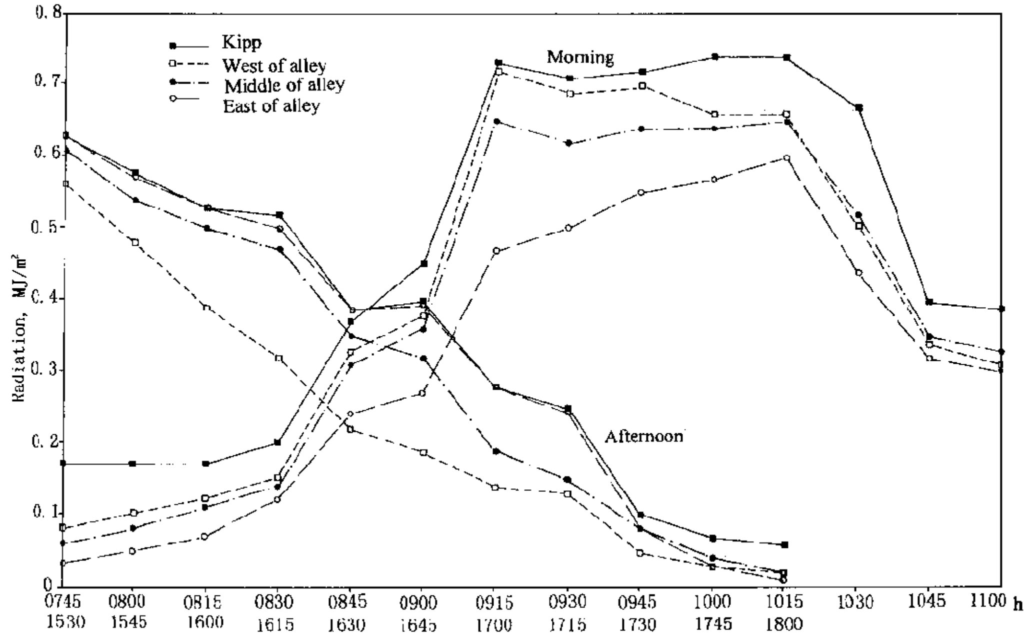

Fig.3 Representative examples of non-intercepted (= transmitted global radiation in AF3, showing the time-course of *Cassia* hedge shading of young maize within the alleys on a clear morning and a clear afternoon of 1/12/88 and 22/11/88 respectively (Mungai, 2000)

The *Cassia* was pruned to a height of 50 cm two weeks before planting. Windy conditions may unevenly redistribute surface mulch or even diminish the quantity present. Prunings were therefore incorporated into the soil, in a process which should be seen as a form of mulching too (Stigter, 1984). This is also an advantage because the rate of mulch decomposition is higher within the soil than when on the soil surface, thereby increasing the rate of nutrient release (Mugendi, 1994). The control plots did not receive any prunings. Maize stover was not retained in the plots after harvest since the farmers would normally feed it to their animals (Tessema, 1984).

1.3 Measurements carried out

To quantify the above- and below-ground influence of *Cassia siamea* on the growth and yield of maize, measurements were made in two middle alleys of incoming global radiation (weekly and occasional 15-minute values in one alley), soil moisture (weekly), soil temperature (weekly and occasional diurnal 10-minute values in one alley), the distribution in time and space of the fine roots of both maize and *Cassia*, occasionl transpiration and photosynthetic rates for maize, plant height (weekly) and maize grain. Measurements were made in the middle alley of two AF plots and in similar places in two control plots (Mungai, 1991). Particulats on data taking for global radiation, soil moisture and soil temperature may be found in Mungai *et al*. (Mungai, 1997; 2000).

1.4 Transpiration and photosynthesis data taken

Diurnal patterns of transpiration and photosynthetic rates for maize were determined on two occasions, during flowering in the 1987 long rains (Mungai, 1991) and on six occasions during the 1989 long rains and 1990 short rains (Netondo, 1991), with an infrared gas analyzer (ADC, Hoddeson, UK) with Parkinson leaf chamber. The measurements by Mungai (Mungai, 1991) were made on the abaxial side of the two youngest fully expanded well exposed leaves, under clear sky conditions, using three randomly selected maize plants per row, while Netondo (Netondo, 1991) used one such a leaf from five randomly selected plants and measured both sides of the leaves separately. Additional physiological measurements, including stomatal resistance determined using a Delta-T (UK) Mk II automatic porometer, were also made during the short rains of 1989 and the long rains of 1990 (Netondo, 1991). Some of the errors that can be made with this kind of instrumentation in field use were discussed by Coulson *et al*. (Coulson, 1988).

1.5 Root data taken

Investigations of the fine roots of both maize and *Cassia* at the interface of a *Cassia* hedgerow and an equivalent maize row in the adjacent control were carried out using trench profiles extending to the bedrock. Auxiliary root observations in the cropped alleys were carried out by auger sampling at three depths and four sampling distances from the hedgerows. Details and results were recently reported in this journal(Umaya, 1999).

1.6 Maize height and yield data collected

To assist in the interpretation of the moisture, shade and temperature data, the heights of a representative number of maize and *Cassia* plants was determined on a weekly basis using ten randomly selected plants per row as reported by Mungai *et al*. (Mungai, 2001).

Grain yield was determined on both a per row and total planted area basis for all AF and control replicates. Comparisons of yield/plant and yield/row for the full rows showed that for all seasons the omission of grain yield adjustments for the missing plants did not alter the conclusions reached with regard to within- and between-treatment differences. However, yield/row data take account of all environmental influences and were therefore preferred for the analysis. The yield/row values were intercompared using the three alley rows and their equivalent control rows. Given the higher possible influence of the *Cassia* roots on the control rows nearest to the hedges (Mungai, 2001), the use of yield/row for these inner rows provided more reliable data.

2 Results and discussion

2.1 Grain yield

On average, the eastern maize row of the agroforestry treatment outyielded the middle maize row by about 22%, while the western maize row outyielded the middle row by about 15% (Mungai, 1991). Such within-treatment differences were, however, not statistically significant except for the short rains of 1988 ($p \leqslant 0.05$). With the exception of the short rains of 1986 and 1987, the grain yield per row was 12%—241% higher in the agroforestry treatment than in the control (Fig.1). The t-tests performed on the data showed that these treatment differences were statistically significant ($p \leqslant 0.05$) except for the long rains of 1987. In the short rains of 1987, the maize failed in the agroforestry treatment because the very low and poorly distributed rainfall led to severe competition for water (Fig.1). The largest yield difference mentioned above (241%, in the long rains season of 1989, Fig.1) has been suggested to have been due to the planting of a hybrid maize variety (H511) during the previous short rains of 1988, because H511 must have been phenotypically different in nutrient uptake from Katumani Composite B (Mungai, 2001).

In alley cropping systems in semi-arid areas competition for water and nutrients is high and only a limited quantity of mulch can be produced. In the seasons when yield was not influenced by the use of a hybrid variety, the observed higher grain yields per row and, therefore, per unit area in the AF treatment, were therefore never sufficient to compensate for the cropping area "lost" to the *Cassia* hedges. In our case 44%, when expressed in terms of the land occupied by the hedges relative to the area in the alley, should have been the yield increase to break even, but the maximum obtained in Fig. 1 for these seasons was 32% for the long rains of 1988.

Fig. 1 gives a linear relationship between grain yield per row of Katumani Composite B maize and total seasonal rainfall for the experimental period. The equations are:

$$YAF = -827 + 8.7X \text{ and } YCONT = -614 + 7.3X$$

for the yields YAF in the agroforestry plots and $YCONT$ in the control plots respectively. ANOVA tests showed that the two slopes were statistically significant ($p = 0.03$ for AF and $p = 0.004$ for the controls) at the 5% level of significance, but the difference of the slopes is not significant ($p = 0.38$) at this level.

The main reason for the absence of a statistically significant difference between the lines is the limited number of only four seasons of data that could be used, because the short rains of 1988 and the long rains of 1989 were spoiled for this analysis by the sowing of the hybrid (Mungai, 2001). Moreover, the data for the short rains of 1986 had a large error range. However, this does not discredit the method as such. The existence of an amount (or a range of amounts) of rainfall, above which the AF treatment is more likely to yield higher per row than the controls, the competition from the trees not withstanding, while below that amount the competition for water deteriorates the AF yields, has been made plausible indeed. Whether this point is about 150 mm, as in the present results, or would become about 200 mm, in case of more measuring points, or whether the yield reversal is more fluid in range, is not important for the assessment of the methodology. Mathuva *et al*. (Mathuva, 1998) and Kinama, Ong, Stigter (unpubl.) found much higer values for this yield reversal in their experiments of adding trees to the field crops instead of replacing them.

The obvious limitations of the method applied in Fig. 1 are due to the importance of seasonal rainfall distributions for yields and possible carry over effects of previous seasons with respect to soil moisture and mulch applications. Such effects and some remaining influence of tree roots in the control plots are behind the variations in the relative yields in the different seasons.

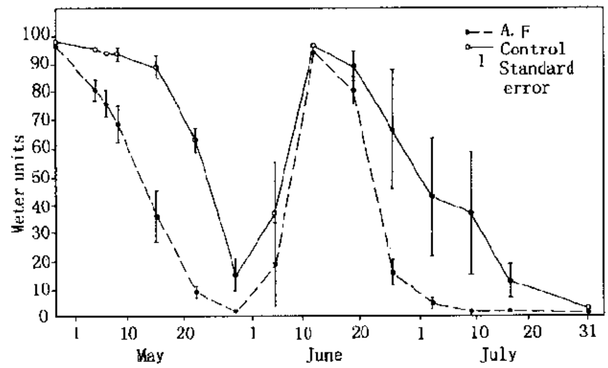

Fig.4 Seasonal time course for soil moisture at 40 cm depth, spatially averaged for the area occupied by the three maize rows in the alley and the equivalent rows in the control, long rains 1987. AF soil was drier(lower meter readings) than that in the control except during two wetter periods at the beginning of the season and within the first three weeks of June. Standard error bars are not shown where the values were negligible

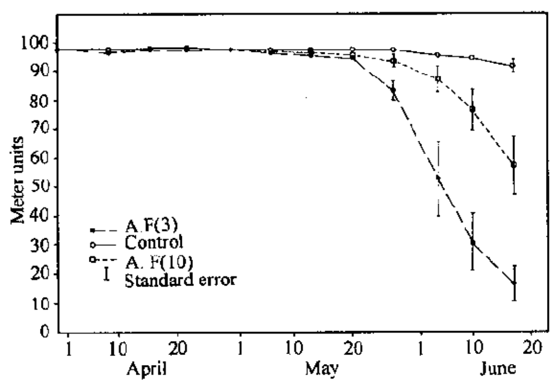

Fig.5 Seasonal time-course for soil moisture at 40 cm depth, spatially averaged for the area occupid by the three maize rows in the alley and the equivalent rows in the control, long rains 1988. AF soil was drier(lower meter readings) than control soil from the end of May onwards. Differences between the drier AF3 plot and wetter AF10 plot were due to differences in maize growth, with AF3 having the tallest maize plants(Mungai, subm.). Standard error gars are not shown where the values were negligible

2.2 Shade

Photosynthetic effects of the observed shading from *Cassia* are assumed to have been insignificant for several reasons: (a) in the early and late periods of the day, when the differences in shading occurred, clouds are often obscuring the sun; (b) earlier in the season, when the entire maize plant may have been shaded, the *Cassia* was still small under the prevailing pruning schedule; (c) self and mutual shading between maize plants that had grown as high as or higher than *Cassia*, during the later parts of the season, was higher than or comparable to the shading provided by grown up *Cassia* and (d) during the early and late parts of the day when the additional *Cassia* shading was received, the stomata in maize may be expected to be not yet fully open or already partly closed due to the inherent diurnal rhythm of stomatal movements, effects which would only have been strengthened by shading.

2.3 Soil moisture

The values indicated that soil water extraction was higher in the agroforestry treatment than in the control (Mungai,

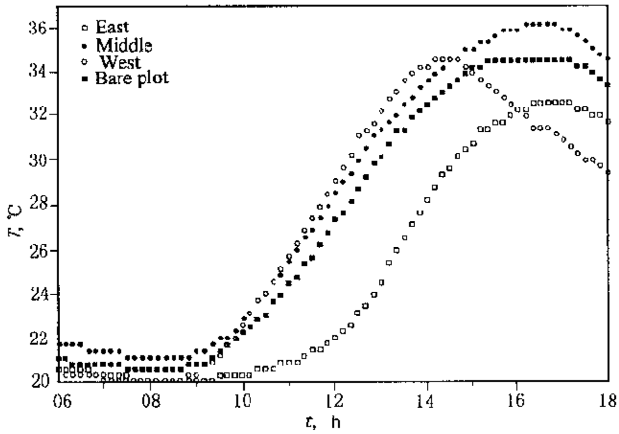

Fig.6 Effect of *Cassia* hedges on soil temperature for a representative clear day, with 80 cm high *Cassia* hedges and no maize. Eastern parts of the alley had the lowest soil temperatures in the morning, while temperatures in the west show a clear drop with the onset of afternoon hedge shade

2000). On average, soil moisture depletion was higher in the middle maize rows than in those adjacent to the *Cassia* hedgerows (Mungai, 1991). These results explain the yield differences well. Variability in the above-ground growth of the maize among the agroforestry treatment plots was observed to be related to differences in soil moisture extraction (Mungai, 2000). The differences in soil moisture extraction became more pronounced with depth, indicating the role of *Cassia* roots in the water balance of the system (Mungai, 1991).

2.4 Soil temperature

Temperature results were reported on by Mungai *et al.* (Mungai, 2000). Differences in temperature between the bare plot and the central position between the hedges may be assumed from energy balance considerations to be due to (1) soil thermal conductivity/capacity differences resulting from the incorporation of mulch and soil moisture differences; (2) net radiation differences caused by the presence of the hedges and (3) heat and water vapour transfer differences caused by differences in wind exposure. The eastern part of the alley had by far the lowest soil temperatures from morning until about 1600h, when the temperature of the western part dropped below it. This must have been due to *Cassia* hedge shade. Middle rows had higher tempertures.

It may be concluded from the soil temperature measurements that the hedgerows reduced the mean and maximum soil temperatures at 7.5 cm depth more than an equivalent maize row (Mungai, 2000). This led to soil temperatures nearer to the known optima for maize during the early part of the season, when the growing point of maize is still close to the soil surface (Watts, 1973). This may have influenced yields positively. The results further confirmed that temperature interpretations could easily be developed into an operational methodology for shade quantification, as an alternative or in addition to using the more cumbersome and error prone (because direction dependent) tube solarimeters (Mungai, 1997), provided night conditions and the phase difference between soil temperature and the time of occurrence of the shade of the taller component are taken into account (Mungai, 2000).

Table 1 Mean transpiration rates ((a) in $mmol.m^{-2}.s^{-1}$) and mean photosynthetic rates ((b) $\mu mol \cdot m^{-2} \cdot s^{-1}$) around midday for the youngest fully expanded, well exposed maize leaves at the end of the flowering stage, on two representative clear sunny days during the long rains 1987. Control (C) data were statistically significantly higher than agroforestry (AF) data (see paper text)

a	3/7/87		10/7/87	
Row	AF	C	AF	C
West	3.8 ± 0.6	4.4 ± 0.6	2.1 ± 0.7	4.1 ± 0.6
Middle	3.1 ± 0.5	4.2 ± 0.5	1.9 ± 0.6	3.7 ± 0.7
East	3.2 ± 1.0	4.1 ± 0.6	2.3 ± 0.8	4.0 + 0.4
b	3/7/87		10/7/87	
Row	AF	C	AF	C
West	13.9 ± 1.9	16.1 ± 2.5	6.6 ± 3.0	15.8 ± 3.1
Middle	10.8 ± 3.0	15.5 ± 3.1	6.0 ± 2.8	12.9 ± 4.1
East	11.4 + 5.2	16.1 ± 2.5	8.4 ± 4.2	15.0 ± 2.4

2.5 Results on transpiration and photosynthetic rates

According to *t*-tests performed on the sample data, the around midday transpiration and photosynthetic rates reported were significantly higher in the control than in the AF treatment on both sampling dates ($p < 0.05$) during the season of below-average rainfall when these measurements were made (Table 1). This was not translated into yield differences.

Although the middle rows generally exhibited the lowest values, these within-treatment differences were not statistically significant at the 5% level. Only very few statistically significant differences ($p \leqslant 0.01$) in maize leaf stomatal resistance and transpiration rates were found, with small absolute differences, during two wet seasons (in 1989 and 1990) at the same site (Nctondo, 1991).

2.6 Root distribution results

Greater risks of competition for water and nutrients exist under water and/or nutrient stress conditions during periods and in regions of greater root overlap. A statistically significant ($P \leqslant 0.01$) variation of *Cassia* root length density with depth was reported by Umaya *et al*. (Umaya, 1999), while there was no significant interaction between distance from the *Cassia* and depth for *Cassia* roots. The highest *Cassia* root length density occurred at the 20 – 50 cm depth. For those depths in the middle of the alley, association with maize roots was highest, leading to lower yields (Umaya, 1999). Analysis of variance showed that particularly distance influenced maize root distribution statistically significantly ($p < 0.001$ to 0.05). This was mainly due to the places of measurement selected. This confirmed the rooting patterns observed previously in profile pits (Mungai, 1991). The greater association of the two root systems occurred particularly during the reproductive and maturity stages of the maize. On average, maize root length was greater in the upper 10 cm than below 20 cm (Umaya, 1999).

3 Conclusions

Rainfall and soil fertility together determined the results shown in Fig. 1, in line with recent longer term data for other AF systems (Mathuva, 1998). The observed within-treatment differences in maize grain yield were due to several interrelated factors. The grain yield patterns across the alleys followed the observed soil temperature, soil moisture, transpiration, photosynthesis and root association patterns. The highest potential for competition for growth resources existed in the middle of the alley below 20 cm, where the overlap between the two root systems was observed to be greatest. Yield differences between the AF treatment and the controls and the limits of these differences were mainly due to the treatment (mulch) differences interrelated with rainfall and competition for resources (Mugendi, 1994; 1997).

From the results obtained, it is concluded that, for the selected tree/crop combination, the chosen management of the system and the prevailing climatic and soil conditions, the higher grain yield per row in the AF treatment due to mulching will in most seasons not be enough to compensate for the land "lost" to *Cassia* hedgerows. This is due to the low biomass production of *Cassia* under semi-arid conditions and below- and/or above-ground competition, as was also concluded by Ong *et al*. (Ong, 1992), Torquebiau and Akyeampong (1994), Ong (1994) and Mathuva *et al*. (1998) for their AF systems. With its most quantitative approach, our study supports ICRAF scientists' initial but at the time unquantified assessment that alley cropping under semi-arid conditions represents a high risk and least-known option for farmers (Rocheleau, 1985). Our work also justifies the judgement of local farmers not to incorporate wider adoption of alley cropping with the presently used tree species and management practices, on non-sloping land (Pegorie, 1990). AF systems must at least provide strong physical protection of crops and/or soils and/or have a strong economic incentive to be of more interest to the farmers. This conclusion remains valid for sloping lands as well (Ong, 1996).

Acknowledgments: The Traditional Techniques of Microclimate Improvement (TTMI) Project, in which context this work was carried out, was core funded by the Directorate General of International Cooperation Research Focal Programme (DGIS/DST/SO) of the Ministry of Foreign Affairs, The Netherlands. The Kenya Forestry Research Institute and Kenya Agricultural Research Institute gave permission to carry out this work at the Katumani Experimental Station. The University of Nairobi and the National Council for Science & Technology funded the operational costs of the research and the International Centre for Research in Agroforestry (ICRAF) assisted in many ways. We acknowledge thankfully the contributions of all these organizations.

References:

Arap Sang F K, Hoekstra D A, 1986. On-station hedgerow trial results of the development phase [R]. Machakos, Kenya: Dryland Agroforestry Research Project. Research Report 3.

Breman H, Kessler J-J, 1995. Woody plants in agro-ecosystems of semi-arid regions [M]. Berlin: Springer.

Coe R, 1994. Agrofor Today [J], 6(1): 9—11.

Corlett J E, Black C R, Ong C K, Monteith J L, 1992. Agric For Meteorol [J], 60: 73—91.

Coulson C L, Stigler C J, Akunda E *et al*., 1988. Instrument-based distortions of leaf/air temperature differences and interpretations of bean drought stress resistance [J]. Trop Agric, 65: 352—354.

Hoekstra D A, Torres F, Raintree J B *et al*., 1984. Agroforestry systems for the semi-arid areas of Machakos district, Kenya [R]. Nairobi, Kenya: ICRAF. Working Paper 19.

Kang B T, Reynolds L, Atta-Krah A N, 1990. Adv Agron [J], 43: 315—359.

Mathuva M N, Rao M R, Smithson P C *et al*., 1998. Fieldcrops Res [J], 55: 57—72.

Mugendi D N, Mochoge B O, Coulson *et al*., 1994. Arid Soil Res Rehabil [J], 8: 363—372.

Mugendi D N, Mochoge B O, Coulson C L *et al*., 1997. African Crop Sc J [J], 5: 201—207.

Mungai D N, 1991. A micrometeorologial investigation of yield differences in alley cropping trials in the semi-arid areas of Machakos District, Kenya [D]. University of Nairobi, Kenya, Ph.D thesis.

Mungai D N, 1995. The TTMI-project and the "Picnic"-model. An internal evaluation of approaches and results and of prospects for TTMI Units [M] (Stigter C J, Wangati F J, Nganga J K, Mungai D N ed.). Wageningen: Agricultural University. 111—123.

Mungai D N, Stigter C J, Ng'ang'a J K, Coulson C L, 1996. Arid Soil Res Rehabil [J], 10: 169—177.

Mungai D N, Stigter C J, Coulson C L *et al.*, 1997. Agric For Meteorol [J], 86: 235—243.

Mungai D N, Stigter C J, Coulson, C L, Ng'ang'a J K, 2000. Theor Appl Climatol [J], 65: 63—78.

Mungai D N, Coulson C L, Ng'ang'a J K *et al.*, 2001. J Environm Sc [J], 13, in print.

Muniafu M M, Macharia J N M, Stigter C J *et al.*, 1999. J Environm Sc [J], 11: 449—456.

Netondo G W S, 1991. Assessment of competition for water between *Cassia* siamea Lam. and *Zea mays* L., using various parameters, in alley cropping under semi-arid conditions in Machakos District Kenya [D]. University of Nairobi, Kenya, M.Sc. thesis.

Ong C K, Rao M R, Mathuva M, 1992. Agrofor Today [J], 4(2): 4—5.

Ong C K, 1994. Agrofor Today [J], 6(3): 8—10.

Ong C K, Kinama J, Chiti R, Gichuki F, Stigter C J *et al.*, 1996. People and institutional participation in agroforestry for sustainable development [M] (Mugah J O ed.). Nairobi: NAFS + ICRAF. 297—308.

Pegorie J, 1990. Agrofor Today [J], 2(4): 4—7.

Rocheleau D E, 1985. Criteria for re-appraisal and redesign: intrahousehold and between-household aspects of FSRE in three Kenyan agroforestry projects [R]. Nairobi, Kenya: ICRAF. Working Paper 37.

Stigter C J, 1984. Arch Meteorol Geoph Bioclim Ser B [J], 35: 147—154.

Tessema S, Emojong E E, 1984. E. Afr Agric For J (Special Issue) [J], 44: 408—415.

Torquebiau E, Akyeampong E, 1994. Agrofor Today [J], 6(4): 14—15.

Umaya G O, Macharia J N M, Onyango J C *et al.*, 1999. J Environm Sci [J], 11: 462—467.

United Nations Development Programme, 1990. Human development report 1990 [R]. New York: Oxford University Press.

Watts W R, 1973. Exp Agric [J], 9: 1—8.

(Received for review March 13, 2000. Accepted September 20, 2000)