An investigation of the influence of mulching and agroforestry systems on the microclimatic conditions affecting soil moisture and a maize/bean intercrop in semi-arid areas of Laikipia district

BY

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DECLARATION

This thesis is my own original work and has not been presented for a degree in any other university

28/11/95

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This thesis has been submitted for examination with our approval as University Supervisors

Prof. J.K. Ng'ang'a — 27/12/95 Date

Dr. D.N. Mungai — 4.1.96 Date

Prof. C.J. Stigter — 28/11/'95 Date

DEDICATION

I dedicate this humble effort, the fruits of my thoughts and study to my affectionate parents: my late father Mzee Januarius Omuli Oteng'i Wanjala and my mother Paulina Juma Buluma Oteng'i whose efforts have steered and inspired me to higher ideals of life.

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Abstract

The main thrust of this research was to come up with relief measures as a strategy to protect the small-scale farming environment, using agroforestry systems in the semi-arid areas of Laikipia district. Based on this thrust our hypothesis for the research was that the relief measures introduced via on-station and on-farm experimentation can indeed be used to improve the semi-arid microclimate for crop production, resulting in higher yields. For yield improvement the relief measures had to provide protection against and mitigation of yield losses due to: (i) competition for water between agroforestry trees and the intercrop and water loss by evaporation or by run off from the soil surface; (ii) destructive and desiccating strong winds, high radiative load on plants and the soil and high soil temperatures; (iii) lack of water in this area is a major constraint.

We experimented, at Matanya on-station and Kiahuko on-farm plots, with a farming system used by small-scale farmers in Laikipia, in which an intercrop of maize (variety H511) and beans (variety rosecoco) is used in association with *Grevilleas* in an agroforestry plot surrounded by a live-fence of *Coleus barbatus* shrub.

During the main experimental period (LR92-SR94) plots (agroforestry and non-agroforestry controls) were divided into (i) two mulched plots with minimum tillage (digging till 4 to 5 cm), one with root pruned and one with unpruned trees and (ii) two unmulched plots with only deep tillage (digging till 20 to 25 cm), again one with root pruned and one with unpruned trees. Five mulched and five unmulched plots and a bare soil plot located in the open, away from any tree influence, were used as control plots.

For determination of near surface soil temperatures we used 16 thermistors in AF at two distances from *Grevilleas* and 16 in NAF. including 2 in the bare soil plot. for soil temperature determination at 7.5 and 15 cm depth.

Sheltering effects against strong winds provided by the live-fence and the trees to the intercrop in AF plots were quantified. The southerly winds reaching Mulched pruned minimum tillage (AFM1) and Local pruned deep tilled (AFL1) plots were differently reduced. The maize plants in AFM1 were therefore somewhat better protected and grew taller and had higher biomass yields.

The results of the relative magnitude and direction of concentration of tree canopy shade showed that during the Short Rains (SR) seasons the region of heaviest tree canopy shading affects mainly the NW and NE sectors below the tree canopy. with the former getting the highest degree of shading. During the Long Rains (LR) seasons the region of heaviest tree canopy shading affects mainly SW and SE sectors below the tree canopy. where SE tends to get the highest shading. Compared to UT1. the PT2 canopy shading was less discernible than the UT1 shading.

The results of biomass yields (YLD) correlated with fractional radiation received by maize plants show the dry matter yields of maize generally to decrease with decrease in intercepted solar radiation through *Grevillea* canopies until about a fraction of 0.60 till 0.65 of that in the open. below which it virtually stops.

We may conclude from the results of analyses of extreme temperatures that although mulching at 3 t/ha was light. it was useful in influencing soil moisture. by shading and insulation but particularly by decreasing run off. and consequently in moderating extreme soil

The inter-comparison of the yields mainly reflected weather events, particularly low rainfall with poor distributions, that affected the soil water status for each season differently. The bean seed and other biomass yields also reflected seasonal differences that depended on these weather events. The results show that agroforestry (AF) has advantages as well as disadvantages in the area studied.

For soil moisture determination in the on-station conditions we used 28 access tubes in AF plots at different distances from the *Grevillea* trunks and 14 in non-agroforestry plots (NAF) for data taking with pre-calibrated neutron probes (type CPN 501 or CPN 503). In the on-farm AF plots with *Grevilleas* at Kiahuko-B we had 24 access tubes in the AF plots, installed at two distances from the tree stems, and 4 in NAF plots. We also used 19 access tubes in the live-fence experiment at Kiahuko-A at different distances from 3 pruned and unpruned portions of a live-fence.

For measurements of wind speeds on-station we used 13 WAU electrical cup anemometers in AF plots, 4 in each of 3 rows in the same direction as the crop and the *Grevillea* rows. Each anemometer was used in association with a shaded Piche atmometer for wind speed interpolation and extrapolation experiments. For wind direction we used four Woelfle anemographs, two in AF and two in NAF plots, one of each was adjustable to grow with the maize.

For determination of crop shading by trees from solar radiation we used 13 E-W oriented tube solarimeters (12 in AF at three different distances from trees, and 1 in NAF) at 2 m above the ground under two *Grevilleas* (unpruned UT1 for SR91 till SR93 and later on pruned PT2 for SR94 and LR94).

temperatures by affecting the temperature amplitudes and phase shifts.

The results of soil moisture contents during LR seasons show that root pruning of *Grevilleas* in combination with minimum tillage plus our mulching conserved more moisture than unpruned trees with minimum tillage plus mulching as well as pruned and unpruned trees with deep tillage without mulching. The differences between access tubes in pruned and unpruned areas were repeatedly higher than ±2.0% which we took as a value above which differences may be expected to become agronomically important. This indicates that pruning was agronomically more important than shading in on-station plots, due to large spacing between trees (5 m by 7.5 m). The unpruned *Grevilleas* and the unpruned *Coleus* live-fence competed strongly with the maize/beans intercrop for soil moisture.

The results of soil moisture in the on-farm situations show that root-pruning of the *Grevilleas* is only marginally agronomically important when the trees are planted close to each other (as they result in differences between access tubes of less than our criterion of ±2.0%), such that they heavily shade one another due to small spacing between trees (3 m by 5 m). In that case shading may become more important than root pruning. The on-farm *Coleus* live-fence experiment confirms that soil moisture was most often highest in the areas closest to the pruned portions of the live-fence.

In the driest season of study period, LR92, indicate that the control plots gave the lowest maize and beans yields of all seasons. The minimum tilled pruned Mulched plot (AFM1) had the highest maize biomass yields followed by Local control while the deep tilled pruned Local and the Mulched control had the lowest. The yield differences between upper and lower halves of AF plots varied between 20 to 25% in pruned and 35 to 45% in unpruned plots, with higher yields being in mulched plots.

The exemplarious results of the measurements of the per cent yield components of maize (i.e. cob, grain and biomass weights) for SR92 in both AF and NAF show that the ratio by weight of cob, grain and biomass in the total weights produced per row was on the average nearly 1:3:6. The cob and grain weights were directly related to each other and inversely related to the biomass weights. The cob weights tended to be more stable around their mean values than the grain and biomass weights.

The following weather advisory summarizes our most important findings as set out in the hypothesis for the protection of farming environment in the semi-arid areas of Laikipia district: to root prune agroforestry trees and hedges; to plant agroforestry trees with suitable economic returns and with canopy spacings and crown densities (after pruning of roots and eventually branches) that compromise between crop protection through shading from too strong solar radiation and throughfall of sufficient light to match in the best rainy seasons the rate of photosynthesis allowed by the fertility of the farmer's plots; to use (residue) mulch, of preferably more than 3 t/ha, for soil moisture improvement, particularly on somewhat sloping land, where runoff prevention appears essential. More mulch would also mean a higher contribution for soil fertility; to combine mulching with minimum or low tillage to improve physical soil properties near the surface; to design hedge and tree configurations that maximize wind protection preferably ≥ 35%, and do not introduce tunnelling through gaps. The plot environments should not generate turbulence that can harm the crops and/or hedges and trees; to utilize the observed spatial differences in seasonal rainfall over short distances (of a few kilometers); to try drought resistant maize varieties with shorter growing seasons, that are acceptable to the local farmers; and to try maize varieties with higher rooting depths that would use percolated water in deeper layers in seasons with irregular rainfall.

CHAPTER ONE

1. Introduction

1.1 Problem identification

Some of the main problems in the semi-arid highlands west and northwest of Mt. Kenya (Laikipia district) center on the food production by small scale immigrant farmers from the high potential areas in the neighboring districts. This immigration accounts for a population increase of 4% (e.g. Kohler. 1987: Republic of Kenya. 1994a). These immigrant farmers form the core of the resource poor small-scale farming community in Laikipia district. The immigrant small-scale farmers own parcels of land ranging from 0.8 to 2.0 ha on which they must eke a living. These immigrant farmers who are forced to farm on more drought-prone land hence in appreciably harsher climatic conditions than where they came from, face recurrent crop failures due to soil degradation through water and wind erosion and lack of inputs. They also face low production of grass for grazing and decreasing availability of firewood (Liniger. 1991). Rainfall variability is very high making water become a major limiting factor to rain-fed farming. The farmers rely on low external inputs to produce food (Reijntjes et al.. 1992) but lack sufficient knowledge of dry-land farming. Extension services are rather inadequate. The use of proper weather advisories could therefore assist these farmers greatly. More details on their situation may be found in sections 1.3.

1.2 Relief measures (applied or proposed)

1.2.1 Historical perspective

The above problems were identified by the LRP way back in 1985 (Liniger, 1991). To support demonstrations of relief measures LRP set up two agro-ecological stations in 1986, one at Matanya and one at Kalalu (Figs.1 and 2). These stations have since been giving useful meteorological data. Additionally, LRP started carrying out demonstrations of possible relief measures by agronomic and agrohydrological trials on gentle slopes of 4 - 5 %. The sites are situated on Mt. Kenya volcanic soils (Phonolites) and in two different agroclimatic zones (see Fig. 2): Matanya is in a semi-arid zone (agroclimatic zone V) and on a dark clay (*Vertoluvic phaeozem*) at an altitude of 1840 m a.s.l. and Kalalu is in a dry semi-humid (using Braun (1980)' s terminology) to semi-arid zone (agroclimatic zone IV) and on a red clay soil (*Ferric luvic*) at an altitude of 2020 m a.s.l. (e.g. Desaules, 1986; Liniger, 1991).

The main aims were to assess the possibilities of improving water use and the farming systems in general, to a degree that it would contribute to solving farmers' problems in line with the Kenya National Food Policy. The trials included intercropping of maize and beans in several treatments. These were (i) local (unmulched) - deep tilled (depth of 20-25 cm) with no conservation measures (ii) mulched-minimum tilled (depth of 4-5 cm) with mulch of 3 t/ha crop residues applied, (iii) agroforestry (AF) plots planted with a maize/beans intercrop in association with *Grevillea robusta* trees and with the AF plot fenced with a live-fence of *Coleus barbatus* shrubs, (iv) ridging, that is planting a crop on raised earth built along the contours, mainly to conserve soil moisture and restrain runoff. Sometimes two adjacent ridges are connected with transect raised earth to make a rectangular depression where water accumulates. Such ridges are called 'tied ridges'. This raised earth is also useful in beneficially increasing

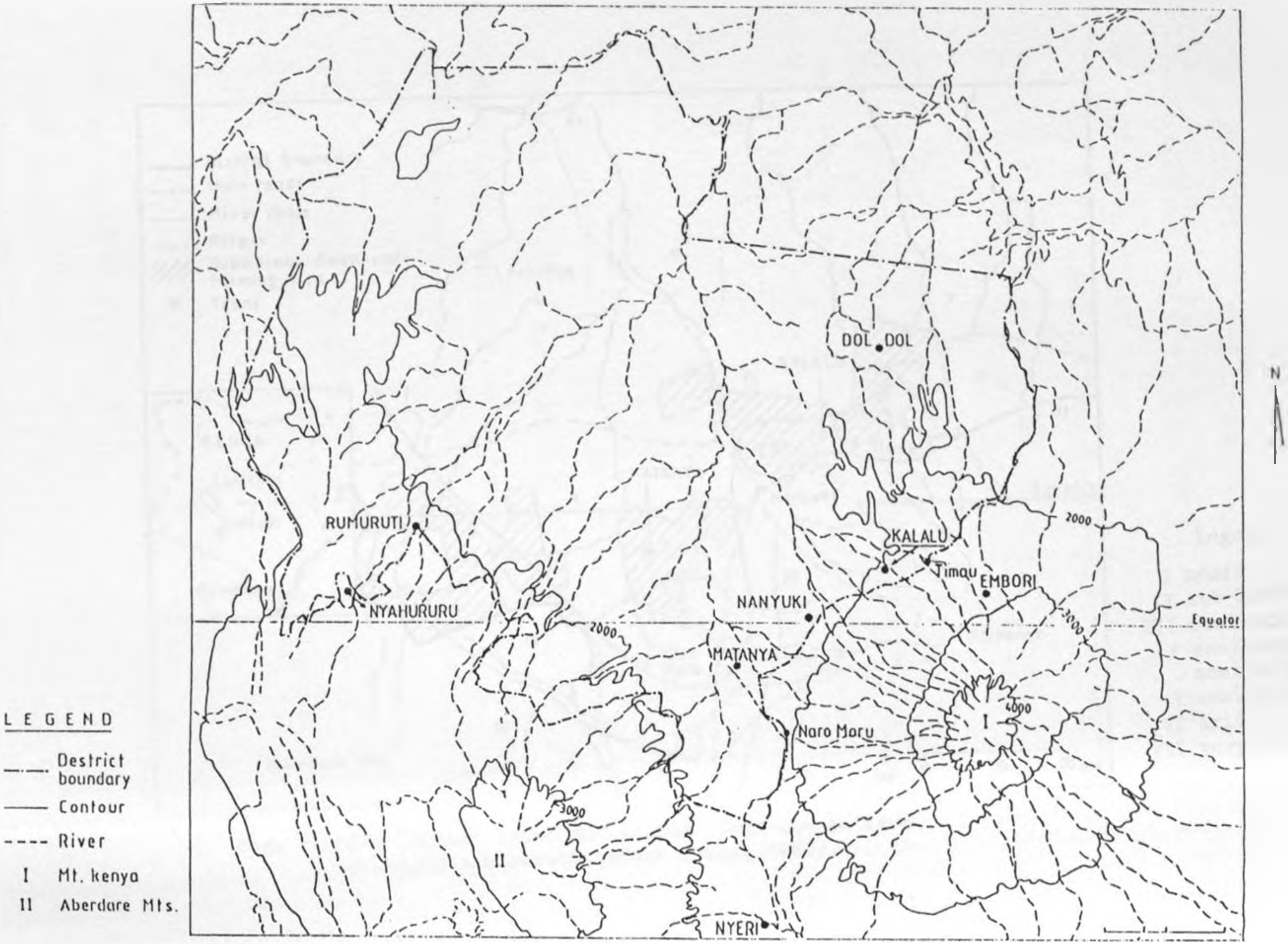
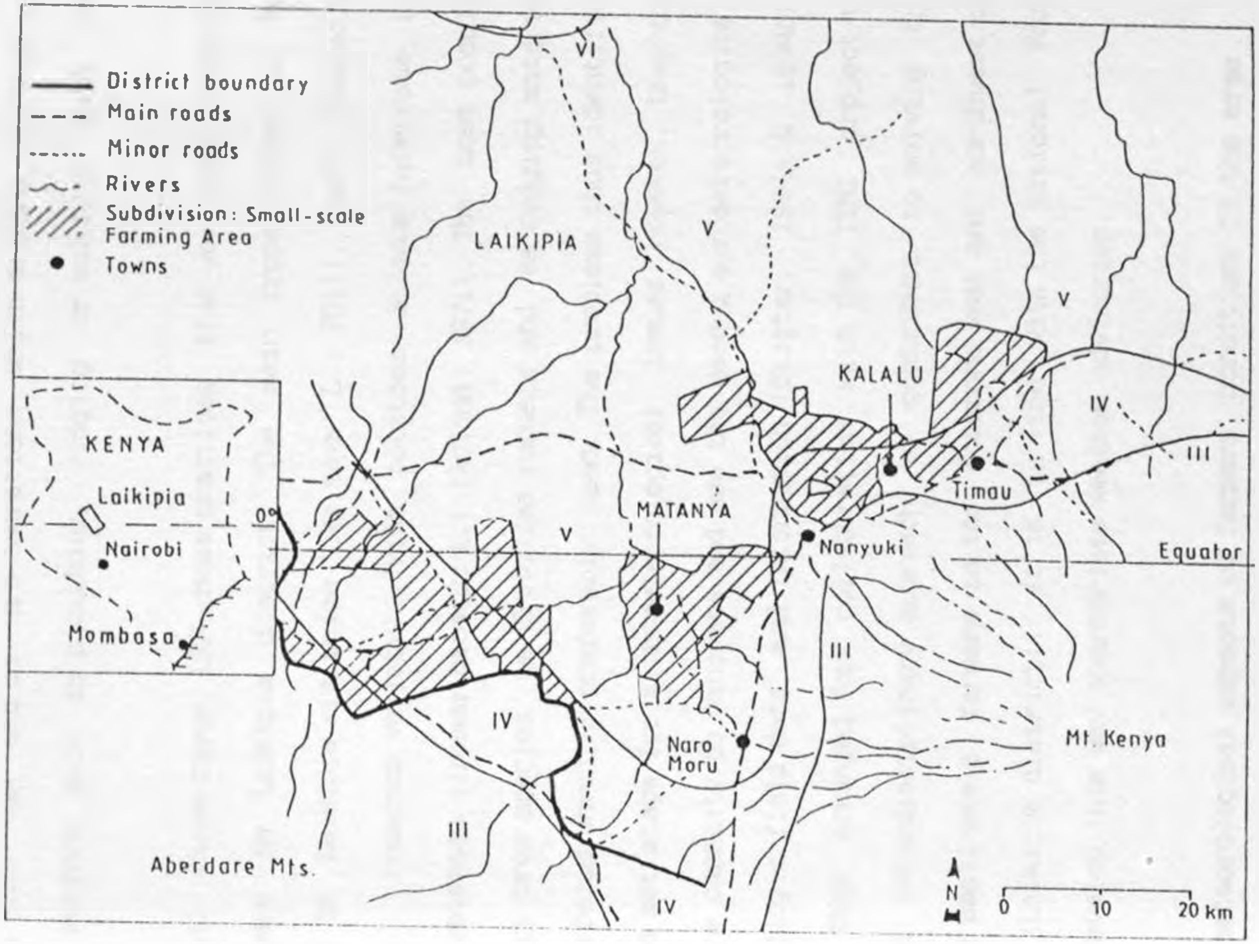


Fig. 1. Mt. Kenya and the Aberdare Mts. areas showing Laikipia district and Matanya, Kalalu and Embori experimental stations.



Legend

I humid
II sub-humid
III semi-humid
IV semi-humid to semi-arid
V semi-arid
VI arid
VII very arid

Fig. 2. Agroclimatic zones and dynamic land-use pattern of Laikipia district (after Flury, 1986).

surface roughness at the ground level if wind is strong and problematic (Webster and Wilson, 1966). A rough surface reduces wind speed and tends to trap particles moving in saltation or by surface creep. Cloddiness is beneficial this way and so are operations which produce a rough or irregular surface such as ploughing, ridging or mulching with crop residues.

In all these cases, LRP chose practices that were most prevalent with farmers in Laikipia district. The main crops grown by the immigrants in Laikipia are maize (*Zea mays* L., H511), beans (*Phaseolus vulgaris* L., rosecoco variety), Irish potatoes (*Solanum tuberosum* L.) and sweet potatoes (*Ipomea batatus* L.) (Acland, 1971). The most popular agroforestry tree species is *Grevillea robusta* and as hedging material *Coleus barbatus* shrub is preferably used. The problems thus identified by LRP had set stage for micrometeorological issues. However, they did not have the capacity to generate and use the needed agrometeorological/ agroclimatologic field data and information (Stigter, 1994a & 1994b). Therefore they arranged for collaboration with the TTMI project to develop an interdisciplinary approach to contribute to solving the problems of small-scale farmers in the Footzone west and northwest of Mt. Kenya (Laikipia district). It is in line with the National Food Policy to develop this way appropriate weather advisories.

1.2.2 Micrometeorological aspects of farmers' conditions in the area

Introducing crops, agroforestry trees, live-fences, homesteads and rural access roads in "opening up" newly acquired, previously open ranch-lands (i.e. with only sparse trees) drastically modifies the microclimate of the now farmed lands and to some extent the mesoclimate of the areas. The following micrometeorological factors in air and soil are influenced: (i) wind speed and air movement: (ii) surface reflectivity: (iii) surface infiltration and soil water retention: (iv) soil thermal properties and temperature and (v) micro-organic activities. Because of the changes in (i). (ii) and (iv) air temperatures also change: because of the changes (i) and (iii) air humidity also changes. These are consequences of energy and water balances that have to find new equilibria.

This new land use, however, also allows management and manipulation of microclimate for improvement of crop and animal production of the resource poor small scale farmers who come to live in the area (Gilbert. 1995). This calls for innovative management of water and soil fertility. It should be understood from the beginning that a resulting weather advisory of the kind that reads "local conditions are not suitable to small-scale agroforestry production systems" are not acceptable. These farmers have to live and to grow crops there. They are in first instance not willing to give up their present staple crops, in which maize/beans intercrops take the most important position.

1.3 Approach to more detailed problem identification after selection of relief measures.

After independence in 1963, the immigration of small-scale farmers into the semi-arid fringes of the Kenya highlands, such as Laikipia district, led to a significant change and intensification in land-use. The immigrants, mostly originating from densely populated high potential districts (e.g. Nyeri, Kirinyaga, Kiambu, Murang'a. Nyandarua, Meru, Tharaka-Nthi, Embu, etc., see Fig. 3) initiated the process of shifting towards more intensive land-use. Rain-fed crop production became predominant although the ecological suitability for this activity is rather marginal. The risks of crop failures are therefore very high. The farmers were ill-equipped to practice semi-arid farming. They lacked proper management knowledge and well researched extension advisories for these conditions. They introduced their traditional farming methods from medium and high potential areas into these ASALs. They grow intercrops of maize (often maize H511 and sometimes other highland cultivars e.g. H614. H624. H625 etc.) and beans (often rosecoco variety) in association with agroforestry trees. mainly Grevillea robusta. They also keep livestock on their small pieces of land.

In our detailed problem identification. we had to focus our attention on the existing agricultural production structures. These would help us develop more appropriate relief measures which would guarantee a reasonable level of subsistence farming under the semi-arid conditions of Laikipia district. Preliminary work of LRP (e.g. Berger. 1989; Flury. 1986. 1987 & 1988; Kohler. 1987; Liniger. 1991; Moges. 1991) gave leads as to which direction our research approach could take. Firstly. there was information on immigrant movements and their take-over of large ranch-land farms from the previous white settler owners. Also available was information on the subdivision of the acquired land into smaller units on which they applied traditional production techniques from their areas of origin (Flury. 1986). Secondly. there was preliminary information from soil moisture conservation trials of intercrops of maize and beans (Liniger. 1991) at Matanya and Kalalu. Thirdly. there was also preliminary information on competition for soil moisture between maize/beans intercrops and *Coleus barbatus* live-fence around the AF plot at the Matanya station (Moges. 1991). Finally.

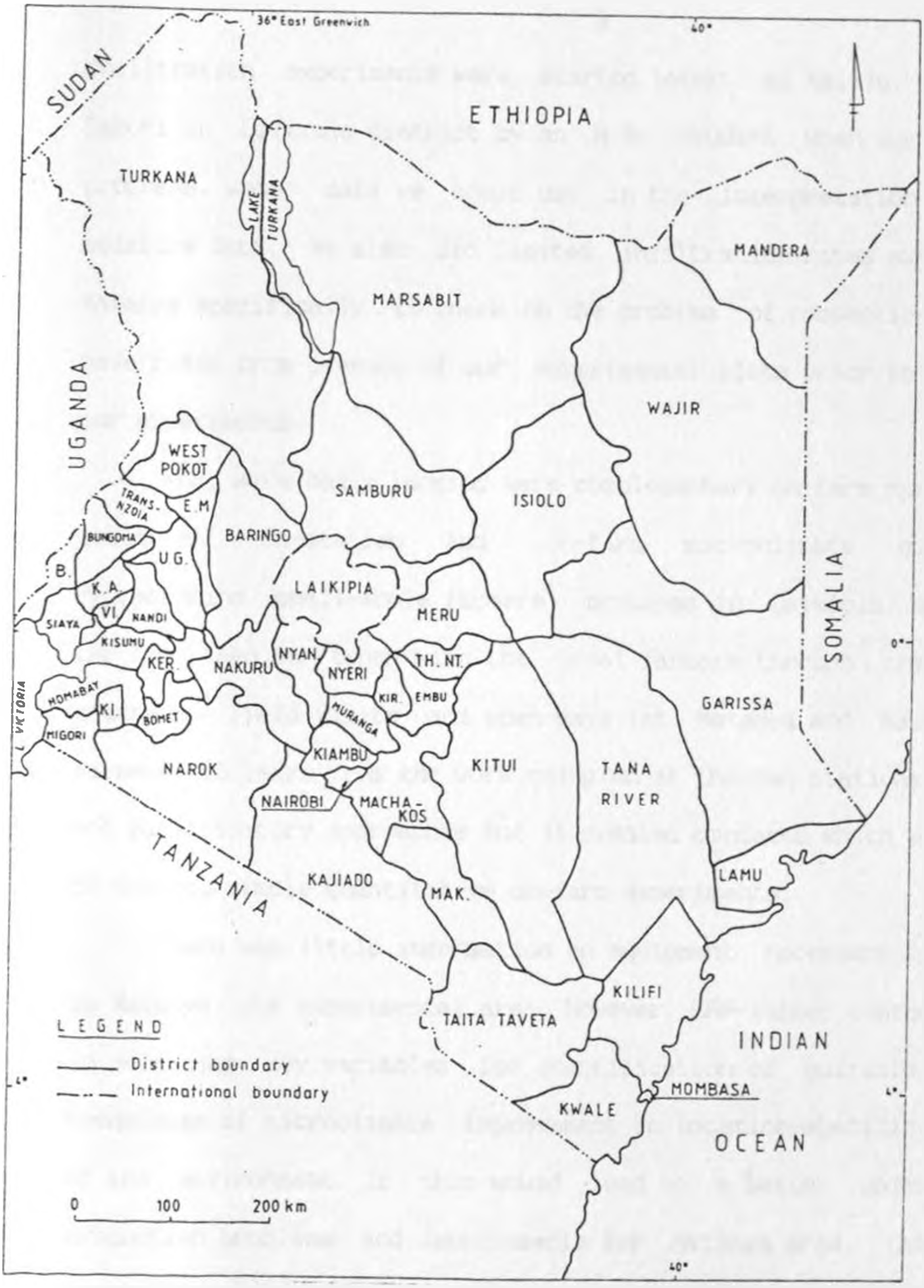


Fig. 3. A district map of Kenya showing Laikipia and neighbouring districts where immigrants originate from.

Legend

E.E.	Elgeyo Marakwet
U.G.	Uasin gishu
K.A.	Kakamega
B.	Busia
VI.	Vihiga
KER.	Kericho
KI.	Kisii
NYAN.	Nyandarua
TH. NT.	Tharaka Nthi
KIR.	Kirinyaga
MAK.	Makweni

infiltration experiments were started later, at Kalalu, Mukogodo and Embori in Laikipia district by an M.Sc. student, when our work was in progress, whose data we could use in the interpretation of our soil moisture data. We also did limited infiltration rates experiments at Matanya specifically to check on the problem of compaction which might have risen from overuse of our experimental plots prior to the start of our experiments.

What were badly lacking were complementary on-farm experiments and sufficient on-station and on-farm microclimate quantification representing small-scale farmers problems in Laikipia. Nevertheless, LRP had been in touch with the local farmers through organization of seminars, field visits and open-days (at Matanya and Kalalu) for the farmers to learn from the work going on at the two stations. These were not participatory approaches but it created contacts which we could use to develop simple quantitative on-farm experiments.

There was little information on equipment necessary to start work in Matanya, the experimental area. However, LRP-farmer contacts assisted in selecting key variables for quantification of suitable traditional techniques of microclimate improvement in location-specific protection of the environment. If this would lead to a better understanding of production problems and improvements for Matanya area, this could be extrapolated to other areas in Laikipia district in particular and the Kenya ASAL in general (Stigter, 1994b). It would have been difficult to issue meaningful weather advisories and to start to validate them without farmer participatory research on the on-farm conditions which was lacking by the time of starting this work. This gap was left for the TTMI project to tackle.

1.4 TTMI - Project

The core operation of TTMI is the Ph.D.-degree research training component at African universities using the PICNIC model (Stigter, *et al*., 1995). The approach should basically involve the understanding and subsequent use of indigenous (or traditional) technical knowledge (ITK) (or concepts) of microclimate management and manipulation. The management and manipulation selected for transfer and dissemination of African ITK and ITK concepts/principles have worked elsewhere under African constraints and conditions. Results from TTMI-programs in the participating countries have been discussed in numerous papers (e.g. Stigter, 1990, 1994 a, b & c; Mungai and Stigter, 1994).

At the time of the start of the TTMI-project mulching, shading, wind protection and surface modification were thought to be the most in need of attention and were most likely to yield operational results for local validation and acceptance. Most of the research work is done in collaboration with a third party organization with which the local TTMI-Unit has signed a letter of understanding. These parties deliver scientific and logistical support. In our case this was the Laikipia Research Program, a Swiss funded program of which agroforestry research is this days funded by the Netherlands.

In line with the aspirations of the TTMI-Project (Stigter, 1994a & 1994b; Mungai and Stigter, 1994) in Laikipia district we had to start this study with purposes that had to satisfy the Kenya National Food Policy spelt out in Republic of Kenya (1981, 1983 and 1986) and later revised in Republic of Kenya (1994a).

1.5. Thesis objectives

1.5.1 The Kenya Government Research Priorities

The major food policy spelt out in Sessional Paper No. 4 of 1981 (Republic of Kenya. 1981) and later consolidated in Republic of Kenya (1986) gave sixth Development Plan (1989-1993) strategies which emphasized research into drought resistant crops for the ASAL areas e.g. sorghum. millet. Irish potatoes. sweet potatoes. pulses and oilseeds. There is some potential for expansion in areas such as Laikipia. Machakos and Nakuru districts and parts of Coast province (Republic of Kenya. 1994a. Mungai. 1991). The Government research priorities for increased food production in the ASAL focus on conservation of soil moisture and of soil fertility levels to minimize reliance on chemical fertilizers (Republic of Kenya. 1981. 1986 & 1994 a).

These priorities include:

(i) increased intercropping with agroforestry trees in ASAL:

(ii) increased multiple cropping:

(iii) use of organic manures:

(iv) improvement in other cultural practices including soil moisture conservation efforts:

(v) improved soil analysis and increased and efficient use of fertilizers.

Food crop research was recommended to get more emphasis in the ASAL. especially maize growing in agroforestry systems. Other suggested areas were agronomic research on small scale production systems and on environmental protection. The TTMI research policy on environmental protection issues fits in quite well with the above. This study was formulated taking into consideration the above National Food Policy because it was our first general objective to be part of the priorities of national policies.

1.5.2 Meteorological hazards in the study area

Meteorological hazards such as long droughts and few aperiodic excessive rainfall episodes are major constraints to food production in the ASAL of Laikipia district. Rainfall variability is very high. The rains mainly occur in two distinct seasons: Long Rains (LR, March - May) and short Rains (SR, October - December). These seasonal rains are associated with the movement of the intertropical convergence zone as the sun apparently travels seasonally from north to south and back (e.g. Jackson, 1989a). A few areas, such as Kalalu, another LRP station, receive a third maximum in July - August (Flury, 1986). There is high variability of rainfall from year to year and season to season. These temporal variations greatly affect water availability for people, livestock and crops. A considerable proportion of rainfall may be concentrated in a comparatively small number of heavy torrential storms. Such a rainfall is not effective in crop production, as it will hardly be available to plants unless in irrigated areas. It will hardly contribute to soil moisture reserve to be drawn on in dry spells. It will mostly be lost as surface runoff, creating problems of flooding and water erosion and accelerating land degradation through loss of soil organic matter, including humus, as well as soil nutrients (also vertically through leaching) and minerals and soil micro-organisms (e.g. Harrison, 1987; Jackson, 1989a).

Strong winds that occur in Laikipia and neighboring districts every year towards the end of the LR based growing season (June-September) hit Matanya with full force. Hourly average speeds of up to 12 m/s have been recorded. These winds are due to the channelling of the S.E. trade winds between the Aberdare ranges and Mt. Kenya. LRP (Liniger, 1991) had identified these strong winds as particularly a menace to crop production and as destroyers of the environment in

Laikipia district during the June-July period.

The ASALs of Laikipia experience cooler daytime conditions due to altitude and proximity to Mt. Kenya. The nights are chilly and frost occurrences are quite regular from November to February because of very cold gravity (katabatic) winds from the mountain at night. The second general objective of the study was therefore to protect agricultural production environment in the area as best as possible against consequences of these occurring meteorological hazards. Such protection of the agricultural environment indeed ranks high in the TTMI priorities (Stigter *et al*.. 1989a: 1989b).

1.5.3 Scope of the study

With the given objectives the present study was carried out through both on-station and on-farm experimentation. The aim was to help develop low external input farming systems with mulching and agroforestry in which the air and soil microclimate were manipulated to benefit crop performance and yields. It should be noted that in the agroforestry system concerned no mulch is derived from the trees, that have a protective function (against winds) and an economic function (wood and/or fruits). These functions were mentioned by Mungai *et al*. (1995) as necessary to improve agroforestry in semi-arid regions. Some benefits combined provide ecologically more sound conditions for crop production.

Mulching and agroforestry (without mulching) do not require any other external input than land to grow crops and collect mulch and AF trees, eventually together with additional nutrients for sustainability at a required level. In poor infrastructural conditions associated with semi-arid areas, mulching as low input agricultural technology may provide farmers with an accessible economically sustainable alternative to other farming systems such as shifting cultivation, normadism etc. However, to close the nutrient balance with only little fertilizer additions, mulch should come from other land than that cropped (Acland, 1971) and leaching should be prevented.

Studies on the management and manipulation (the latter leading to modification) of microclimate by the above mentioned systems in the Laikipia ASALs had therefore the particular objectives to contribute to: (i) optimizing the use of soil moisture by both trees and crops in an agroforestry system; (ii) creating sufficient wind protection by the AF trees and the live-fence between June and September; (iii) optimizing net radiation of the crops, which means here no heavy shade but enough to protect them from serious night radiation losses by the influence of the AF trees and the surrounding live-fence; consequently (iv) increasing low temperatures that occur between November and February.

This would enable us to issue preliminary relevant weather advisories regarding the use of such systems. The small-scale immigrant farmers will have demonstrations of existing relief measures for dry-land farming in the area and may therefore be able to use their land more economically, be it at low yield levels. They will be able to produce food as well as firewood, may be including other AF products as well, depending on the choice of trees, in their AF systems. The full economics and sustainability levels of such a system can only be derived when some of such types of farming systems have settled in the region.

1.6 Hypothesis

Crop production by small-scale farmers in semi-arid Laikipia, as discussed earlier in section 1.5.2, is faced with the constraints of (i) lack of, and competition for water for, farming; (ii) strong winds which necessitates planting of AF trees on the plot and live-fence (sometimes with additional trees) around the plot: (iii) shade and competition for water and nutrients from the AF trees and the hedge: and (iv) very high daytime and very low nighttime soil temperatures that could cause physiological stress in plants.

We formulate a research hypothesis on protection of the small-scale farming environment in the semi-arid areas of Laikipia district based on these constraints and the proposed relief measures. We postulate that the relief measures introduced via on-station and on-farm experimentation can indeed be used to improve the semi-arid microclimate for crop production, overall and therefore the intercrop yields, notwithstanding the added competition.

On soil water conservation our hypothesis means that with other factors controlled by the system's conditions, use of crop residues, from the intercrop produced on the farm and fallen leaves of Grevillea robusta trees, as mulch will lower runoff and soil evaporation from the intercrop root zone and increase final yields. This implication on mulch suggests that the 3 t/ha mulching rate of crop residue would provide adequate surface cover to considerably influence soil moisture regimes. Root-pruning (trenching) of both *Grevillea robusta* trees and the *Coleus barbatus* live-fence are also implied as soil water conservation relief measure. Our hypothesis also assumes that minimum tillage as another relief measure will assist conserving soil moisture in semi-arid AF systems. Optimum crop performance and yields would so be expected under conditions determined by the behaviour of rainy seasons, and by other microclimatic factors altered as a consequence of the AF system design.

Our hypothesis means for wind protection that agroforestry trees and live-fence (location specifically influenced by nearby structures, e.g. houses, cattle sheds, piggeries, etc.) provide sufficient protection to cropland and intercrop yields against strong winds. Here management aspects of windbreaks and shelter can be determining factors.

Our hypothesis means for the effect of the AF tree (and eventual live-fence) shades that at the spacing of 7.5 m by 5 m the *Grevillea robusta* trees should reduce yield unacceptably through shading and reduction of photosynthetically active radiation (PAR) as their canopies grow large. Here management aspects of lopping and pollarding and provision of mulch materials and firewood can be determining factors. Any economically acceptable yield reduction has to be off-set with appreciable gains from tree products.

The hypothesis means for soil and air temperature that 3 t/ha well distributed maize/beans intercrop residue mulch together with acceptable shade and therefore joint influence on net radiation, is adequate to have a positive impact on soil and air temperature regimes by mitigating temperature extremes and ameliorating crop performance.

Having spelled out the microclimate implications of the hypothesis, the onus is to prove or disprove from the research results that the relief measures have positive microclimatic and yield effects under the semi-arid conditions of Laikipia. We have to prove that on these relief measures proper weather advisories can be formulated that can be validated and applied by the small-scale immigrant farmers in Laikipia district and other areas with comparable problems.

1.7 Other expectations

The few seasons we have worked with farmers' plots (on-farm experimentation) at Kiahuko-A and Kiahuko-B we have realized that farmers' expectations from research results are very high. They themselves have experimented with different cropping combinations involving maize, beans, potatoes, cowpeas, pegionpeas, tomatoes etc. on their lands to try to come up with cropping patterns that could survive to maturity during recurrent periods of inadequate rainfall. They therefore expect a lot from research results like ours. To assist these farmers, and measure up to at least a part of their expectations, there is an urgent need for extension services based on weather advisories that could be obtained from up-to-date agroclimatic/ agrometeorological quantitative information of the scales discussed in this study.

Most importantly, these small-scale farmers may adopt changes brought about by research results, but should factors such as recurrent rain failures lead to successive crop failures at early extension stages (i.e. in the validation phase) of adopting the suggested technology, the farmers will distrust these new methods and revert to their earlier techniques. Therefore introduction of weather advisories has to include complete mobilization of extension services during the validation phase. Suggestions for involvement of the administrative arm of government in the area will be included.

CHAPTER TWO

2 Literature review

2.1 Crop growing in semi-arid areas

2.1.1 Climate and cropping systems

Farmers in rain-fed semi-arid lands practice cropping systems mainly centered on subsistence farming. These cropping systems have often been developed traditionally by experience, using trial and error methods with crop mixtures and crop rotations influenced by uncertainty of rains. Crops grown and cultural methods adopted vary widely, depending on a variety of factors, chief among them being the climate. Crop production in the semi-arid areas depends on the amount, distribution and onset of the main rains, on winds, on soil and also on the dietary habits of the people (e.g. Jackson, 1989a). Inadequate rainfall and often desiccating strong winds, within and outside the growing season (erosion!), are the main environmental factors limiting crop production in many semi-arid areas. Even when seemingly adequate, rainfall amounts are generally so irregularly distributed while evaporation rates and runoff are so high, that losses in crop yields are very common (e.g. Ruthenberg, 1976; Harrison, 1987; Reijntjes *et al.*, 1992). Increasing climate variability worsens these problems (Stigter *et al.*, 1995).

In countries like Kenya density and growth of population in the high potential areas have greatly affected farming systems and the availability of other natural resources. Such population increase in high potential areas coupled with increasing production of cash crops (e.g. coffee, tea, pyrethrum etc.) and fodder for improved livestock that require large tracts of lands have caused severe pressure on land.

Lack of arable lands due to over-population in high potential lands has, in countries like Kenya, forced a part of the population into semi-arid areas where they have introduced unadapted cropping systems (e.g. Webster and Wilson, 1966; Flury, 1986; Kohler, 1987; Liniger, 1991).

Mixed cropping (intercropping and sequential cropping) is a universal feature of semi-arid agriculture. Ideally all annual and perennial crops can be grown in different crop mixtures and crop geometry in these areas (e.g. Ruthenberg, 1976; Palaniappan, 1985; Davis and Garcia, 1987; Davis *et al.* 1987; Wiersum, 1988). Stresses attendant in semi-arid environments, such as overgrazing, water and wind erosion and low availability of water and nutrients, intensify competitive interaction between species. The dry season, when winds blow from hotter land masses, especially large deserts, is normally a time of fairly desiccating winds, which retard plant growth and induce wind erosion (McArthur, 1976). Such drying effects are major limitations to semi-arid cropping systems and these stresses worsen recurrent hazards such as droughts etc.

Cultivation of land in such fragile areas during good years can be dangerous and can aggravate soil moisture and nutrient problems during drier seasons (Bowden, 1977; Jackson, 1989a). Droughts can wipe out both crops and animals and pauperize the farmers who then become really slaves to climate. Mixed cropping results in the interaction (competition as well as complementarity) between species as each component species adapts to the environment modified by the presence of the other. When any growth factor (e.g. light, water and nutrients) is limiting, the species that is better equipped to use the limiting factor will gain at the expense of the other (e.g. Webster and Wilson, 1966; Bowden, 1979; Palaniappan, 1985; Reijntjes *et al.*, 1992).

In an agroforestry system the perennial tree component whose roots have colonized the soil layers for a considerably longer time than the crop component have an advantage over the latter component with respect to the use of growth factors (e.g. Dhyani *et al.*, 1990; Nicoullaud *et al.*, 1994).

Intercrops may actually share crop space by either having their needs in different periods or by spatial complementarity very often one component renders services to the other or there are mutual services rendered (Stigter and Baldy, 1994) In intercropping risks are lower as food security can better be addressed. Some crops are likely to give a fair return even in bad weather. As example of services rendered one can mention legumes that provide nitrogen to non-legumes (be it on a long term basis) and higher plants that shade shorter ones from excessive radiation loads (Palaniappan, 1985; Stigter and Baldy, 1994).

2.1.2 Nature of soils and their influence on crop growth in the semi-arid areas

Semi-arid soils are derived from main classes of Alfisols, Vertisols, Entisols and Inceptisols (e.g. Lal, 1979; 1987; Norman *et al.* 1984; Desaules, 1986; EUROCONSULT, 1989; Liniger, 1991). These soils are very fragile and vary enormously in suitability for farming. Erratic and heavy rains lead to extensive leaching which carry most soluble plant nutrients below the root zone, as the vegetation is mainly grass with shallow root systems (e.g. Nair, 1984). These soils are easily erodible. Soils in semi-arid areas which are denuded of vegetation or litter (mulch) receive heavy impacts of weather (e.g. Ruthenberg, 1976;

Reijntjes *et al*.. 1992: Harrison. 1987). High radiation load results in too high soil temperatures and too dry soil. The roots in such soils grow sub-optimally.

Rainfall impact seals the surface of loamy soils and results in sandy soils losing its coherence. The soil generally loses edaphon. Trolldenier (1988) defined edaphons as the totality of organisms. for example micro-organisms (bacteria and fungi). soil algae and soil microflora. Edaphons contribute to the formation of humus which is closely associated with clay particles. Clay-humus (loamy) complexes give the soil its internal structure. Soil organisms play a very important role in development and stability of air and water spaces in soil. When soil is subjected to high radiation. erratic and excessive rains and strong winds. edaphon functions in the soil are interfered with and soil life becomes endangered (e.g. Ruthenberg. 1976: Lal. 1979: 1987: Trolldenier. 1988: Reijntjes *et al*.. 1992).

Most organic matter in semi-arid areas breaks down differently with different rainfall episodes (Jackson. 1989a). Due to their varied textural compositions and structure. soils of semi-arid areas differ in their workability and mode of N mineralization from one growing period to another in sequential cropping (e.g. Palaniappan. 1985: Norman *et al*.. 1984: Abrecht and Bristow. 1990). At the onset of the main rains N is mineralized and makes the soil poor in this nutrient. The C/N ratio is raised resulting in slow decomposition of vegetation. Cultivation encourages mineralization of the added organic matter. accelerating the breakdown of the more stable humic substances (e.g. Lal. 1979; 1987: EUROCONSULT. 1989: Liniger. 1991). Semi-arid soils are also easily compacted. Bennett *et al*. (1986) demonstrated that at high nitrogen levels water stress had relatively less effect on maize water use than at low nitrogen levels despite similar reductions in leaf water potential during periods of low soil water availability. Both nitrogen and water stresses were imposed in combination to examine the interactive effect of N and water stresses on maize. Jones *et al.* (1986) showed that plants grown with little N were more sensitive to water stress and were less efficient in utilizing intercepted radiation, although this was partly due to lower leaf area indices (LAI's). The effects on both carbon dioxide exchange rates (CER) and canopy evapotranspiration (ET) of combining nitrogen stress with water stress have been found to be additive. The relationship between CER and photosynthetic photon flux density (PPFD) was found to have appreciable diurnal hysteresis at low and as well as high N, with considerable sensitivity on this nitrogen level of the crop. Jones *et al.* (1986) conclude that most of the diurnal variation in CER/ET was the result of differences in vapour pressure deficits. Management of soil moisture and N as well as canopy vapour pressure deficit in agroforestry systems in the semi-arid areas could therefore contribute to their sustainability.

2.1.3 Soils in Matanya experimental area

Most soils in the semi-arid areas of Laikipia district are mainly derived from Vertisols, Ferralsols, Nitosols and Phaeozems (e.g. Liniger, 1991; Desaules, 1986; Sombroek and Braun, 1974). Their classification systems were based on the Commission for Technical Cooperation in Africa (CCTA) taxonomy, which was adopted by FAO from French and US approaches (e.g. Norman *et al.*, 1984; Desaules, 1986; EUROCONSULT, 1989).

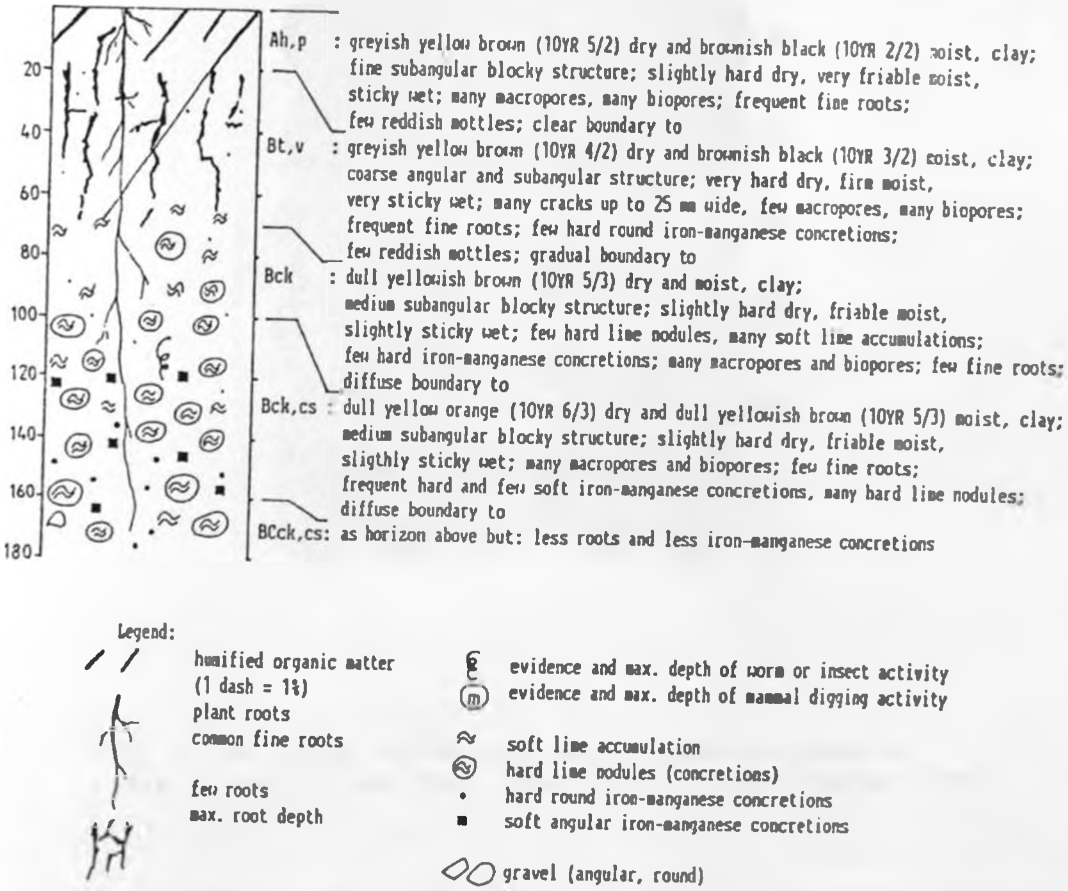
These soils belong to the *vertic-luvisols* class, which are widespread in Laikipia district (Desaules 1986). They are dark-coloured and have high clay contents. They display wide deep cracks during dry periods. The cracks are sealed off during cultivation when surface vegetation cover and aggregate sizes in surface soil are reduced. Nevertheless water infiltration via cracks becomes an important mechanism for water recharge at the onset of the rains. If water can infiltrate via cracks to depths below 15 cm, thus bypassing the surface layer, water storage will be improved.

The Matanya soils have high water content in the lower layers, as summarized by Figs. 3, 4 & 5 and Tables 1 & 2. These soils also swell when wetted and self-mulch when drying, following rainfall events (e.g. Van de Weg, 1978; Norman et al. 1984; EUROCONSULT, 1989; Abrecht and Bristow, 1990). They have a high CEC, high base status, neutral-alkaline reaction and high moisture-holding capacity. Their surfaces are generally granular, a factor that is causing their self-mulching characteristics.

On drying, large clods naturally breakdown into small aggregates. These soils are relatively fertile given the semi-arid conditions with relatively high calcium (Ca) content but generally low in N, P and Zn. They are hard to cultivate during dry seasons, apart from the mentioned self-mulch layer. Their surfaces become sticky during wet seasons, making it difficult to work (e.g. Van de Weg, 1978; Desaules, 1986; Liniger, 1991). Water infiltrates in these soils but hardly goes beyond the layer 90-150 cm.

The top soil has high organic matter content which makes it belong to the family of phaeozem soils (Liniger, 1991). These soils have the following characteristics:

- deep dark grey soil in the top 20 cm. black from 20–60 cm and yellow brownish below 60 cm..
- high organic matter content in the top horizon (3.4 %).
- highest clay content in the black layer.
- formation of cracks during the dry season from the surface to 60 cm depth in the black layer.
- imperfectly drained. mottled. in the top 60 cm. (mottles: patches of oxidized iron (or Ferric oxides) content of the soil. formed by frequent wetting and drying of soil containing iron).



Ah,p : greyish yellow brown (10YR 5/2) dry and brownish black (10YR 2/2) moist, clay; fine subangular blocky structure; slightly hard dry, very friable moist, sticky wet; many macropores, many biopores; frequent fine roots; few reddish mottles; clear boundary to

Bt,v : greyish yellow brown (10YR 4/2) dry and brownish black (10YR 3/2) moist, clay; coarse angular and subangular structure; very hard dry, firm moist, very sticky wet; many cracks up to 25 mm wide, few macropores, many biopores; frequent fine roots; few hard round iron-manganese concretions; few reddish mottles; gradual boundary to

Bck : dull yellowish brown (10YR 5/3) dry and moist, clay; medium subangular blocky structure; slightly hard dry, friable moist, slightly sticky wet; few hard lime nodules, many soft lime accumulations; few hard iron-manganese concretions; many macropores and biopores; few fine roots; diffuse boundary to

Bck,cs : dull yellow orange (10YR 6/3) dry and dull yellowish brown (10YR 5/3) moist, clay; medium subangular blocky structure; slightly hard dry, friable moist, sligthly sticky wet; many macropores and biopores; few fine roots; frequent hard and few soft iron-manganese concretions, many hard lime nodules; diffuse boundary to

BCck,cs: as horizon above but: less roots and less iron-manganese concretions

Legend:

/ / humified organic matter (1 dash = 1%)
plant roots
common fine roots
few roots
max. root depth

evidence and max. depth of worm or insect activity
(m) evidence and max. depth of mammal digging activity
≈ soft lime accumulation
hard lime nodules (concretions)
• hard round iron-manganese concretions
■ soft angular iron-manganese concretions
gravel (angular, round)

Fig. 4. Soil profile description at Matanya (after Liniger. 1991).

- high water holding capacity.
- hard top soil when dry, and sticky and heavy when wet.
- fertile soil with no major constraints in nutrients.
- plenty of lime and iron-manganese concretions from around 80 cm downwards.

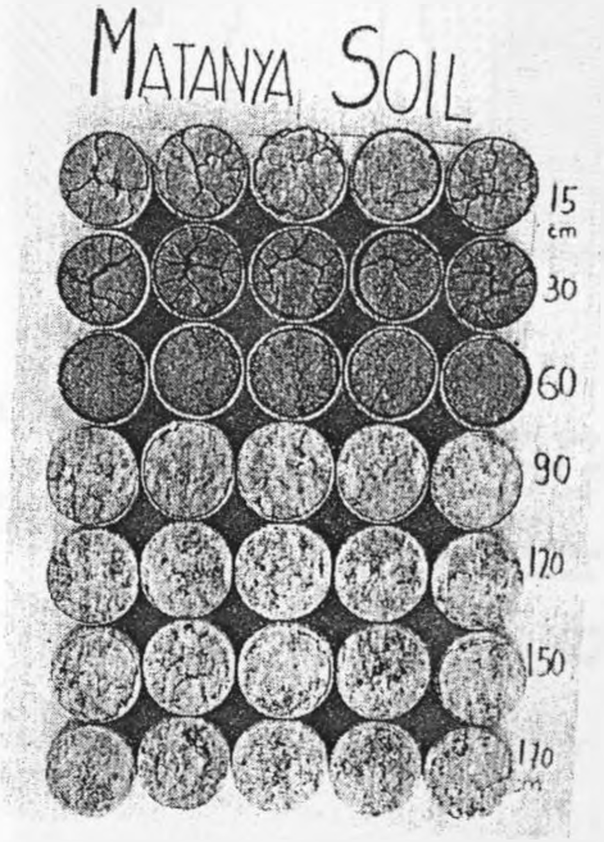


Fig. 5. Shrinking for Matanya soils (samples taken at field capacity and then oven-dried), after Liniger, 1991.

indicating that water after infiltrating to that depth is taken up by plants, while the lime washed in from the top horizon accumulates. These accumulation poses potential danger to crops and trees, hence a negative factor as to soil fertility.

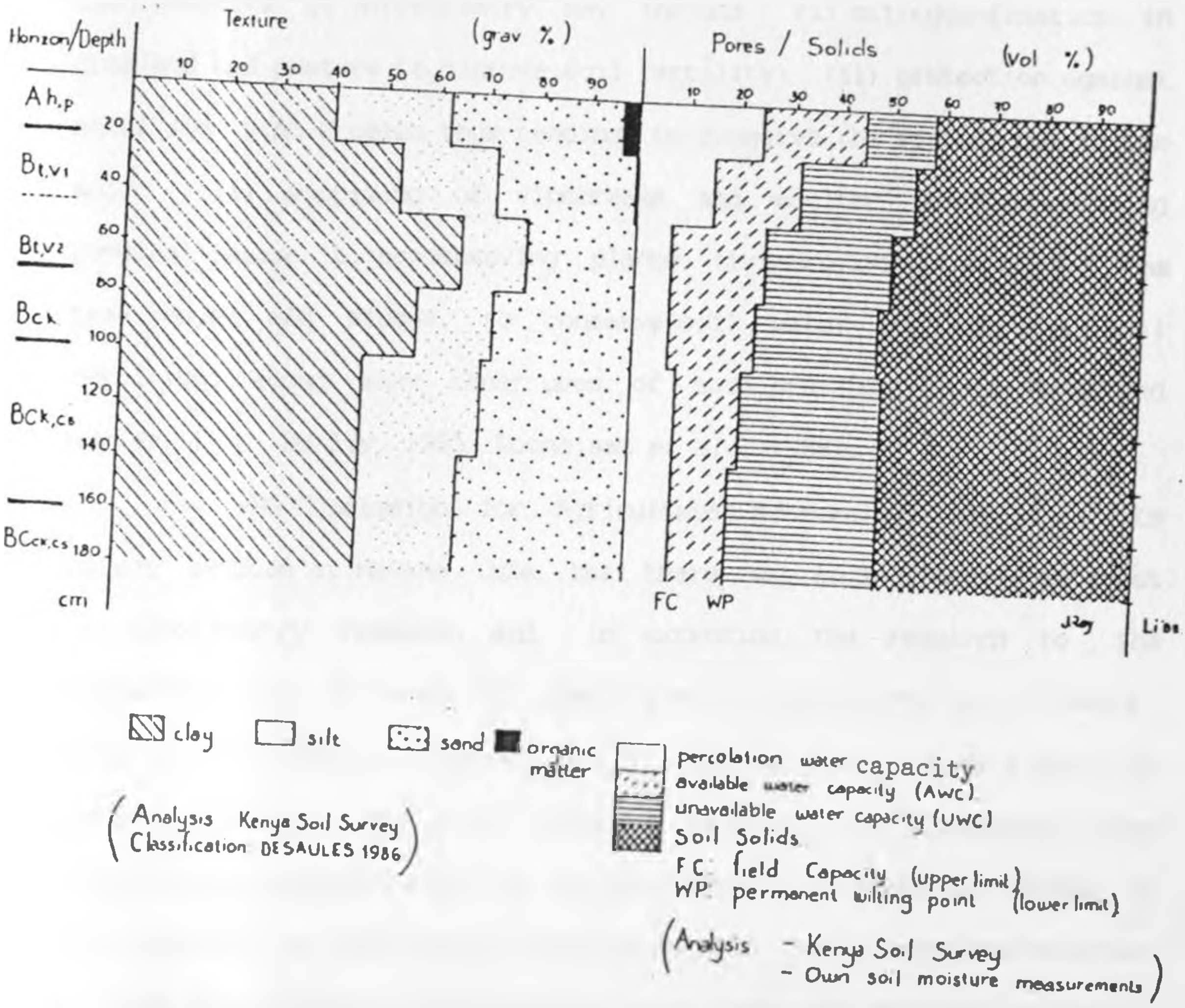


Fig. 6. Soil texture and soil water capacity (after Liniger, 1991).

2.2 The role of agroforestry (AF) systems in crop production

2.2.1 The benefit of agroforestry systems

Agroforestry (AF) is frequently mentioned as a possible alternative solution in semi-arid and arid areas to problems of land and water degradation as well as a contribution to solve shortages of food, and/or fuel-wood, and/or cash income, and/or animal fodder, and/or building materials (Rocheleau *et al.* 1988). Agroforestry may offer at least partial solutions to many rural land-use and production problems. The benefits of agroforestry may include: (i) nitrogen-fixation in cropland and pasture to improve soil fertility; (ii) protection against water and wind erosion thus tending to conserve the status quo in the soil; (iii) supplying of windbreaks and shelter thereby reducing physical damage to accompanying plants; (iv) provision of mulch from tree leaves and stumps, to conserve soil water and increase soil fertility, among many other uses of such prunings (e.g. Mongi and Huxley, 1979; Burley, 1985; Rocheleau *et al.*, 1988).

The WMO Commission for Agricultural Meteorology agreed in its latest session at Havana, Cuba, that there was an increase of interest in agroforestry research and in extending the research to the agrometeorology of trees. It stated also in its report that, however, "this area of research remained fairly limited, due, to some extent, to various organizational and financial reasons. The Commission also recognized the difficulties in the development of research, caused by the complexity of agroforestry systems as well as the problems relating to experimental design and availability of cheap and reliable equipment. The Commission, therefore, once more called upon the research community to increase its attention to these matters, including equipment suitable for on-farm quantification" (WMO, 1995).

Agroforestry (AF) is most often defined as "the land use systems in which trees or shrubs are grown in association with herbaceous plants (crops and pastures), in a spatial arrangement or time sequence and in which there are both economic and ecological interactions between the tree and non-tree components of the systems" (e.g. Lundgren and

Raintree, 1983: Young, 1987: Nair, 1988). AF trees may have wide and varying economic and environmental functions to the farmer (MPT (multipurpose trees), but so far remain least successful in the semi-arid areas, mainly because of the low biomass production.

The most important traditional knowledge of shading, mulching and windbreaks and their effects in AF (and other cropping) systems over the years, have been elaborately presented by Stigter (1988). Traditional farmers all over the world are aware of the harmful and beneficial effects of climate in different crop stages. Such damages as caused by high radiation loads to young seedlings, desiccation of the topsoil under dry windy situations, wind carried sand and wind erosion have been traditionally addressed. The environmental roles of AF systems are similar but the approach and their actual mitigation vary in different parts of the world and are even location specific within comparable climatic conditions (e.g. Lundgren and Raintree, 1983: Rachie, 1983: Hazra, 1985: Stigter, 1985a: Stigter, Darnhofer and Herrera, 1987: Kerkhof, 1990: Lawson and Kang, 1990).

The micrometeorological aspects of AF systems include:

(i) mulching by materials provided by trees/bushes:

(ii) protection against the mechanical impacts of wind, rain and hail:

(iii) shading against strong radiational loads, for example in some commercial crops. Among others, *Cordia abyssinica* and *Grevillea robusta* have been used in Kenya as shade trees in coffee plantations (Acland, 1971);

(iv) control of soil erosion: and

(v) improved water holding capacity, water infiltration and some other related soil factors by provision of organic matter.

Other functions of agroforestry in the semi-arid areas may include to (i) alleviate fodder situation during dry seasons: (ii) provide fuel-wood: (iii) satisfy timber needs: (iv) provide nutrients (e.g. nitrogen) to the crop component of the system. in case of tree legumes.

The functions of AF systems may thus be divided into two broad areas. i.e. productive and service functions. Productive functions include: provision of firewood. domestic timber. fodder. food. oils. fibre etc.: and service (or protective) functions include: provision of shade. shelter (against heavy radiation load and high wind speeds) and hedging. soil conservation. water conservation and soil nutrients (mulches) (e.g. Young. 1987: Nair. 1988). In semi-arid areas soil and moisture conservation. provision of nutrients and fuel-wood provision are the most important.

2.2.2 Soil moisture and soil nutrients in AF system

AF systems are mainly used in attempts to optimize beneficial effects of the interactions of the woody components (trees) with the non-woody components (crop and/or animals). The aim is to obtain a production pattern that improves on the exploitation of resources under traditionally prevailing social, agroecological and economic conditions (Kerkhof. 1990). Here issues like total yields (both seeds and biomass from the AF systems). diversity of end products and sustainability have to be included (e.g. Lundgren. 1978: Nair. 1984: 1988: Young. 1989). AF systems are developed which consist of trees of desirable forms and root systems. using appropriate management to minimize competition for resources with the crop components. To optimally share water and nutrients. the ideal perennial trees for an ideal AF system colonize deeper soil layers whereas the annuals colonize the shallower layers.

This would minimize competition for these resources between the two components. The roots of the trees loosen the soil and enhance infiltration. The trees stabilize the soil by anchoring it against erosion, preserving the nutrients in the top soil.

In the undisturbed vegetated ecosystems, water movement under saturated conditions takes place in soils through macro-pores that dominate the pore space (e.g. Nair, 1984; Jackson, 1989a). Surface run-off is generally low, even in periods of heavy rains with a high drop-size distribution. Infiltration rates and infiltration capacity are generally high. The soil bulk density is low. However, removal of vegetative cover from such soils increases their bulk density, decreases their porosity and reduces their infiltration rates. The removal of bush and forest cover accelerates storm-flow, leading to increased soil erosion.

Fereira (1979) observed that development of tea estates in rain forest areas of East Africa increased run-off during initial clearing and terracing operations. This drastically reduced when the tea canopies were properly established. Muchena (1979) observed high infiltration rates in uneroded forest soils, but these rates were later greatly reduced due to compaction by grazing animals.

As to nutrients, leguminous MPTS, like *Cassia spp.*, *Acacia spp.*, *Leucaena spp.*, etc. fix nitrogen but do extract phosphorus and potash from the nutrient reserve in the soil, thereby making the soil poorer in these elements. Non-leguminous MPTS like *Grevillea spp.*, *Balanites spp.*, *Zizyphus spp.* etc. do not fix nitrogen but deplete nutrient reserve without replacing any (e.g. Connor, 1983; Rachie, 1983; Burley, 1985).

The model on nutrient recycling and distribution in an ideal AF system described by Nair (1984) is based on:

(i) addition of nutrients to the soil for use by the AF system from (a) rain. e.g. N. S. P. K etc. from the air: (b) litter fall, pruning or lopping "pumping mechanism from deeper layers by the perennial"; (c) release to the soil through root decay and: (d) release of nutrients from the soil by weathering.

(ii) nutrient export compensated by turn-over within the system and its efficient use.

(iii) nutrient removal from the AF systems occurring at reduced rate through: (a) little erosion and runoff: (b) little loss from the system due to deep percolation (leaching) and: (c) complementary sharing of nutrients.

A rainfed agroforestry cropping systems in semi-arid areas could therefore be improved with mulching from outside the system for conservation of soil water and addition of nutrients.

2.2.3 *Grevillea robusta* in agroforestry farming systems

Grevillea robusta A. Cumm. ex. R.Br. (also known as *silky oak*) is a tree species native to subtropical eastern Australia. The genus *Grevillea* comprises over 260 species and belongs to the tribe (a tribe consists of a group of several genera with similar chacteristics) *Grevilleae* within the family of *Proteaceae* (e.g. Jeffrey, 1973; 1982: Harwood. 1989: 1992; Owino, 1992). *Grevillea robusta* is the largest species in the genus. It can reach 40 m high and a diameter of 100 cm. It grows naturally in the northern New South Wales and southern

Queensland. from the coast to about 160 km inland. at an altitude of 1120 m a.s.l., and between the latitude 30° 10'S and 25° 50'S. The rainfall there is from 720 to 1710 mm while the mean temperatures range from 14.7 to 20.1° C (Harwood. 1989; 1992).

Grevillea robusta occurs in two natural habitats within the latitudes mentioned above: first, on alluvial soils in the riverine forests along the banks of rivers and streams and in valleys of small creeks and rivers away from forests; second, though at low density, in the vine forests and thickets in the upper valley slopes and rolling terrain away from the rivers.

Grevillea robusta was brought to Sri Lanka and India for use as shade tree for tea. coffee and cinchona (Harwood. 1989 and Owino. 1992). It was brought to East Africa from India as shade tree for tea and coffee around 1910. It is still being used for that purpose to date (Acland. 1971). *Grevillea robusta* is light demanding, pioneering colonizer of disturbed sites as it has fast initial growth then slows down as competition from surrounding vegetation increases (e.g. Ongugo. 1992; Owino. 1992).

Grevillea robusta is conspicuous in landscapes of the high potential parts of Kenya. where it is grown along plot boundaries as ornamental tree. As such it has aesthetic value enhanced by: fernlike leaves; brightly coloured dense flowers; a near conical pine-like crown and a racemose branching (i.e. unbuttressed. erect. tapering bole surmounted by a small tufted crown) system (e.g. Harwood. 1992; Owino. 1992). It is widely grown along farm boundaries as well as intercropped with maize. beans. Irish potatoes. sweet potatoes and other crops in row planting on small-scale farms in the high potential areas of Kenya (e.g.

Kerkhof, 1988; Ongugo, 1992). It was imported from the high potential areas into semi-arid areas by the small-scale immigrant farmers, as a component of what we have learnt is basically inappropriate traditional farming technology in these areas. Grevillea robusta trees grown along boundaries act as windbreaks.

Grevillea robusta is being grown less and less as shade tree for coffee and tea in Kenya, because under application of fertilizers it is said to reduce productivity of these crops by its shade. It is also said to spread *Armillaria mellea* which is a disease that attacks roots (Owino, 1992; Ongugo, 1992). *Grevillea robusta* is increasingly being grown in agroforestry with crops such as maize, beans, potatoes, etc. because it grows fast, is relatively easy to grow and exhibits little negative reaction (competitive) effects with crops. It is popular among small scale farmers in Kenya.

In the semi-arid environment, intensive on-farm use of *Grevillea robusta* could provide self-sufficiency in wood products. It could provide the farmer with fuel-wood and building (construction) poles, shade, litter mulch and saw timber of acceptable quality (e.g. Young, 1989, Neumann, 1983). It has relatively little interference with adjacent agricultural crops under adequate moisture conditions (Spiers and Stewart, 1992). From interviews with Farmers in Meru and Embu districts Spiers and Stewart (1992) found that dense stands or large unpruned *Grevillea* trees could reduce crop yields. Competition for soil factors between *Grevillea* and the intercrop may increase under dry conditions because of increased efficiency of *Grevillea* under these conditions. This integration of wood production into the farming systems would avoid the land-use distribution conflicts which may require setting aside areas for plantation forests to meet rural wood requirements (e.g. Republic of Kenya, 1994a; Owino, 1992).

Issues such as mineral nutrition, nutrient cycling and biomass, geometry, and distribution and turn-over of roots are important to determine the success of intercropping Grevillea with annual crops. Proteoid roots in *Grevillea* are said to develop under low soil moisture status and play a similar role as mycorrhizal associations in other tree families, harvesting nutrients and water more efficiently than the normal roots (e.g. Nair, 1988; Harwood, 1989). *Grevillea robusta* exhibits auto-allelopathy which prevents young *Grevillea robusta* seedlings from growing near the older ones (Webb *et al*., 1967). Chemical analysis of *Grevillea* barks has indicated the presence of mono- and di-saccharides while leaves have been found to contain for example nitrogen, phosphorus and potassium in the proportion of 1.18%, 0.12% and 0.50% respectively (Gosh and Rao, 1972).

Grevillea robusta trees are regularly side-pruned and pollarded to reduce shading of the ground crops and to supply firewood and poles. *Grevillea* has typically a short growing life in plantations and poor coppicing ability. *Grevillea* is currently the most popular agroforestry tree species for the small-scale farmers, which can improve and sustain productivity and maintain environmental stability in the semi-arid areas (e.g. Ongugo, 1992; Owino, 1992).

In agroforestry systems that came into existence in the Laikipia semi-arid areas, *Grevillea robusta* is often planted either randomly or grown in association with maize/beans intercrops. *Grevillea* regularly sheds its leaves, providing abundant quantities of leaf mulch. Reddy (1992) observed *Grevillea robusta* leaf mulch to accumulate to a considerable depth, with the top hardly decomposing, the middle remaining partially decomposed and the bottom layer forming a good decomposed humus. *Grevillea robusta* leaves are used occasionally as dry season animal fodder in the semi-arid areas of Laikipia, although they are not quite palatable to the animals. The leaf litter is used as mulch for soil moisture conservation and soil temperature moderation.

2.2.4 *Coleus (Plectranthus) barbatus* as live-fence materials

Coleus barbatus shrub locally known as "*Maigoya*" is a soft hairy shrub which grows up to 4-4.5 m tall with rather fleshy angled stem, with velvety, soft and hairy leaves of up to 10 cm long (Gachathi, 1989, Lind and Tallantire, 1975). It is normally propagated through cuttings during rainy seasons to establish a permanent boundary around cropped areas and/or houses. It is widely used in Laikipia district as hedges to exclude domestic animals from entering into the cropland (Moges, 1991). Moges (1991) observed from the experiments on soil moisture competition between Coleus barbatus live-fence and maize plants that the leaves of Coleus could be used for mulching and stems for firewood, the purposes for which it is normally not used. The dried leaves were instead left to decompose at the roots of the hedges and were never collected and spread in cropland as mulch.

2.2.5 Crop performance and yields

2.2.5 (a) Maize in semi-arid environment

Crop productivity in semi-arid Laikipia district is substantially lower than yields obtained with adequate irrigation. The total ecosystem should be considered when choosing yields criteria because yields are highly variable in semi-arid environments (Hall *et al.* 1979). Maize is a main staple food of semi-arid inhabitants.

Early development stages of maize were delineated by Hanway (1963) in terms of the appearance of leaf pairs. This development index has subsequently been refined to suit local climates and has been related to above ground growth (e.g. Todorov, 1977; Brown, 1976; Liniger, 1991). Todorov (1977) suggested that the middle leaf, that is 9th leaf, be used in East Africa Meteorological Services as the third phenological stage after germination and emergence stages. The 9th leaf stage and conversion to a reproductive apex coincides with internode elongation. Leaf production on a tiller ceases usually after eight to ten leaves. At this stage initiation of ear primordia occurs by development of buds in the leaf axil. Fertilization requires pollen shedding from the tassels and development of receptive silks through elongation of carpels of female spikelets, starting from the base of the ear (Todorov, 1977).

In the lowland tropics depending on varietal differences cultivars such as Katumani composite B an early maturing variety reach anthesis in about 50-60 days and come to maturity in 80-120 days. Development before anthesis is highly dependent on temperature (Hartfield, 1976).

In East Africa maize is grown from sea level to over 3500 m altitude depending on variety (Hartfield, 1976). It is therefore not possible to generalize development patterns and time to maturity, as observed in Kenya. In the equatorial region in Kenya when, maize cv. H6302 is grown at various altitudes, the duration to maturity increases at a mean rate of 7.6 days per 100 m, from 131 days at 1270 m to 205 days at 2250 m altitude (Hartfield, 1976). Such altitudinal effects are normally taken into account by agricultural authorities in Kenya when choosing maize genotypes for a particular area (Republic of Kenya, 1994).

Most cultivars of *Zea mays* are sensitive to drought but this crop is grown in semi-arid environments due to food preferences. The land-races of maize, such as Katumani composite-B, which produces grain within an annual rainfall of less than 500 mm in the warm semi-arid area of Machakos in Kenya, represent sources of characteristics that confer drought resistance (Hall *et al.*, 1979).

The large seed of maize (usually 0.2-0.4 g) leads to rapid radicle and epicotyl growth after imbibition. The radicle appears from the seed before the epicotyl (i.e. at lower seed water content) and both, radicle and shoot, elongate linearly with time, sharing a temperature optimum of about 30°C and showing a negligible elongation at less than 9°C or above 40°C. Maize seed has a relatively large water requirement at imbibition, hence maize is more sensitive to low soil water at sowing. Maize does not go into dormancy (e.g. Blacklow, 1972; Hall *et al.*, 1975; Hartfield, 1976; Todorov, 1977).

Photosynthetic rates of maize peak at 30-40°C, they are negligible at 40-50°C. Rates of leaf emergence and lamina expansion also peak at 30°C (e.g. Blacklow, 1972; Swan *et al.*, 1981; Hartfield, 1976). One would therefore expect greatest maize growth in environments conducive to leaf temperatures of 30-33°C during the day but with cool nights (low respiration). One expects higher dry matter yields in the wet-and-dry cool semi-arid tropics (SAT) than in the wet or humid tropics which usually have less diurnal variations, with higher night temperatures, expected to produce less total growth.

In the tropics efficiency of conversion of PAR into maize dry matter averages 5.1 to 7.2% (e.g. Trenbath, 1976; 1986; Norman *et al.*, 1984). High growth rates are achieved at a maize population of about 50. 000 plants/ha. Higher population during early growth increase rates of dry matter accumulation, but under rainfed conditions long-term growth, water use and particularly grain yield may or may not respond to population depending on soil water availability. In the tropics total above ground maize dry matter yield at maturity is between 12 and 20 t/ha, for well nursed experimental crops, but grain yields range from average of 1.0 to 1.5 t/ha to 5.0-8.0 t/ha with good management and 10.0-12.0 t/ha in experiments at 1500-2000 m altitude (Norman *et al.*, 1984). Low maize grain yields in the tropics are usually attributed to dry matter distribution within the crop and to the sensitivity of both, net photosynthesis and partitioning, to environmental stress, particularly water deficit.

The physiological mechanisms of dry matter distribution, that is short and long distance translocation, are documented (Eastin 1969; Hofstra & Nelson, 1969; However, very little is known of quantitative partitioning to roots in field environments, given their function in water and mineral uptake and the provision of support. Flowering in tropical maize is accelerated by short days. Critical day lengths are 14.5-15.0 hrs. Time to flowering is accelerated by increasing temperatures (Hartfield, 1976). After flowering there is a 'lapse phase' which is of 3-8 days duration in open pollinated tropical cultivars. The actual grain filling period is about 20-30 days. Maximum grain weight is attained and growth terminated at maturity. The number of grains that fill depends on temperature: directly through fertilization and photosynthate production and indirectly through an increase in axillary tillering at low temperature. The number of filled grains is linearly related to radiation received after floral initiation or above ground growth rate. Drought reduces leaf area and leaf photosynthetic rate during stress periods, delays silking and reduces grain yield components, particularly grain number. Reduction in grain number is due to increased asynchrony in flowering water deficit reduces the rate of pollen production during periods silks are receptive and reduces the periods the silks are exposed to pollen.

Maize in the tropics has low yield, depending on variety and altitude, relative to temperate maize, because of supra-optimal temperature, inefficient redistribution of dry matter to grains and sensitivity to water stress that influences both vegetative and reproductive growth.

Maize is predominantly intercropped with beans in many parts of the world, for example in East Africa and Central and South America (Nadar and Faught, 1983; Nadar, 1983; Rao, 1986). Maize is intercropped with bush beans in the semi-arid lowland areas of Kenya. Both crops are planted with the beginning of the rainy season. Beans mature here in about 90-110 days and maize is harvested in about 120-150 days depending on variety and temperature (altitude influence). The early maturing varieties are grown in lowland area where temperatures are relatively high and mature earlier than the highland varieties.

2.2.5 (b) Common bean (*Phaseolus vulgaris*)

Beans, just like maize, is a most popular crop second only to maize as a staple food of semi-arid areas of Laikipia district. The variety widely grown in Laikipia is rosecoco. This is a determinate type which is short, self-supporting (or bushy) and of short growth duration, and it matures in about three months (Smart, 1969). The rosecoco cultivar is normally intercropped with maize in Laikipia district (Liniger, 1991). Rosecoco bears flowers on short, lax, axillary racemes; the flowers are self-fertilized and develop slender pods which usually carry four to six seeds.

The development pattern of bush types to which rosecoco belongs is predictable (e.g. Todorov, 1977; Norman *et al.*, 1984; Liniger, 1991). Full maturity, that is to dry seed, is reached from between 45 to 150 days after emergence, depending on growth habit, type and location. Most of the bush types are not sensitive to day-length (CIAT, 1978). Growth duration depends primarily on temperature. The relative duration of various development events are fairly constant under a wide range of thermal environments. Since bush types are of short duration they have only four to ten nodes on the main stem at maturity (CIAT, 1978).

Phaseolus vulgaris has very wide geographical distribution. It is grown whenever temperatures between 10 and 35°C prevail. Nearly all bean genotypes are found where temperatures at flowering lie between 17.5 and 25°C (CIAT, 1979). The optimum temperature for flowering is about 21°C which correspond to about 1250 m altitude in the tropics. Yield reductions below or over the optimum are related to plant mortality at high temperatures, reduced photosynthesis and to failure of flowers to produce mature pods. Failure rates are about 50-70% of opened flowers and the proportion increases above 30°/25°C day/night temperatures (Kay, 1979).

Water is a major climatic constraint to yield in the semi-arid areas (including the SAT). Bean-growing areas have an annual rainfall of 500–1500 mm. In East Africa bean production is most successful where rainfall during the growing period is 300–400 mm and seed maturation occurs in dry weather (Kay, 1979). Beans stomates close at moderate leaf water deficit (–0.5 hPa). Stress during flowering, when the crop is most sensitive, reduces yield through increased flower failure and to a lesser extent by reducing the number of seeds per pod (Stocker, 1974; Todorov, 1977). On the other hand heavy rainfall creates micro-climatic conditions conducive to fungal diseases.

Partitioning of bean dry matter during vegetative growth has received little attention. Stofella *et al.* (1979) found that 40% of root dry weight was in the tap root and its branches, 50% in the basal root system and only 10% in adventitious roots.

Beans are nitrogen fixers. Nitrogenase activity is highest at the beginning of seed development and may contribute up to 90 kg nitrogen ha^{-1} during the life of the crop (Norman *et al.* 1984).

Seed yield is closely correlated with number of pods per plant and number of plants surviving to maturity. Varying plant population or intercropping may affect yields, depending on cultivar mortality and sensitivity in pod formation (Chui and Nadar, 1983). Chui and Nadar (1983) found from experiments carried out at the National Dry-land Farming Station at Katumani in Kenya, on Oxic Paleustalf, and at the Iowa State University U.S.A., on a Nicollet sandy clay loam, that intercropping reduced bean yield by an average of 67% due to a decrease in number of pods per plant for the plants of interrow spacing of 60 cm. The decrease in number of pods per plant ranged from 31 to 38% while the decrease in number of seeds per pod ranged from 9 to 20%. On the other hand higher maize grain yields were obtained in intercrops than in sole crops. Willey and Osiru (1972) observed in Uganda that maize/bean intercropping was 38% more productive than a combination of sole crops. The higher productivity of the intercrop was attributed to better utilization of growth resources, particularly light.

2.3 Meteorological and soil factors affecting maize/beans intercrops in the semi-arid areas.

2.3.1 Soil moisture

2.3.1 (a) Volumetric water content (VSMC) and bulk density

The relation of available soil water to plants, climatic conditions and plant development are major factors in water conservation efforts. Plant growth depends on the amount and distribution of water in the soil. Climatic conditions control the rate of growth. Monitoring of water content in order to determine its rate of change in the soil provides very useful information on crop performance and ultimate yields.

The nature of the soils and their water holding capacity give useful information on the distribution of soil water and its availability to plants. Textural composition of soils, water storage capacity and the amount of swelling and shrinking of clay soils could give an indication of the available water to plants (e.g. Liniger, 1991; Ibrahim, 1992).

Table 2 shows the shrinking factors for Matanya soils. Undisturbed ring samples, collected from all horizons (i.e. 15-170) at field capacity and oven dried, were placed on a photocopying machine (Linger, 1991). The photocopies were used to work out the percentage of cracks in different directions through the center of the ring. From this linear form, volumetric shrinkage factors (a) were calculated. Shrinkage factors (b) were obtained from (a) using the assumption that shrinking is proportional to water loss. From Liniger's (1991) data (Table 2) we learn that on drying Matanya soils reduce their volume by 14-20% between field capacity and wilting point in the top 60 cm of the soil profile.

The factors that determine the supply of water to plants are (Mugah, 1983; Nicoullaud *et al*, 1994):

(i) the storage capacity of the soil;

(ii) the soils ability for recharge from the surface water (infiltration rate or capacity);

(iii) its internal drainage, and

(iv) plant root distribution in the soil.

The water available to plants falls between two limits, Field Capacity and Wilting Point. The upper limit, which is the Field Capacity (FC), is defined as the water content at a suction from -0.1 to -0.33 bar. The lower limit, which is the wilting point (WP) is defined as the water held at a suction of -15 bar. The field measured upper limit for water retention of the soil, the real FC is defined as the volumetric water content attained 2-3 days after saturation and after free drainage has practically ceased (Russel, 1980; Ratliff *et al.*, 1983; Gardner, 1988). The field measured lower limit, or permanent WP, is the volumetric water content of the soil at which plants are practically dead or dormant as a result of the soil water content (Russel, 1980; Ratliff *et al.*, 1983; Gardner, 1988; Liniger, 1991). The lower limit could be determined under grass cover where the rooting depth is deep enough to extract water even further than the lowest measured depth of

Tables 1 & 2 (170 cm). The difference between FC and WP is the available water to plants. In order to develop appropriate water conservation measures in the semi-arid areas, soil moisture data down to the lowest rooting depth of annual crops for a period of about 4 years may be used (Liniger, 1991).

Analysis by Kenya Soil Survey of the Matanya Verto-luvic phaeozem soils as given in Table 1 (see Liniger 1991) show that the surface layers contain 40% clay and 3% organic matter fractions. These layers, till a depth of 25 cm, were holding 30% of soil water available for plant use and 14% not available to plants. The 14% occurs partly as constitutionally bound hydrogen atoms in the clay minerals and in organic matter and this part may be referred to as equivalent water (e.g. Greacen, 1981; Ibrahim, 1992).

2.3.1 (b) On neutron probe: Nature of neutron probe

A neutron probe is made up of two main components: the source and the detector. Test neutrons are emitted from the Americium 241/Beryllium-9 source. They pass through the detector without causing a response and fly into test the material (generally soil) bouncing around in the material and gradually slowing down in the process (Greacen, 1981). The detector tube, a boron tri-fluoride (BF3) detector, is responsive to weak, thermal neutrons but is not responsive to high energy fast neutrons. When neutrons bounce around sufficiently to slow down to thermal level they can be detected by the BF3 tube. Neutrons are drastically slowed down if they collide with hydrogen atom which has the same mass as the neutrons and the energy loss is great. In most soils, except soil with organic composition e.g luvisols, the only source of hydrogen is water. Hence the only major moderation of fast neutron is water, reason why neutron probe is used to measure soil moisture.

The neutron probe measures volumetric water content and its spatial and temporal changes. Calibration of a measuring instrument is usually made by obtaining the readings of the instrument for a range of accurate independently determined values of the parameter to measure. The relationship between the readings and the calibration values provides the calibration curve. The calibration curve for the determination of volumetric water content takes the form of Eq. 1:

Table 1. Composition of the Matanya *Verto-luvic phaeozem* soils (After Liniger (1991).

Depth	clay (%)	silt (%)	sand (%)	organic matter (%)
18	40	23	34	3
30	53	19	27	1
60	65	13	22	0
90	56	16	28	0
120	47	22	31	0
150+	47	21	32	0

Table 2. Shrinking factors for Matanya soils (after Liniger, 1991).

Depth (cm)	Shrinking factors (a)		Shrinking factors (b)	
	F.C. till linear	oven dry volumetric	F.C. till linear	wilting point volumetric
18	0.88	0.68	0.93	0.80
30	0.84	0.59	0.93	0.81
60	0.88	0.68	0.95	0.86
90	0.97	0.91	0.99	0.96
120	0.99	0.97	1.00	0.99
150	0.98	0.94	1.00	0.99
170	0.98	0.94	0.99	0.98

(a) measured

$$\theta = b * Cr + a \tag{1}$$

where θ ($cm^3\ cm^{-3}$) is the volumetric water content of free water (water released on drying at 105°C for 12 hours), Cr is the calibration (count) ratio of the count rate in the soil to the count rate in a standard medium, b is a calibration regression coefficient and a is the intercept (Greacen, 1981; Liniger, 1991 and Ibrahim, 1992). The calibration curve depends on Cr but is also affected by soil properties such as dry bulk density of the soil, volumetric content of constitutional hydrogen (expressed as equivalent water), chemical components of the soil and the soil solution.

Ibrahim (1992) found from his work with the Gezira clay (Vertisols) soils that count rates vary diurnally with temperature, attaining maximum values when the temperature is maximum and reaching a minimum at the time of minimum temperature. The neutron meter responds more strongly to the soil properties close to the detector and source. This complicates the calibration process for cracking clays such as the Matanya vertisols. It is difficult to obtain a soil with properties that give a simple calibration curve (e.g. Parkes and Sian, 1979; Greacen, 1981; Ibrahim, 1992).

Matanya soils, as vertisols, have these complications that affect count rates (Liniger, 1991). The calibration curve may be site and horizon specific due to complexity and variability of soil composition. Additional soil parameters e.g. soil depth, soil dry bulk density and texture, constitutional hydrogen and neutron absorbing elements may be corrected for where coefficients may differ with different soils for particular instruments and installation where the latter parameters (constitutional hydrogen and neutron absorbing elements) can be estimated. The differences in slope of the calibration curve may be due to soil composition and dry bulk density (Greacen, 1981). Greacen (1981) contends that by making the calibration in terms of constitutional hydrogen θ_e we may overcome the gross errors caused to the calibration curve by total water content (Eq. 2). That is free plus equivalent water.

$$\theta_t=\theta+\theta_e \tag{2}$$

The depth to start measurements also has to be corrected for during calibration (Greacen, 1981).

The radiative source (Americium-241 and Beryllium-9) used in this type of probe has a half-life of 458 years. Greacen (1981) supplies the following information that is used here. For 1 X 10^6 neutrons s^{-1} coming from beryllium the γ dose rate at a distance of 1 m is 1 $mremh^{-1}$, coming from Americium. The probe radiative source emits 2.5 X 10^3 neutrons s^{-1} mCi^{-1}, which is the emission of neutrons by beryllium (neutrons s^{-1}) when irradiated by 1 mCi (from Americium). The Curie (Ci) is a unit of radio-activity (e.g. Jerrard and McNeill, 1972). The Americium generates γ-rays in its disintegration, that is in the process of producing neutrons from beryllium. The rem is a unit of ionizing radiation such as gamma radiation (e.g. Jerrard and McNeill, 1972). The alpha particles used in the neutron generation process have very low penetrating power and are easily confined within a restricted range by shielding. The γ-rays, on the other hand, are highly penetrating and require heavier shielding for adequate containment. The probe can maintain an effectively constant neutron production rate for many years. The low γ-radiation from americium-241 is advantageous in this respect.

The emission from a spherical volume around the source influences the detector count rates (Van Bavel *et al.*, 1963, Ibrahim, 1992). This so called sphere of **importance**. affects 95% of reflected thermal neutrons. It is defined as the sphere around the source which, if all soil and water outside it is removed, will yield 95% of the expected neutron flux from an infinite similar medium. Hydrogen content of soil is the determining factor of the sphere of importance, which according to Visvalingam and Tandy (1972) and Kristensen (1973) is given by Eq. 3:

$$Q_j = \frac{100}{1.4 + 0.1 * \theta_t} cm \qquad (3)$$

where Q_j is the radius of sphere of importance. The water in the soil closer to the source/detector has greater influence on the count rates than that farther away. We therefore expect distortions of the sphere of importance in heterogeneous soils.

Van Bavel *et al.* (1963) found from the formula that the data taken with a neutron probe at a depth of calibration 20 cm and shallower were erroneous for all water contents below about 35%. Kristensen (1973) showed that lower soil moisture contents of clays ($\theta \leq$ 25% by volume) could accurately be measured from 20 cm downwards. Long and French (1967) showed that accurate measurements from 20 cm depth in clay soils could be obtained at very low water content (θ = 13% by volume). They showed for a probe held in air at 20 cm from a water body that the radius of the sphere of importance attained an infinite value and hence its effect on the counting rate was minimal. The sphere of importance therefore determines the depth at which measurements made could yield data with minimum error. Eq. 3 is generally used to determine:

(i) the permitted minimum access tube spacings;

(ii) the advisable minimum depth intervals;

(iii) the shallowest measuring depth permitted; and

(iv) minimum dimensions needed for the calibration drums to avoid the influence of any air/soil interface, which underestimates to a certain extent the soil moisture content (Ibrahim, 1992).

According to Eq. 3, the radius of the sphere of importance varies according to the seasons. Neutron transport tends to decrease with increasing soil density at the same pore volume. The count rates, and so the ratios, therefore tend to increase with increasing soil density (Ibrahim, 1992). The bulk density affects both the slope of the calibration curve and the intercept. Media with different bulk density distributions would give different calibration curves between bulk densities (Bd's) and the slopes (b's) of their calibration curves. Ibrahim (1992) obtained Eq. 4 for Gezira soils.

$$b=14.43+19.84*Bd, (r=0.97) \qquad (4)$$

where 'b' is the slope of the calibration curve. An increase of 40 percent in the slope of the curve was obtained for an increase of bulk density (Bd) from 1.0 to 1.7 g (cm)$^{-3}$.

2.3.1 (c) Agronomy and soil management with respect to soil moisture

In natural situations plants in a semi-arid environment use water from rainfall, underground lateral recharge from nearby high grounds.

soil moisture reserve and in some cases from capillary rise. Soil moisture intakes by plant roots are among other factors influenced by weather parameters such as radiation and relative humidity. These parameters may influence stomatal behaviour. Wind has an indirect influence on root intakes by carrying away water vapour and other influences (see below). Soil water, nutrient status, textural and structural stratification (based on soil taxonomical composition), salts and water table level etc. strongly influence root development and distribution in the soil (e.g. Mugah, 1983; Nicoullaud *et al.*, 1994). Crop yields have been observed to be directly proportional to the soil water reserve conditions at the beginning of growing seasons (Stewart, 1982a; 1982b). In the semi-arid areas, high wind speeds, low humidities, high radiational loads etc. heavily influence evaporation, thus water intake by plants. Lack of adequate water supply therefore becomes a major constraint to crop production. Water management is therefore crucial to alleviate the effects of recurring droughts which seriously affect crop production in the semi-arid areas.

To be able to take up moisture from the soil the plant roots must exert a higher and more negative suction (matric head) than the force with which the soil holds to the water (Russell, 1961; Da Costa *et al.*, 1986). Soil moisture taken up by roots has to be replenished, otherwise the soil will dry out and stress will be induced causing plants to wilt and die: a regular occurrence in the semi-arid areas.

Generally an increase in wind speed (i.e. a decrease in air diffusion resistance) increases transpiration rates. However, incidentally the leaf temperatures at very high tropical irradiances may decrease so much that transpiration rate decreases with increase in wind speed (e.g. Grace, 1977; 1988). Stomatal closure interferes with the CO_2 flux, soil moisture and soil nutrient intake by plants and hence influences assimilation rates and dry matter production (Grace, 1977; Lomas and Lewin, 1977). Water stress, induced at any phenological phase before senescence, reduces its final yield. The yield reduction depends on the phenological phase at which the stress was induced (e.g. Denmead and Shaw, 1960; Shaw, 1977; Harder *et al.*, 1982). Increase in soil moisture stress in young plants results in increase in yield reduction. Large and well developed plants are not as much affected as the younger ones (Shaw, 1977).

Water shortage constrains plant productivity in the semi-arid areas because of unfavourable temporal distribution of rainfall. Losses due to runoff deprive roots of moisture. Productivity could be analyzed in terms of the supply of water to the plants by expressing dry matter (DM in t/ha) as the amount of transpired water (W in mm) and the amount of dry matter produced per unit of water extracted (q in g/kg), which is strongly dependent on saturation deficit of the air (Sd in kPa) (Squire *et al.*, 1987). This is expressed as Eq. 5

$$DM = \frac{W*(q*Sd)}{Sd} = W*q \qquad (5)$$

where (q*Sd) is a conservative quantity with a characteristic value for each crop species. In optimum weather conditions, which favour good yields, the emergence of the male flowers (tassels) at the top of the maize plant coincides with the'appearance of the silks (female flowers) borne near the middle of the plant. If, however, a shortage of water occurs in the two weeks before and after flowering, there is poor pollination which results in low yields, even if subsequent rains are adequate. During drought, the tassels compete against the silks for available carbohydrates. This means that by the time the silks are ready for pollination, the pollen grains from tassels have come and gone and no fertilization has taken place, hence low crop yields results (e.g. Shaw, 1977; Lomas and Lewin, 1977; Harder *et al.*, 1982). In dryland maize farming this is the principal cause of low yields during a cropping season where showers are separated by long dry spells.

Water stress at a critical phase may result in total crop failure. Inducing water stress at either silking or tasselling could have severe effect on yields. Water stress occurring at any stage of the plant development could have comparatively less effect than that at tasseling-silking stages (Shaw, 1977; Harder *et al.*, 1982). Tasseling and silking stages are also critical for fertilizer application (top dressing) to minimize yield reduction.

Vertical root distribution for maize has been observed to be highest near the soil surface and decreasing exponentially with depth (e.g.Mugah, 1983, Nicoullaud *et al.*, 1994). Mugah (1983) reported high root length density for Katumani maize to occur at 30 cm depth and sharply decreasing beyond 60 cm, with the lower densities at lower depths observed in drier soils. Comparing maize root distributions in four different soils, Nicoullaud *et al.* (1994) observed that the exponential vertical pattern was valid only for vertisols, with the maximum in the 10-30 cm layer. The other three soils (arenosols, luvisols and planosols) presented non-monotonic root distribution. In arenosols the maize roots concentrated entirely in the surface layer.

Dhyani *et al.* (1990) investigated the root distribution of five tree species (i.e. *Bauhinia purpurea. Grewia optiva. Eucalyptus tereticornis. Leucaena leucocephala and Ougenia oojeinensis*). They observed that the bulk of their roots were concentrated in the soil layer 90–120 cm. This would make them good companions with maize which has most roots in the soil layer 0–50 cm (Umaya. 1991). Umaya (1991) working on a well drained, dark, brown, reddish-brown sandy clay luvisol observed that the top 0–10 cm soil layer was occupied by maize roots. There was an overlap in alley cropping of maize and Cassia siamea roots at depths of 20–30 cm and 40–50 cm which led to competition for soil factors and depressed maize yields.

2.3.1 (d) Effect of surface cover and tillage mode with respect to soil moisture

(i) Role of mulches in crop growth

Direct evaporation from the soil constitutes a pathway of water loss which is wasteful, since it does not contribute to crop production. In growing crops, direct evaporation from the exposed soil surface, E, accounts for a substantial part of evapotranspiration, ET. It has been estimated that in a widely spaced row crop such as maize, if the soil is wetted frequently, by rain (or irrigation), E may be as high as 50 % of ET, even when the canopy is fully developed (Tanner et al. 1960). Obviously, reduction of this loss by surface mulch is necessary since this will increase the storage of plant available water in the root zone and cause a greater portion of ET to be used by transpiration. Dry matter production is a linear function of transpiration by the crop. Direct evaporation from the soil induces upward movement of soil water.

This reduces soil water storage and also may deposit salts within the root zone thereby contributing to salinization of the soil.

Mulches applied extraneously at the soil surface reduce evaporation and soil salinization. Mulch is for tropical conditions best broadly defined as any shallow layer that appears at the soil/air interface with properties that differ from the original soil surface layer (e.g. Stigter, 1994a). Soil covers like dead and live mulches (including crop residues or standing stubble) influence the microclimate of a plants' environment. These covers affect the water, nutrient and, indirectly, CO_2 intake by plants (the latter due to differences in stomatal opening because of soil moisture status), especially under semi-arid conditions, and hence their growth and development rates. In dry land farming, where soil water is limiting and its effects dependent on weather, soil fertility, soil physical conditions, type of cultivars as well as population and geometry of planting, application of mulches will influence crop productivity (e.g. Stewart, 1982b; Huxley, *et al.* 1987).

A wide range of organic and inorganic mulches has been studied over the years with respect to their influences on soil moisture conservation, soil fertility improvement, soil temperature fluctuations, etc., that result in increased crop yields (e.g. van Wijk *et al.*, 1959; Davies, 1975; Bohn *et al.*, 1979; Ross *et al.*, 1985a; Stigter, 1987; Bristow, 1988; Budelman, 1988; 1989; Liniger, 1991). Incorporation of mulches (which is another form of mulching) into the soil increases their soil fertility improvement effects, by faster decomposition, but appreciably reduces their evaporation reduction and temperature effects unless the top layer remains dry (e.g. Mungai, 1991).

Generally, mulches may provide a range of benefits to semi-arid cropping systems such as:

(i) maintenance and conservation of soil moisture to reduce water stress in crops. Some mulches reduce runoff. Mulches can alter the root moisture budget of the plant;

(ii) maintenance or reduction of the soil bulk density, that is, improvement of soil structure. Mulches therefore enhance infiltration and storage capacity, as it acts as a sponge, and changes the pattern of leaching and erosion;

(iii) maintenance and improvement of soil nutrient contents (chemical properties) of the soil. Mulches provide a suitable environment for microbial decomposition;

(iv) moderation of soil temperature by reducing extreme temperature fluctuations, that is, reducing the amplitude of the daily temperature wave and lowering or raising the average original soil temperature, depending on the energy balance. Mulches for example help alter the heat budget of the plant root zone to exclude heat stress;

(v) related reduction of radiation, heat and moisture exchanges between the original surface and the sky and atmosphere through shading, reduced conduction, convection and turbulence. Here mulches help to keep the soil either cool or warm depending on the amount and type of mulches applied and the prevailing microclimatic conditions again depending on the energy balance;

(vi) protecting the soil from mechanical impacts of rain, hail and wind; and

(vii) control of weed growth (by shading and mechanical suppression).

We notice here that the cardinal benefits of surface mulching in semi-arid areas are conservation of soil water (reduction of evaporation and runoff) and lowering of average soil temperatures. These aspects are particularly important in the early stages of crop growth when drought may cause death of the seedlings, excessive high temperatures may cause low emergence rates, stunted shoot and insufficient root development (Harrison-Murray and Lal, 1979; Abrecht and Bristow, 1990). The main effect of mulch incorporation is increased soil fertility (e.g. Mungai, 1991).

On the other hand mulches have been reported to encourage attacks by certain pests and diseases. Pests such as birds, rodents, termites and nematodes have been known to live and hide in the trash and eat away the crop, thus reducing the crop yield in mulched fields (e.g. Davies, 1975, Budelman, 1988; 1989).

Abrecht and Bristow (1990) observed, on clay loam (Oxic Paleustaff) at Katherine Research station in Australia, that plant residue mulch increased shoot growth rate before and after emergence of maize seedlings. The surface mulch also increased the length of the first internode, thereby partitioning the apical meristem of the plant at a shallower depth in the mulched soil.

(ii) Influence of mulching on soil moisture

By restraining water loss through evaporation, surface mulches (such as crop residues) improve water use efficiency (WUE) (i.e. weight of economic yields per unit of water applied). These mulches may reduce evaporation from the original soil surface by shading, by increasing the reflectance of the soil surface and by reducing the speed of the wind so the convectional exchange at the soil surface (insulation effect). Some surface mulches are very effective in restraining runoff, thereby reducing erosion, increasing infiltration and conserving soil moisture. The decomposition rates of surface mulches determine the effect they have on mitigating soil temperatures and conserving soil moisture as well as their effect (be it somewhat limited) on soil fertility (Budelman, 1989). Slowly decaying mulches have either low or high initial impact on modifying soil temperature and conserving soil moisture, but their effects last longer. Rapidly decaying mulches may have high or low initial impact but their effects are shorter in time (e.g. Othieno *et al.*, 1985; Stigter and Darnhofer, 1989; Budelman, 1989). If not renewed, slowly decaying mulches may be more beneficial for soil fertility increase. Vertical distribution of soil moisture within the soil could be influenced by different mulches, mulching rates, soil type, rainfall distribution and other climatic parameters (Papendick *et al.*, 1973).

Budelman (1988; 1989) observed that the leaf mulch of *Flemingia macrophylla* applied at 5 t/ha dry matter (DM) restrained soil moisture loss, moderated soil temperature in the first 5 cm and retarded weed growth more than either *Leucaena leucocephalla* or *Gliricidia sepium* applied at the same rate. The slowly decomposing mulches had longer lasting effect in conserving soil moisture, resulting in the highest yields (Budelman, 1988; 1989). The slow decomposing mulches allow enough time to retain soil moisture during dry periods unlike the fast decomposing ones which break down rapidly and have to be reapplied. To prevent soil erosion in young tea at Kericho, it was found that low initial impact, low decay rate grass mulch was ideal as there was too much reduction of soil temperature by the high impact grass mulches which affected tea root growth in these highlands (Othieno *et al*., 1985).

Wilhelm et al. (1986) observed, on no-till soil, a linear response between maize grain/stover yields and amount of maize (*Zea mays L.*) residue applied on the surface. The results showed that each $Mgha^{-1}$ (tonne/ha) of residue removed resulted in about 0.10 $Mgha^{-1}$ reduction in grain yield and about 0.30 $Mgha^{-1}$ reduction in residue yield. The amount of water stored in the soil was closely associated with the quantity of residue applied the previous year. The soil temperature at 5 cm depth and total available water accounted for nearly the same amount of variation in yield as the quantity of residue. This was a very interesting observation. These factors should therefore be considered when evaluating response of crops to residue-management practices.

In related experiments on maize (*Zea mays* L.), soybeans (*Glycine max* L.) and sorghum (*sorghum bicolor L.*), Doran et al. (1984) observed that complete removal of residue harvested resulted in average grain and biomass yields of maize (*Zea mays* L.) and soybeans (*Glycine max* L.) falling by 22 and 24% respectively below the plots where residues were not removed. As long as there was a residue mulch cover of 50 % or more of the original cover, the yields were not affected. Sorghum (*sorghum bicolor L.*) yields were not at all affected by residue management manipulation. Yield reductions for maize and soybean resulted primarily from decreased soil water storage and excessive surface soil temperatures where residues were completely removed. Sorghum displays a tolerance to water deficit and high temperatures that maize can hardly withstand (e.g. Konate. 1984: Norman et al. 1984). Sorghum is therefore suited to be grown in semi-arid areas. like Laikipia district.

(iii) Effect of mulching and tillage on soil physical characteristics

Skidmore *et al.* (1986) have demonstrated that management of sorghum (*Sorghum bicolor* L.) and winter wheat (*Triticum aestivum* L.) residues. to influence soil physical properties by residue burning. residue baling and hauling. incorporation of once and twice the amounts produced from the plots. reduced erosion and increased yields but had no effect on the soil under the wheat crop. However. the effects of these managements differed between crops. The methods of residue management to improve the soils had been more effective under sorghum than under winter wheat. The soil aggregates under sorghum were smaller. more fragile. less dense. less stable when dry and more stable when wet than the soil under winter wheat. The size distribution of the Ap horizon (ploughed surface soil) under sorghum plots was more conducive to infiltration than under the winter wheat.

In addition to soil moisture conservation and soil temperature moderation some mulches influence soil rigidity. prevent massive cracking (especially in vertisols) and induce friability (Quashu and Evans. 1967; Liniger. 1991). Less compaction has been observed towards the end of a crop growing season under a special slow decomposing mulch than under bare soil (Liptay and Tiessen. 1970). Soil compaction influences root growth and crop yields (Gerald *et al.*, 1982. Harrison. 1987). A combination of mulching and minimum tillage. however. changes the structure of the soil through lowering the bulk density and prevention of crusting in clayey soils.

Papendick *et al.* (1973) observed that applying mulches just before the main rains resulted in higher maize yields since mulches provided maximum soil protection against erosion, compaction and soil water loss through evaporation. Mulches applied at the onset of the rains delays development of strong surface seals by limiting rain impact on the soil (e.g. Papendick *et al.*, 1973, Bristow and Abrecht, 1989; Abrecht and Bristow, 1990).

Under semi-arid conditions soil moisture could also be conserved through deep tillage. The deep tillage breaks the capillary connection to the surface and acts as a mulch in conserving soil water in lower layers (Wilken, 1972; Papendick *et al.*, 1973; Unger, 1987; Freebairn, 1992). Deep tillage conserves water under dry land conditions by providing maximum resistance to vapour and liquid water flow and also maximum thermal insulation.

Deep tillage is very energy intensive and exposes the bulk of the top soil (surface layer clods) to atmospheric evaporative forces (Tyler and Overton, 1982). In so doing the exposed surface clods dry out while the non-tilled layer remains relatively moist because of the clods mulch (e.g Wilken, 1972; Papendick *et al.*, 1973; Nicoullaud *et al.*, 1994). Deep tillage therefore provides maximum soil moisture conservation in the non-tilled layer. The amount of water lost as a result of tillage depends on the soil's moisture content, the amount of soil disturbance (depth of tillage) and atmospheric conditions.

On the other hand, no-tillage (variously known as zero-tillage, slot plant, direct drilling or chemical tillage-tilling land whose vegetation cover has been killed chemically by spraying) conserves more soil water in the whole soil profile up to the surface. It could therefore conserve more water in semi-arid areas than tillage methods (deep and minimum tillage). At the latest meeting of the Commission for Agricultural Meteorology (Havana, Cuba), the Commission encouraged its members to continue to provide agro-meteorological input to the development of multiple cropping systems. The Commission further supported the development of the systems which conserved soil moisture and the adoption of zero-tillage procedures (WMO, 1995). This method allows live vegetation, stubble and crop residue to remain intact and act as mulches. The live vegetation, nevertheless, has to be maintained at low height to minimize competition for light and solar radiation (Finch, 1988) as well as water and nutrients. Clean weeded plots remain worse at conserving soil moisture as opposed to mulched plots (Liniger, 1991).

Preliminary results at Matanya showed that both maize stalk and leaf residue mulch could restrain rainfall runoff to nil, although a low density of mulch (which covered only 60% of surface) was applied, even though the former are light and are easily blow away by strong winds or get readily eaten by termites. Infiltration rates were increased which enhanced soil water recharge resulting in higher yields of maize/beans intercrops. The previous season crop residues provided the basic mulching materials in addition to fallen leaves and decomposed branches from *Grevillea robusta* trees (Liniger, 1991).

2.3.2 Strong winds

2.3.2 (a) Overview

Unplanned and uncontrolled land-use in the semi-arid areas e.g. overstocking, overgrazing and over-cultivation of farms interferes with soil physical and chemical properties (e.g. Russell, 1961). These operations lay bare the top soil which then gets exposed to strong winds and strong radiational heating and volatilization of inorganic chemicals in the soil. Such soils are exposed to erosive winds which then reduce the survival, growth, yield and quality of agricultural crops.

Natural vegetation of Laikipia district is very sparse and consists of scattered thorny trees, shrubs and grasses (e.g. Jatzold and Schmidt, 1983). **Exploitation of these semi-arid areas by immigrant** small-scale farmers for crop and livestock production and habitation, after the exit of the white highland settlers, the original ranch owners, necessitated growing of trees (together with annual crops) and live-fences to:

(i) indicate farm boundaries:

(ii) exclude intruders:

(iii) provide fuelwood:

(iv) provide building posts;

(v) provide fodder:

(vi) provide food (fruits): and

(vi) provide protection from strong winds, irradiation and rainfall (e.g. Flury, 1986; Liniger, 1991; Moges, 1991).

These trees and live-fences, therefore, conserve soils by restraining erosive winds as well as consequences from erratic torrential rains. They also conserve soil moisture in the upper horizons by reducing wind speeds, advective heat and direct solar heating by shading of soil and crop (e.g. Harrison, 1987; Stigter, 1988; Otengi, 1994). The strong winds are troublesome since they shuffle (or redistribute) applied mulches, making it impossible to retain mulch cover on the soil surface for a reasonably long time for effective soil moisture conservation (Liniger, 1991).

Hazards caused by strong winds to agricultural operations in Laikipia district could be ranked second only to that caused by high rainfall variability (Berger, 1989). Strong winds come as a result of:

(i) relatively strong seasonal winds blowing from a particular direction, say, S.E. (see Fig. A7);

(ii) vortices of discrete rotational winds e.g. gusts, dust-devils, etc.

These two systems of air movement contribute to primary and secondary damages of soil and plants. Most important is the occurrence of strong winds in relation to the growing periods.

In Laikipia district, including Matanya, the highest wind speeds normally occur towards the end of the long rains growing season, June-September and may start earlier than usual in some years, resulting in desiccating effects on crops at earlier growth stages. The high speeds are due to the S.E. trade winds which occur from June to September, that get channelled (or funnelled) between the Aberdares Mts. and Mt. Kenya (e.g. Griffiths, 1972; WMO, 1981; Berger, 1989; Liniger, 1991). These channelled winds affect Matanya as they blow from between south east and south west directions during this period. These winds interact with the mountain-valley circulation between the two mountain systems to produce diurnally varying winds of considerable strength and persistence (and sometimes varying direction) (MacHattie and Schnelle, 1974).

2.3.2 (b) Role of winds in soil degradation

Wind is a great destroyer of the top soil as well as an agent of deposition and soil formation. It sorts the soil by removing the finer and lighter constituents, leaving behind the coarser and denser ones. These are transported according to their sizes from the smallest to the largest. This size selective process is the main similarity between wind and water erosion because water erosion also takes place in a size-selective manner (e.g. WMO. 1983; WMO. 1989; McTaish *et al.*, 1992). This sorting mechanism has transformed some fertile soils into sandy wastelands. In removing, the wind carries and scatters the top soil hundreds of kilometers. In depositing, it forms various forms of aeolian materials representing extensive areas of loess soils. In mixing, it carries the soil across the land, creating surprising uniformity of minerals in the soils (WMO. 1983. 1985 & 1989 and Zhou. *et al.*, 1992).

Soil erosion is due to the interplay of three main factors: the slope and structure of the soil; the erosive power of wind and rain; and (intervening between the previous two) the amount of protective vegetation cover (Harrison. 1987). Particularly loose. dry and finely granulated soil is vulnerable to wind erosion. Soil surfaces that are smooth, with sparse or no vegetation cover over a sufficiently large area highly susceptible to wind erosion (e.g. Harrison. 1987; Lyles. 1988).

Loss of top soil through wind erosion reduces its nutritive value and affects its hydraulic properties (e.g. soil texture and structure and hence its water holding capacity). When wind blows off the top soil surface, it augments loss of soil moisture by evaporation from the soil surface. Low proportions of clay and organic matter give rise to great vulnerability to wind's sifting. Even wind speeds of 2–4 m/s are capable of taking away particles and fine dust (loam and clays) on which the soil structure depends resulting in textural impoverishment. The erosive winds physically remove from the field the most fertile portion of the bare, loose and finely granulated soil (Lyles, 1988). Complete loss of the upper horizons (that contain organic matter) exposes lower horizons to runoff, thus substituting wind erosion by water erosion.

Quantitative evaluation of monthly wind erosion could be estimated from the index of Chepil and Woodruff (1963) given in Eq. 6 below

$$C=\frac{U^3}{2.9*(PE)^2} \qquad (6)$$

where C is the wind aggressivity or erosivity,

PE = (P–ETP) for P>ETP is the efficiency of precipitation (or minimal remaining soil moisture without runoff correction).

P is monthly precipitation (mm),

ETP is the monthly potential evaporation (mm),

U is monthly average wind speed in m/s,

The wind aggressivity, C, is inversely proportional to the minimal remaining soil moisture, PE for P > ETP. The erodibility is at its maximum in dry soils, which may be taken as those containing less than a third of the wilting point soil moisture (Chepil and Woodruff, 1963). It drops off with increasing moisture content to the wilting point. Beyond that it remains unchanged.

Wind erosion may be controlled by reducing forces at the soil surface or by creating surface conditions more resistant to wind forces.

Wind erosion could be controlled:

(i) by reducing field widths (by strip cropping, by establishing barriers, by establishing and maintaining vegetation or vegetative residues, stubble residues, etc.) to protect the soil;

(ii) by producing or bringing to the surface stable aggregates or clods large enough to resist the wind force; and

(iii) by roughening the soil surface to reduce wind velocity and trapping drifting soil (e.g. Tibke, 1988; Chepil and Woodruff, 1963).

This reduces soil 'avalanching', which is the soil flown with the distance downwind. The AF methods of wind protection and soil management control include single and multiple shelterbelts, windbreaks, as well as scattered trees, sometimes combined with crop strips on the upstream (Tibke, 1988). Wind erosion control is necessary in areas with low and variable rainfall, high winds, high temperatures, high evaporation and hence frequent droughts. Paez and Rodriguez (1992) compared conservation requirements for small-scale farms with efficiency of land-use, including management systems and conservation practices. They found that the best conservation alternative for cropping systems was minimum tillage with contour planting and support of vegetative barriers. The effect of minimum tillage alone as a protective measure against strong winds is debatable as it is against the general rule mentioned above, unless clod structure remains.

2.3.2 (c) The effect of wind on plants (crops and trees)

In the semi-arid areas strong and gusty winds may cause primary damages such as deformation or blow down of trees and lodging of field crops. Wind also controls the direction of fires (in forest and grassland areas), pollen, seeds, spores and insects (MacHattie and Schnelle, 1974). Fires, pests (mainly insects) and diseases may therefore cause secondary plant and tree injuries caused by winds.

The primary effects result in direct mechanical damages to plants and trees. Such damages may affect whole plants and/or parts of plants and trees. Those that affect whole plants include: swaying, shaking, uprooting, bending and lodging. Those that affect plant and tree parts include: premature shedding of fruits, flowers and pollen, branch and petiole breakages, bruises, lesions and abrasions due to mechanical stress caused by asymmetrical air pressure acting on plants (e.g. Grace, 1977; 1988; Stigter, 1985b; Stigter, 1988; Sturrock, 1988; Kainkwa, 1991; Kainkwa and Stigter, 1994).

Damages due to secondary effects include: rubbing of leaves by soil or other leaves, or scouring by carried particles (i.e. objects and particles carried by wind causing) damage to plants, as in saltation and creep transport of soil particles by wind (e.g. Harrison, 1987; Grace, 1977; 1985; 1988; Kainkwa, 1991). There are other secondary injury effects of wind such as stress in plant-water relations, for instance by evaporation stress and/or soil moisture depletion, and stresses in mineral nutrition due to blown off top soil, in metabolism due to external effects and in photosynthesis when carbon dioxide is limiting due to external effects (e.g. Grace, 1977; Oke, 1987). Others include cold air drainage or hot air stresses resulting in very low or very high temperatures respectively.

For instance, valley and mountain winds descending from high altitudes into an enclosed valley where both horizontal and vertical mixing are poor and hence resulting in very low temperatures at night and frost damage (e.g. Hesketh, 1972; MacHattie and Schnelle, 1974; Oke, 1987).

Strong winds deplete leaf and soil moisture, thus causing moisture stress to plants and reduced plant growth and development. Strong hot wind decreases leaf and field boundary layers resulting in temperature gradients where the leaves have only slightly lower temperatures than the hot air, or sometimes even higher, due to closed stomates, when the increase in the energy flow towards the leaves including radiation is much more than that used for evaporation.

Wind collects and carries such agents of plant damage as salt, pathogens and insects. Desert locust (*Schistocerca gregaria Forsk* in the family of *Cyrtacanthacris*) and army worm damages are regular, particularly in the ASAL areas of East Africa, where they are blown in from breeding places in the Sahelian region (Symmons, 1989). These pests may wipe out large areas of planted land within hours.

A knowledge of the ventilation of leaves at different canopy levels is essential in the calculation of photosynthesis and exchange processes in individual leaves. Declining photosynthetic and translocational activities are due to reduced carbon dioxide availability to leaves damaged by wind, resulting in retarded dry matter accumulation and reduced yield (e.g. Allen *et al.*, 1976; Grace, 1977). **Light winds cause high carbon dioxide concentration available for photosynthesis in plants.**

2.3.2 (d) The role of windbreaks in protection against winds

Agroforestry trees, live-fence shrubs and tall grasses in a semi-arid environment protect soil and crops against erosive winds, by breaking the force of wind, and act against strong advective heat (e.g. Hesketh, 1972; McNaughton, 1988). A live-fence planted around AF plots protects the crops depending on the height and porosity of the fence, the strength of the approaching winds, and the angle of approach of the wind to the side facing it (e.g.Van Eimern *et al.*, 1964; Grace, 1977; Finch, 1988). The effect of the live-fence is greatest when the windward side meets the approaching wind perpendicularly. The protected zone dwindles when the angle of incidence decreases (e.g. Van Eimern *et al.*, 1964; Grace, 1977). Even if the wind approaches a barrier at right angles, it will "cut-in" around the edges, thus reducing the area effectively protected. The sheltered region (or quiet zone) may extend to about 10 X H (i.e. H = shelter height) behind a long windbreak in near-neutral conditions with the wind perpendicular to the barrier (e.g. Grace, 1977; Heisler and Dewalle, 1988; McNaughton, 1988; Stigter *et al.*, 1989; Onyewotu *et al.*, 1994).

The protected zone associated with wind breaks is directly proportional to the height of the windbreak. The number of windbreaks that is required to provide protection for a given field is directly related to the average of the tallest trees or shrubs in the windbreak. Generally, the tallest and best-adapted species for a given site should be selected to minimize the number of the windbreaks required. The windbreak height should be at best two to three times the height of the crop to extend the protected or the quiet zone (e.g. Van Eimern *et al.*, 1964; Finch, 1988). The protected zone is smaller in unstable conditions.

It is necessary to design, for semi-arid areas, windbreaks of several tree and shrub species with different shapes to include tree species that improve the soil, such as *Acacia spp. Prosopis cineraria*, *Azadirachta indica* (e.g. Connor, 1983; Rachie, 1983; Burley, 1985; Young, 1989).

Live-fences (hedges) of various densities differ in the degree of turbulence (and kind of eddies) they create in the flow on the leeward (cropland). The eddies increase with the density of the barriers. Windbreaks present an obstacle to the wind that deflects it upwards and compresses the streamlines of the flow over the top. This increases wind speeds over the top and eddies on the leeward side behind the quiet zone (e.g. Finch, 1988; McNaughton, 1988).

The protective (or shelter) effect, E, also known as effectiveness index (e.g. Konstantinov, 1966; Heisler and Dewalle, 1988) of a live-fence windbreak can be estimated from Eq. 7, with u(x) and u(r) as wind speeds at any point in the protected zone and in the open respectively (e.g. Van Eimern *et al.* 1964; Kainkwa, 1991; Kainkwa and Stigter, 1994)

$$E=1-u(x)/u(r)=1-R \tag{7}$$

The last term in Eq. 7 is the relative mean wind speed, R = u(x)/u(r), variously called wind ratio or horizontal average wind speed ratio or wind speed deficit or wind speed reduction ratio (Chepil and Woodruff, 1963; Van Eimern *et. al.*, 1964; Chepil, 1965; Kainkwa, 1991).

In natural environments airflow is hardly constant and hardly unidirectional. Temporal wind variability could be estimated from standard deviation (sd) or coefficients of variation (cv) to bring out the anomalies in the wind protection brought about as a result of its structure in the open. Kainkwa (1991) worked out the anomalies in wind reduction ratio using normalized standard deviation (Rsd) (or normalized coefficients of variation (Rcv)) as expressed in Eqs. 8 and 9.

$$Rsd=\frac{sd(x)-sd(r)}{R} \qquad (8)$$

or

$$Rcv=\frac{cv(x)-cv(r)}{R} \qquad (9)$$

where sd(x) and sd(r), and cv(x) and cv(r) respectively are standard deviations and coefficients of variation at the distances x and r. R is the wind reduction ratio already defined. The important aerodynamic features of flow around obstacles include: inclination of flow, rolls and separation of flow and formation of roll eddies upstream and downstream of barriers (e.g.Gloyne, 1955; WMO. 1981; Oke, 1987). Gloyne (1955) observed what are now commonly known as the wind structures related to obstacles, that is:

(i) the area of increased turbulence behind a shelterbelt moves closer to the belt the denser it is (e.g. Van Eimern et al., 1964; 1968; McNaughton, 1988);

(ii) behind dense shelterbelts the vertical distribution of wind speed up to the belt height (H) above the ground varies much more than behind porous belts. In the much smaller quiet zone the wind speeds vary much more with height but in the turbulent "wake zone" much less;

(iii) the wind speed on the leeward of the hedge facing the wind is largely affected by the porosity of the hedge to airflow (e.g. Heisler and Dewalle, 1988); and

(iv) the range of wind reduction increases with increasing surface roughness and increasing air stability.

Farms fenced with rectangular hedges are more protected against strong multidirectional winds (Van Eimern *et al.*, 1964; Rocheleau *et al.* 1988; Kainkwa, 1991). Much of the early knowledge on properties of wind structure with respect to shelterbelts and windbreaks was summarized by Van Eimern *et al.* (1964). The reduced wind speed on the cropland (as a result of hedges with sufficient density) decreases evapotranspiration (both potential and actual) depending on the radiation energy received by the leaves (e.g. Grace, 1985; 1988).

Grace (1988) contends that high cold and humid winds blowing over brightly irradiated leaves may even cause a decline in transpiration rates and hence in evaporation. He further states that differences between leaf and air temperatures may decrease which would cause reduction in the difference between mesophyll saturated and air vapour pressures (the driving gradient). Thus an increase in wind speed has two effects: the decline of aerodynamic resistance which tends to increase transpiration); and, the decline in driving gradient (which tends to decrease transpiration). However, increased turbulence behind too dense hedges causes increased evapotranspiration in the "wake" zone beyond about 10 X H.

Because turbulent eddies may form in an air stream when rather dense barriers are encountered, benefit to easily bruised crops (such as citrus fruits, bananas etc.) expected from the reduction in wind speeds caused by such barriers can be cancelled out by the damage caused by eddies beyond the quiet area (e.g. Acland, 1971; McNaughton, 1988;

Rocheleau et al., 1988).

The most tangible shelter benefit is to enhance crop yield by the shelter around the cropland, reducing (all the) negative effects (e.g. Acland, 1971; Davis and Norman, 1988; Grace, 1988). Shelter confers some physiological advantages on plants because sheltered plants may yield more than non-sheltered plants under similar non-limiting soil moisture conditions. It was observed in Uganda that planting bananas in blocks surrounded by a hedge of another banana variety, called *kisubi*, provided protection against strong winds (Acland, 1971).

Barriers may be classified into

(i) open barriers (density, d < 40%),

(ii) medium dense barriers (40% < d < 80%),

(iii) dense barriers (d > 80%) (Oke, 1987).

Average medium dense barriers (density of about 60%) are long known to give the best results against physical damage (e.g. Van Eimern et al., 1964). It allows air to filter through, thus avoiding complete stagnation and producing a minimum speed equal to on average of about 20% of its speed in the open (Gloyne, 1955; Oke, 1987). For fighting heat advection a denser barrier should be selected. In summary: a rectangular barrier (or hedge) enclosing a crop and AF trees affects:

(i) air and soil temperatures;

(ii) balance and exchange of heat by forced and free convection and by radiation;

(iii) evaporation before crop emergence, so moisture content of the air;

(iv) water loss from both soil and plants (through evapotranspiration after crop emergence);

(v) erosion transport and deposition of small particles generally soil. insects. spores. bacteria and pollution (e.g. WMO. 1985: Finch. 1988: Heisler and Dewalle. 1988: Tibke. 1988: Kainkwa. 1991).

Factors influencing selection of trees and shrub species for windbreak plantings include: species adaptability: soils: climate: hardiness: wind firmness: required density: required height: possible crown spread: competitiveness: compatibility with adjacent crops and pest problems (e.g. Cunningham. 1988).

Factors influencing wind reduction by protective hedges include:

(i) porosity.

(ii) shape and width of the hedge.

(iii) roughness of the ground.

(iv) thermal stratification of the air. and

(v) height above the ground (e.g Nagaeli. 1953: Gloyne. 1955: Lawrence. 1955: Van Eimern *et al.*, 1964: Kainkwa. 1991).

The ground roughness in a large area in front of the hedge to a great extent determines the vertical increase in wind speed near the ground. Large gaps and small gaps in live-fences can act as nozzles when their sizes are about the height of the hedge. At the channels provided by these gaps. the wind speeds can even be higher than that in the open (Naegeli. 1953: Van Eimern *et al.* 1964). Naegeli (1953) found an increase in wind speeds in the channel of up to 120% over that in the open beginning at 5 X H on the wind ward side and continued to be noticed on the leeward side at 14 to 18 X H in the relatively large sluices (regulatory gaps).

2.3.3 Solar radiation

2.3.3 (a) Overview

Interactions between the tree component (a relative stable component, although winds have a large influence) and solar geometry produce the solar climate of a tree/crop system. These interactions and their effects include:

(i) interception of radiation by the tree stands of various densities (stem densities, branch densities and leaf area indices and angle classes);

(ii) tree age;

(iii) canopy structures;

(iv) rows and alley-ways orientation and tree spacing;

(v) latitude and time of day and year (i.e. solar altitude and azimuth);

(vi) spectral quality of sunlight under partial shade (e.g Jackson, 1983; 1989b; Jackson and Palmer, 1989; Reifsnyder, 1989; Oteng'i, 1994; Oteng'i et al., 1995).

The tree canopies shade soil and crops, reduce evaporation from crops and soil, and lower soil and air temperatures. Depending on crop and tree components, the economic yields are influenced by radiation response of different crop species, types of yields (e.g. biomass or seeds), and the tree-crop compatibility (Hazra, 1985). The effect of shade could be divided into aspects of protection (positive interaction) and of competition (negative interaction) (Stigter, 1994).

Shading as management and manipulation of solar radiation has a wide range of diverse intentional effects (e.g. Stigter, 1984a; 1984b). These include decreasing evaporation as well as matching growth and available nutrients, preventing serious water and nutrient stresses, decreasing plant, animal or soil temperatures in day-time and increasing these temperatures at night, protecting crops against rain, hail and wind impacts, decreasing airflow, influencing water vapour-, heat- and CO_2-transport from or to the surface and reducing weed growth and preventing sunscorch. Some of these effects may be unintentional consequences of management and manipulation options, such as changes of temperature and humidity away from optimums or towards conditions that increase vulnerability for diseases.

The traditionally used shading materials can be classified into two broad categories: (i) natural and (ii) artificial shades (e.g. Stigter, 1984a; 1984b). Artificial shading materials can further be classified into organic and inorganic shades. Natural shading materials used traditionally in Tanzania and many other African countries (e.g. Acland, 1971; Stigter, 1984a; 1984b) include: trees, high crops (intercropping and multi-storey gardens), shrubs or plants, creeping plants, leaves and standing stubble. Artificial shading materials include materials collected by a farmer and spread over part or all of the soil surface. These include: stems, branches and twigs, large leaves, grasses, left overs from weeding, pruning or harvesting, saw dust and wood shavings, decomposed materials and manure from dung. Roofing provided by large broad leaves stuck in the ground and bent over seedlings and roofs raised on poles, a framework or cage covered with cloth, lattice, grass branches are also used to shade crops. The roof-type shades are more advantageous in cases where drying is important than mulch-type shades because they allow for free flow of air passing the crops while the latter creates a layer in which air is largely stagnant or moves slowly by convection.

In microclimate management and manipulation of shade the interest is the modification of the energy balance at the soil suraface, a crop canopy, a nursery surface or individual plant organs like leaves, stems, flowers or fruits (Stigter, 1984b). Solar radiation is the driving force of the energy balance. Shading implies reflection and absorption of excess solar radiation, transmitting only the requirements of soil, seedling, plant or crop. This transmitted radiation is used for photosynthesis, heating and evaporation (including drying).

These properties of shade in a tree/crop system have a wide range of AF application and can be exploited for beneficial use by man in AF systems to protect crops from extremes of radiational load (Acland, 1971), improve water use efficiency and exclude weeds from the tree/crop intercrop (e.g. Jama *et al*., 1991; Budelman, 1988).

In East Africa, Jama *et al*. (1991) obtained up to 90% reduction in weed biomass under *Leucaena leucocephala* alley cropping in alleys of width 2, 4 and 8 m in Mtwapa, Kenya. This resulted in an increase of 24 to 76% in maize yields in the alleys compared to crop-only, non-agroforestry (NAF) controls. The 2 m alleys had the highest weed reduction, as it closed its canopy earliest thereby limiting light interception by the weed component.

It was also found out in East Africa that in the absence of nitrogenous fertilizers, shade increased tea yields by cutting-out some PAR to match the limited nutrient supply. This was reversed at heavy fertilizer supply of 135 kg/ha rates as shade reduced the yield by 10-25% (Acland, 1971). This resulted in Kenya into excluding shade from tea completely for quality tea which depends on fertilizer supply. However, more recent interpretations of older data revealed that mild shading would be beneficial also to fertilized tea due to a compensatory assimilation mechanism from which the tea leaves to be harvested benefit

(Othieno and Stigter, personal comm.). Banana plants and scattered forest trees have been used to protect coffee in most parts of Tanzania and Uganda (Acland, 1971). However, it was found that bananas somewhat reduced coffee yields because of a negative interaction with coffee which resulted from reduced photosynthetically active radiation (PAR). The reduction in PAR resulted in reduced production of flower buds.

In West Africa, Lawson and Kang (1990) using maize and cowpea grown in alleys of *Leucaena leucocephala, Gliricidia sepium, Alchornea cordifolia* and *Acioa barteu* on an eroded Egbeda soil series (*Oxic paleustaff*) observed decreased yields of maize and cowpea per ha, grown in sequential cropping, when the total dry matter of pruning from shrubs increased under decreasing hedgerow separation. [Palaniappan (1985) defines "sequential cropping" as "The growing of two or more crops in a sequence on the same field in a farming year, in which the succeeding crop is planted after the preceding one has been harvested"]. The shading from *Leucaena spp.* was more pronounced. *Acioa spp.*, the least prolific, had the highest maize yield. This clearly demonstrated the extent of interference between pairs of components in this system with respect to light interception. In order to modify radiation microclimate Lawson and Kang (1990) suggested that the between hedgerows space in *Leucaena spp.* be increased to reduce the effect of shading and the resultant depressing effect on yields through reduction of crop/ tree interface per cropped area.

In India, Hazra (1985) working on red loamy sand (*alfisols*) at the research farm of the Indian Grassland and Fodder Research Institute using four forage winter crops: barley (*Hordeum vulgares L.*), oats (*Avena sativa L.*), Chinese cabbage (*Brassica campestris L.*) and safflower (*Carthamus tinctorius L.*) in association with individual agroforestry tree species components of *Albizzia lebek. Acacia tortilis* and *Leucaena leucocephala* found highest total biomass yields (relative to yields in open) in the four crops in *Albizzia spp.* and lowest in *Leucaena spp.* The forage yields (average of all crops) matched the amount of radiation intercepted by the understorey crop. The yields from the seeds were highest in *Leucaena spp.* suggesting more dry matter partitioning into the seeds at low radiation levels.

2.3.3 (b) Dry matter production and solar radiation

When water is not limiting. the total dry matter produced by vegetation is linearly related to intercepted solar radiation. in the photosynthetically active (PAR) range (0.4-0.7 μm). and the duration of its growth in accordance with Eq. 10 (Allen *et al*.. 1976: Ong. 1989).

$$DM=S*f*e*\sum dt \qquad (10)$$

where DM is the total dry matter produced by the vegetation (t/ha):

S is the total radiation (mean of daily totals) (MJ/m^2):

f is the fraction of mean daily insolation intercepted by the canopy:

e is the amount of dry matter formed per unit of radiation intercepted (conversion coefficient) (g/MJ):

Σdt is the duration of crop growth in days:

The value of S varies from 12 to 30 MJ/m^2 in the tropics. The leaf area of the vegetation determines f at any time and f can be related to the leaf area index by an extinction coefficient that depends only on the orientation and distribution of foliage.

More temporal sharing of light has been reported in intercropping systems when each component makes its demand at different times of the growing period to improve light interception (Stigter and Baldy, 1994). As an example, it was shown that at ICRISAT each component of a groundnut/pigeonpea intercrop, where the intercrop plant density was the sum of the sole crop densities, intercepted 15% more PAR than did sole-cropped pigeonpea because the rapidly growing groundnut canopy intercepted a maximum of the mean daily PAR in 45 to 50 days (e.g. Willey *et al.*, 1986; Ong, 1989). The slower-growing pigeonpea took 90 to 100 days to intercept its maximum.

Biomass production in some intercropping systems also increases due to improvement of the amount of dry matter formed per unit of PAR intercepted, by a spatial sharing of solar radiation (e.g. Willey *et al.*, 1986; Ong, 1989). A combination of one row of millet and three rows of groundnut resulted in a 28% increase in biomass, largely due to a 27% improvement in the dry matter formed per unit of PAR intercepted. As a management measure it was recommended to manipulate the microclimate by allowing the tree canopy to intercept radiation during the early part of the growing season when the water supply is favorable but the crop is too open to intercept more than small energy. Once the crop canopy becomes nearly closed, the trees should be pruned. This pruning of the trees is done so that a fast growing crop like millet can intercept most of the solar radiation during the rainy season. The tree is then allowed to regrow after removal of millet during the dry season.

In the dry matter production model of Allen *et al.* (1976) (Eq. 10), solar radiation is the only environmental factor. If the proportion of PAR intercepted and the flux density of PAR on the crop are monitored over the period of crop growth and the dry matter measured at harvest, the conversion efficiency of each crop could be determined. The remainder of experimental treatments and field management could then be interpreted in terms of their effect on e and f.

This analytical approach could help to determine production in natural ecosystems and agricultural crops using solar radiation data alone. The interpretation comes from increased early interception of PAR, increased canopy duration and longer periods of photosynthesis and/or increased efficiency of conversion of PAR to dry matter. These obvious interpretations also exist in evaluation of dry matter production by intercrops in agroforestry systems (e.g. Jackson, 1989b; Oke, 1987).

2.3.3 (c) Interception of photosynthetically active radiation (PAR) by trees and crops

PAR is transmitted through leaves and between leaves, thus resulting in sun-fleck and shadow patches. PAR is therefore relatively less in the periphery of the sun-fleck and in the shade that fall on the understorey crop. This mode of transmission changes the spectral composition rapidly with depth in the canopy (Szeicz, 1974a; Delta-T Devices Ltd., 1988). Its spectral quality is modified, although very minimally in the sun-fleck areas. Radiation in the shade areas is strongly depleted of photosynthetically active component (PAR). On the average for the sun-fleck and shade areas the PAR content of the total solar radiation rapidly diminishes with depth (Szeicz et al., 1964). The trees which form the taller component (or the upper storey) with higher canopies in an agroforestry system reduce the PAR in the total solar radiation that falls on the lower canopy crop component (e.g. Szeicz, 1974b, Monteith and Unsworth, 1990).

Mathematical solar radiation interception models for trees and crops have been developed by many workers over the years (e.g. Szeicz *et al.*, 1964; Szeicz, 1974a; 1974b; Monteith, 1977; Jackson, 1983; 1989b; Jackson and Palmer, 1989; Monteith and Unsworth, 1990; Ong, 1989).

Transmitted and modified light through a crop volume of one unit of leaf area thick and depletion through layers of such units is given by Beer's law (Monsi and Saeki, 1953) as in Eq. 11:

$$\frac{I}{I_o}=\exp(-k'L) \qquad (11)$$

where I_o is the radiation arriving at the top of the canopy and I total irradiance at the depth considered, with L accumulated leaf area index (LAI) above that level. L is measured LAI downwards from the top of the canopy. For a small incremental leaf area 'dL' is used. If $k'=A_h/A$ is the shadow cast by a unit area of leaf (i.e. A is area of a horizontal leaf assumed to be perpendicular to the sun rays and A_h area of shadow), the product $(A_h/A)*dL$ is the shadow area index, which is the area of horizontal shadow per unit ground area. The parameter k' is known as extinction coefficient which depends on the leaf angle distribution of the canopy elements and the zenith angle of the sun (e.g. Szeicz, 1974b, Monteith and Unsworth, 1990). This model is based on Beer's exponential law of diminishing light as it passes through the atmosphere.

The fraction of radiation transmitted by unit leaf area without interception is called sunfleck parameter, S, and the secondary transmission through leaves is called leaf transmission, τ. Using these parameters the equation then becomes

$$\frac{I}{I_0} = (1-(1-\tau)(1-S))^L \tag{12}$$

Eqs. 11 and 12 use different assumptions with respect to the leaf overlap. Hence, k' and S are not simply related. However, for small L, say L=1, $k' = (1-\tau)(1-S)$ for large S or τ. For large L, say $L > 2$, and S and τ small, k' and S very much differ (e.g. Szeicz, 1974b; Monteith and Unsworth, 1990).

Jackson (1983; 1989b) and Jackson and Palmer (1989) have developed light interception models, based on Beer's exponential law, that could be used in AF systems with any level of complexity, in shade responses of different crops, growing seasons and cropping patterns, to guide the direct planting of AF trees and experimentation with planting systems in AF systems.

Allen *et al*. (1976), Jackson (1983; 1989b); Jackson and Palmer (1989) and Ong (1989) discuss the models developed, taking into account complexities belonging to the agroforestry systems as far as light interception is concerned. In crop and yield improvement studies in agroforestry systems, examination was necessary of two versions of these models:

(i) based on Beer's Law (e.g. Jackson, 1983; 1989b and Jackson and Palmer, 1989); and

(ii) multiplicative models (e.g. Allen *et al.*, 1976; Ong, 1989).

Light interception in discontinuous multistorey canopies, say crop and tree canopies, in agroforestry (AF) systems could be divided into (i) the fraction of light that misses the tree canopies completely but gets intercepted by the crop canopy, and (ii) the fraction that passes through the tree canopy to reach the undercrop, as given in Eq. 13 (e.g. Jackson, 1983; 1989b; Jackson and Palmer, 1989),

$$\Psi=\Psi_f+\Psi_c=\Psi_f+(1-\Psi_f)\exp-kL' \qquad (13)$$

where Ψ = total penetration of light to the undercrop;

Ψ_f = light which misses the trees completely to reach the undercrop;

Ψ_c = light which passes through the tree canopy;

$L' = L/(1-\Psi_f)$, the tree leaf area per unit of ground which it potentially shades, that is, the unit area enclosed by the outline of the projected cast shadows of trees in the direct light;

k = extinction coefficient.

Eq. 13 could be reduced to give the fraction (F) intercepted by the tree canopies alone as $F=F_{max}-F_{max}e^{-kL'}$.

Spectral quality of the transmitted PAR changes when radiation passes through layers of leaves due to differential reflection and absorption by leaves. These changes affect plant photomorphogenic processes (e.g. Allen *et al.*, 1976; Monteith, 1977).

2.3.3 (d) Radiation interception by individual tall trees

The shadows of a system of tall trees intercropped with shorter crops in an agroforestry system sweep daily across the field, depending on the sun's zenith angle. Of the 12 hrs of daylight in Matanya for example, we estimated the *Grevillea robusta* crown shadows to sit on the AF plot for more than 50% of the time, taking into account the plot orientation and the spacing between trees. At low sun (or larger zenith angles) the shading from trees increases. The shadows extend in area as they become elongated. The shading effect of tree shadows also vary with the sun's seasonal declination (e.g. Monteith and Unsworth, 1990; Jackson and Palmer, 1989). The amount of direct solar radiation intercepted by trees, that is, when they are not shading each other, could be evaluated as suggested by Monteith and Unsworth (1990).

Management and manipulation methods that minimize competition for light between crops and trees so that they put more effort into producing seeds, fruits and biomass (leaves, stems, branches and roots) are the most ideal. That way more plants will reach their full yield capacity to increase productivity in an agroforestry system.

Crops normally avoid shades by elongating their stems. In doing so they utilize energy which would otherwise have gone to production of the economically important parts of the plant. The shade avoidance response is actually a response to the presence of far red light of which wavelengths are too long to be visible to the human eyes. When plants grow closely together, this far red light is mostly reflected by them. Receptors in the plants which receive reflected far red light trigger the production of phytochrome B which stimulates the plants to grow upwards (Smith, 1995). In cultivated crops competition simply leads to unproductive growth as the plants try to out-do each other (e.g. Pearcy *et al.*, 1981; Pearcy, 1989; Tieszen, 1983). However, under natural conditions this competition is advantageous to the tall plants (Smith, 1995).

2.3.4 Soil temperature

2.3.4 (a) Overview

The rate of absorption of heat resulting from the solar radiation load to the soil surface and its transport to deeper layers vary for different soils (under identical weather conditions) depending on their composition (i.e. air, water, solid matter and albedo). The geometry of the surface cover indeed also affects the rate of heat absorption and this includes the method of tillage.

Tillage results in soil lumps (clods) of different sizes covering deeper continuous soil layers. Tillage alters the thermal properties of the soil by increasing the air content of the upper layer, which generally decreases thermal conductivity ,λ, more than thermal capacity, C, and therefore thermal diffusivity, λ/C. The soil surface broken by tillage also acts as mulch on the underlying non-tilled continuous layer and diminishes communication of this layer with what happens above it (see section 2.3.1c). The clods act as a better insulating layer than the originally undisturbed soil surface layer by reducing the amount of heat that enters the underlying soil layers. The damping depth (D) is related to the thermal constants of the soil, λ and C, via Eq. 14 (ω will be explained later):

$$D=[2\lambda/C\omega]^{1/2} \tag{14}$$

It follows from the above that tilled soil gets a smaller, D, which is the depth at which the amplitude of the diurnal temperature wave reduces to e^{-1} of its values at the surface, than the underlying more compact soil (van Wijk, 1965). We will mathematically deal with that below.

The rate of heat transfer shows up in the change of the temperature amplitudes with depth. In dry soils D is strongly dependent on the (low) moisture content (eg. Othieno et al., 1985; Van Wijk, 1965). Hence, from the dynamics of soil temperature alone one is able to establish the thermal and soil moisture conditions of various soils, including the influence of mulches.

2.3.4 (b) Diurnal variations of soil temperature

The diurnal variation of soil temperature is greatest on clear days when neither solar radiation nor terrestrial long wave radiation is intercepted by clouds. On such days the variation is essentially sinusoidal in character, and even more so in the tropics with near 12 hour periods of day and night time. For that case the soil temperature, T (z,t), at soil depth, z, and at any time , t, is given by Eq. 15:

$$T(z,t) = \bar{T} + A_o \exp(-z/D)\sin(\omega t+\phi_o-z/D) \qquad (15)$$

where $\bar{T}$ is the 24-hr average soil temperature for the day in question. This $\bar{T}$ for a certain day, week or month is approximately the same at all depths shallower than 30 cm, the depth at which the soil temperature amplitudes start to be less easily discernible. A_o is the diurnal amplitude of the temperature wave at the soil surface. It is half the full range of diurnal temperature variation. Because D is proportional to the square root of the thermal diffusivity, $a = \lambda/C$ (see Eq. 14), the damping depth can be used to calculate thermal diffusivity. In Eq. 15, ω is the circle (or radial) frequency which is 2π times the reciprocal of the diurnal period; thus $\omega = 2\pi/24 = 0.261904$ hr^{-1} = 7.27513 s^{-1}. $\phi_o = \omega t_o$ is a phase constant determined by the time scale used (e.g. van Wijk *et al*., 1959; van Wijk, 1965; Stigter *et al*., 1984a; 1984b).

The term $A = A_o\exp[-z/D]$ in Eq. 15 means that the amplitude of the temperature wave decreases exponentially with depth. When the depth z equals D, the amplitude has reduced to $1/e = 1/2.78 = 0.36$ of its value at the surface, A_o. Thermal capacity depends on soil composition (i.e. water, air and soil solids (texture and structure)). C may be decomposed into its constitutional form as in Eq. 16 below.

$$C = C_s X_s + C_w X_w + C_a X_a \qquad (16)$$

where suffixes s, w and a stand for solid, water and air.

2.3.4 (c) Effects of homogeneity of the soil on D-values

Homogeneity of the soil may be demonstrated by determining damping depth values at various z values shallower than the 30 cm reference depth. Mwampaja (1983) used soil temperature data for Kericho (Kenya) to demonstrate that the damping depths obtained from two methods discussed by van Wijk (1965), that is, one based on the amplitude term (A_o $\exp(-z/D)$ and the other on the time of maximum or minimum temperature in the trigonometric term ($\sin(\omega t+\phi-z/D)$) were close to each other in that soil, proving this way that the soil concerned was homogeneous.

In principle, vegetation shade may be estimated by comparing soil temperatures near the surface (e.g. Mwampaja, 1983; Mungai, 1991; Onyewotu *et al.*, 1994). Mwampaja (1983) found that 60% tea canopy cover provided supplementary shade but did not act as supplementary mulch. Mungai (1991) observed that Cassia hedge shade could be monitored through soil temperature data taken at 7.5 cm depth. Vandenbeldt and Williams (1992) demonstrated that shade induced reduction of soil surface temperature (at 2 cm depth), particularly at the time of millet crop establishment, contributed to the better growth under the *Faidherbia albida* AF trees. The authors proposed greater use of shade in the semi-arid areas of Niger to reduce soil temperatures to the benefit of the crops. Onyewotu *et al.* (1994) showed that an increase of dry soil temperature with distance to a *Eucalyptus camaldulensis* shelterbelt was in the first 12 m immediately related to the diminishing shading.

Mechanistic models of heat and water transfer at hourly intervals in a soil/unchopped mulch system, to simulate soil temperatures and water content changes in coupled heat and mass transfer, and of radiative and convective exchanges in the mulch layer, have recently been developed (Bussiere and Cellier, 1994). These authors validated the model with soil temperature measurements taken at two depth (i.e. 2 cm and 20 cm) in mulched and bare soils. They found that the mulch induced lower daily temperature amplitudes and decreased average temperatures by 6° C at 2 cm and 2° C at 20 cm depths. This thermal effect of the mulch was estimated using Stigter's ratio $R_{sti}=D_{bs}/D_{mi}$ and Eqs. 14 & 15. where D_{bs} and D_{mi} are respectively the differences between the (for example monthly mean) daily temperatures at any time and depths and actual averages at the same time and depths of the bare and mulched soils (Stigter *et al*., 1984 a, b; Othieno *et al*., 1985). They obtained large R_{sti} for thinner grass mulches and small R_{sti} for very dry conditions.

Eq. 14 and 16 suggest that soil traction, that is, working the soil by hoeing or ploughing, could reduce D. Extremely high rainfall influences soil compaction at the surface and erosion of the top soil, thereby increasing D. Eq. 14 and 16 also show that increase in water content of the soil, which reduces its air content, increases C. However, λ, will increase even more and therefore D will increase.

2.3.4 (d) Surface cover effects on soil temperature parameters

Changes of conditions at the soil surface or of the soil's physical properties influence soil microclimate. Soil microclimate is therefore also influenced by irrigation or sprinkling, drainage, shading, soil tillage and windscreen (windbreaks and shelterbelts) (van Wijk, 1965). It is an interesting question whether all these manipulations may be seen as a form of mulching and may in one way or another also be represented by changes in the diurnal temperature behaviour.

2.3.4 (e) Mulching effects on soil temperature

Mulch reduces the range of diurnal soil temperature variations by reducing the temperature maxima and increasing temperature minima. If the reflection of the soil is lower when the surface is covered by plants than in the case of bare soil, this results in increased absorbed radiation. The albedo of a fully covered green surface is approximately equal to 25%. A dry sandy light coloured soil may therefore have a larger albedo. The mulch becomes the effective surface at which the radiant energy is absorbed (van Wijk, 1965; Stigter *et al.*, 1984a; 1984b).

In the soil covered by a uniform mulch layer of the same albedo, which in principle only applies to a layer of another homogeneous soil or other comparable material, we could use the theory of heat conduction in an infinite homogeneous medium since it's thermal properties are assumed to be approximately constant with depth (e.g. Duin, 1956; van Wijk, 1965; van Wijk *et al.*, 1959). If A be the amplitude of the soil temperature at the surface of an unmulched homogeneous soil possessing the same thermal conductivity, λ, and thermal capacity, C, as the soil under the mulch, the ratio of the amplitude of the mulched soil to that of the unmulched soil would be presented in Eq. 17 or its modified form

$$\frac{A_m}{A_u}=[\frac{[r^2\exp(-2d/D_1)+2r\exp(-2d/D_1)}{[r^2\exp(-4d/D_1)-2r\exp(-2d/D_1)} \tag{17}$$

$$\frac{+\exp(-2d/D_1)]\,[\lambda_2 C_2]}{+\cos(2d/D_1+1)]\,[\lambda_1 C_1]}]^{1/2}$$

$$\frac{A_m}{A_u}=[\frac{\lambda_1 C_1\exp(4d/D_1)+2r[\exp(2d/D_1)]\cos(2d/D_1)+r^2}{\lambda_2 C_2\exp(4d/D_1)-2r[\exp(2d/D_1)\cos(2d/D_1)+r^2}]^{1/2} \tag{18}$$

$$r=\frac{(\lambda_1 C_1)^{1/2}-(\lambda_2 C_2)^{1/2}}{(\lambda_1 C_1)^{1/2}+(\lambda_2 C_2)^{1/2}} \tag{19}$$

in Eq. 18 (van Wijk *et al.*, 1959): here (λ_1 & λ_2) are the thermal conductivities of the mulch layer and the soil respectively. C_1 and C_2 are their respective volumetric heat capacities. D_1 is the damping depth of the mulch layer. The parameter r is defined by the expression in Eq. 19.

The weakness of the above approach is that it cannot be used in practice but in a few rather particular cases. The albedo of mulches is normally different from that of the soil and homogeneous mulches are exceptional. Therefore the approach with an apparent radiation change, where the energy absorbed under the mulch is dealt with as if only the albedo changes is much stronger (Stigter et al., 1984).

Soil temperatures and water losses under chemically killed vegetative mulch canopies in no-tillage crop production have been examined using a numerical dynamic model of soil, canopy and lower atmosphere coupling, including liquid and vapor movement in the soil, and free and forced convection in the canopy (Ross *et al*., 1985a; 1985b). For example, mulch canopies that intercepted 80 and 50% of incoming radiation could keep the soil temperatures within 10 and 20° C respectively of ambient temperaturesin a situation where the bare soil temperatures could rise to 30° C above ambient. The model also found that a moderate wind could reduce soil temperatures under mulch only a few degrees but cooled the canopy much more. Roughening surface could help cool the surface.

On the mulched soil, mulch acts as a shade as well as an insulating layer, both reducing the amount of heat that enters the soil. A lesser fraction of incident radiant energy is converted into heat at the surface if the reflection coefficient of the mulch exceeds that of the unmulched soil. However, in partly transparent mulches the heat from net transmitted radiation is spatially very differently converted into heat. The emission coefficient for terrestrial long wave radiation is assumed to be practically the same for the soil and for the mulch layer. Evaporation is reduced by dry mulch, because of less heat being available. Hence, a smaller fraction of the total heat generated at the surface is used as latent heat of vaporization (van Wijk *et al*., 1959, Stigter *et al*., 1984a).

Stigter *et al*.(1984a; 194b) derived a relationship known as Stigter's ratio, R_{sti}, for two homogeneous soils with identical thermal properties but different (apparent) albedos where the heat reaching the soil is considered as diminished by albedo changes only, with average temperature, $T(z,t) = \bar{T}$. (D_{ba} and D_{ml} were abbreviations used in sections 2.3.4 (c) for a comparison of a bare soil and a mulched soil).

$$R_{st1}=\frac{1-\rho_1}{1-\rho_2}=\frac{T_1(z,t)-\overline{T_1}}{T_2(z,t)-\overline{T_2}}=D_{bs}/D_{ml} \qquad (20)$$

Eq. 20 is valid for harmonic variations. At the soil surface this relation applies also to the amplitudes (A_{o1}, A_{o2}) of the surface temperature waves at two sites, one of which for example being completely bare. Eq. 21 therefore becomes

$$R_{st1}=\frac{A_{o1}}{A_{o2}} \qquad (21)$$

This ratio of the amplitude of the soil temperatures in the homogeneously mulched to that of the unmulched soils was earlier used by Duin (1956), van Wijk *et al.* (1959) and van Wijk (1965) in the mulch more limited approach as given in Eqs. 17 & 18, to quantify the effect of a homogeneous non-transparent mulch on the soil temperatures, where the heat flux entering the unmulched and mulched soils is uniform and the heat exchange takes place identically. This ratio is similar to the one later derived by Stigter *et al.* (1984a; 1984b) in Eq. 20 for two homogeneous soils with identical thermal properties but different albedos. However, that methodology was subsequently extended, by the use of apparent albedos, to all mulches for which the heat entering the original but now covered soil surface could be expressed as due to an apparent change in albedo alone. These ratios (Eq. 20 and Eq. 21) were used by Othieno *et al.* (1985) to demonstrate thermal efficiency of different grass mulches that were used for erosion prevention in young tea.

At the CSIRO Davies Laboratories in Australia, Bristow (1988) observed that mulch architecture (horizontal and vertical- chemically killed) influenced soil temperatures only after the soils under different mulching architecture had dried significantly after a heavy storm (or irrigation). The soil temperatures under both systems of mulches differed markedly with the soil temperatures in the bare soil. This was attributed to the slow effect of mulch architecture on energy balance (that is differences in spatial heat exchange) which became apparent only after significant drying had taken place, which was after 12 days. This sort of change could not influence seed germination, which takes about 7 days to occur.

It has been observed that rainy periods may even result in negative daily heat fluxes near the surface while positive fluxes occur during intervening dry spells (Krishnan and Kushwaha, 1972).

CHAPTER THREE

3 Materials and Methods

3.1 Crop

3.1.1 Materials

3.1.1 (a) Matanya experimental site

On-station experiments were carried out at Matanya LRP station situated 25 km southwest of Nanyuki town, on the slopes of Mt. Kenya. The station is located on latitude 0° 04'S and longitude 36° 57'E at an altitude of 1840 m a.s.l. (see Figs. 1 and 2). The land at the station has a slope of 4-5%.

Although the bulk of the work was started in the long rains (March-June) of 1992 (LR92), when the actual experimental layouts to measure various parameters were set in place, in order to familiarize ourselves with the existing problems, we did some preliminary field work in the short rains of 1991 (SR91).

We put all plots in same treatment by deep-tilling and mulched all the plots at 3 t/ha crop residue (Plate 1). The experimental plots had been used by LRP, the host institution, ever since the station was started in 1986. Placing all plots under the same treatment (i.e. deep-tilled and mulched with 3 t/ha crop residue), for the SR91, was meant to do away with differences that might arise as a result of usage of past years and to lessen compaction. Results of SR91 were therefore meant to show the effect on crop growth and development as well as on biomass and grain yields of the crop component in the agroforestry system under mulching and deep tillage which was the same for all plots. The *Grevillea robusta* root pruning exercise had to continue for the assessment of competition for soil moisture between the intercrop and AF trees and live-fence. The plots hitherto used and their layout are presented in Figs. 7. 9 and 10 (for agroforestry plots) and Fig. 8 for the entire Matanya station. They are:

(i) mulched control (replicated three times) (M1. M2 & M3).

(ii) Local control (replicated three times) (L1. L2 & L3).

(iii) agroforestry (AF) plots (root-pruning and unpruned replicated once for each).

Note that some plots which were still used by the LRP during our experimental periods are marked 'NU' in Figs. 8 and 12 meaning 'not used by us'. Farm-yard manure was not applied in SR91 because the same had been applied LR91 at 10 t/ha and was considered adequate even for SR91.

3.1.1 (b) Experimental layout in agroforestry (AF)

For LR92 and later seasons. the part of AF with Grevillea robusta trees. which measured 25 m by 30 m. was divided into four strips (AFM1. AFM2. AFL1 and AFL2) each of 30 m by 5 m parallel to the shortest side of the entire AF plot. which measured 55 m by 30 m. The strips run roughly east-west. The four strips are shown in the layout (Figs. 9 & 11 and Plate 2). Two plots (AFM1 & AFM2): one in the pruned (AFM1) and another in the unpruned (AFM2) portions of the AF plot. were treated to 3 t/ha mulch plus minimum tillage. AFM1 and AFM2 were minimum tilled by tilling a depth of 4 to 5 cm and then mulched with 3 t/ha crop residue from the previous season. Two other plots (AFL1 & AFL2): again one in the pruned (AFL1) another in the unpruned (AFL2) portions of the AF. were treated to deep tillage but without mulch. AFL1 and AFL2 were deep tilled by tilling a depth of 20 to 25 cm. All of the plots at the station were treated with a low rate of farm-yard manure at 5 t/ha each season. except SR91. Root-pruning was done by digging a trench of 30 cm


LEGEND
◎ grevillea robusta - unprunned
○ grevillea robusta - prunned
X fruit trees
● access tubes

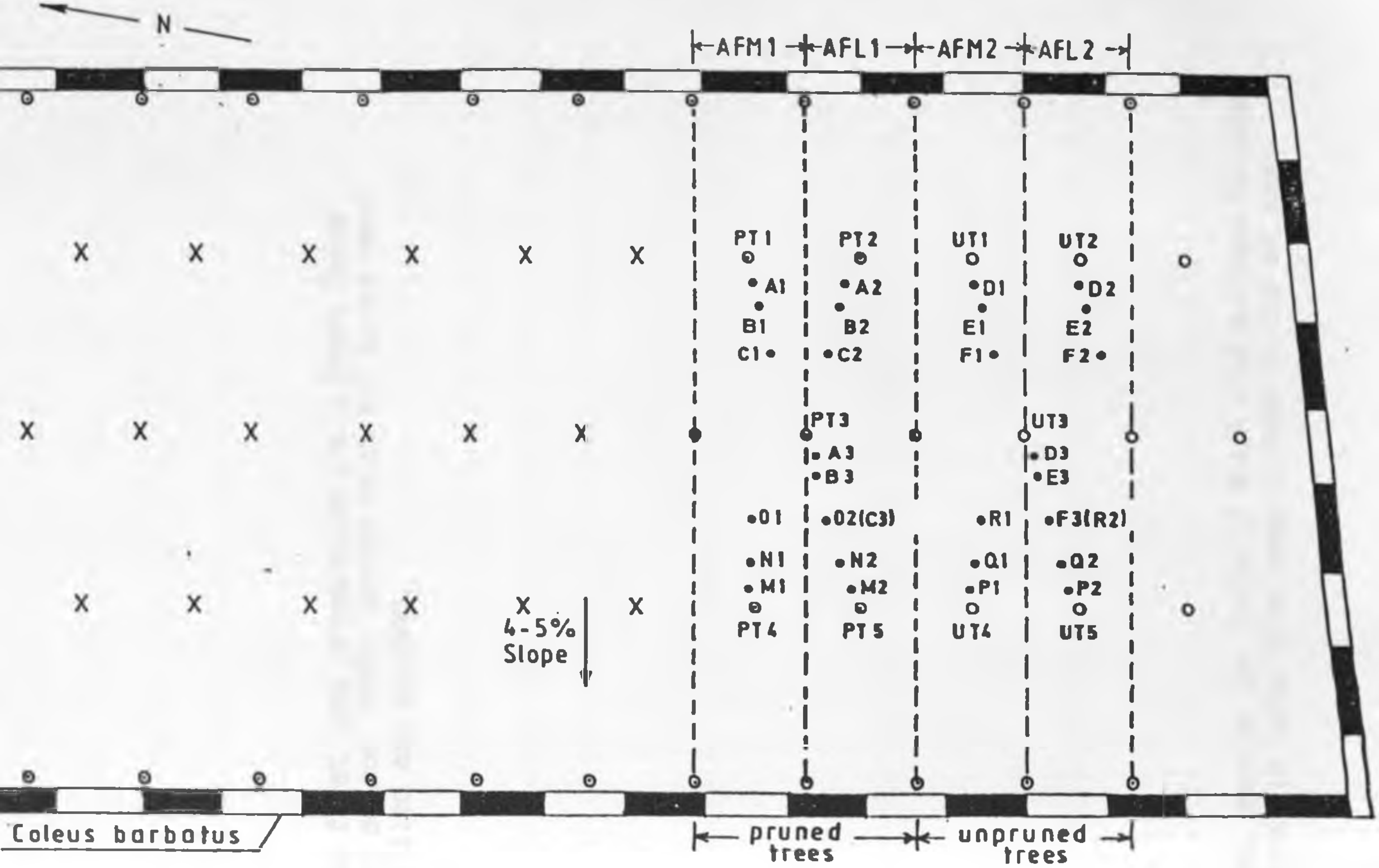


Fig. 7. A layout of access tubes installed at 94, 188 and 376 cm from Grevillea robosta trees in agroforestry plots at Matanya.

Plate 1. The first land preparation for a Short Rains growing season (SR91) during which all plots were deep tilled and mulched.

Plate 2. LR92 showing two plots of Mulch plus minimum tillage and plots of Local plus deep tillage in the AF plot.

deep and 20 cm wide, starting at a distance 50 cm around Grevillea trees stem (Fig. A1).

3.1.1 (c) Experimental layout in non-agroforestry (NAF)

During LR92 we opened up new control plots (i.e. Local control marked L4 and L5 and Mulched control marked M4 and M5 in Fig. 8 & 13) in addition to those given in (i) and (ii) of section 3.1.i above, because we had found that the old control plots (marked L1, L2, L3 & M1, M2, M3) were not uniformly exposed to the prevailing strong winds, which is a great menace in the area between June and September. This was meant to try to homogenize control plots, given their historical background. Each of these new plots measured 12 m by 3 m on a fallow area of 25 m by 13.5 m, with a footpath of 0.3 m between them. The design of the new NAF plots was such that mulch plus minimum tillage and unmulched plus deep tillage were replicated twice in diagonally opposite plots (Plate 3 and Fig. 8). A one metre wide buffer area planted with a row of maize, was created around these plots. For practical reasons the averages of all Local control plots (L1, ... L5) and Mulched control plots (M1, ... M5) will hereafter be referred to Local (L) and Mulched (M) respectively.

Although all plots at Matanya had been put under the same treatment for SR91 as explained above, contrary to the AF plots, that previously had identical treatments, pruning apart, for LR92 and later seasons the control (local: L1, L2 & L3 and Mulched: M1, M2 & M3) reverted to the same treatments as previously used by LRP. This was meant to avoid heterogeneities that would result from changing treatments. It should therefore be noted that in the AF/NAF comparisons during our experimental period, yield comparisons were made between AF

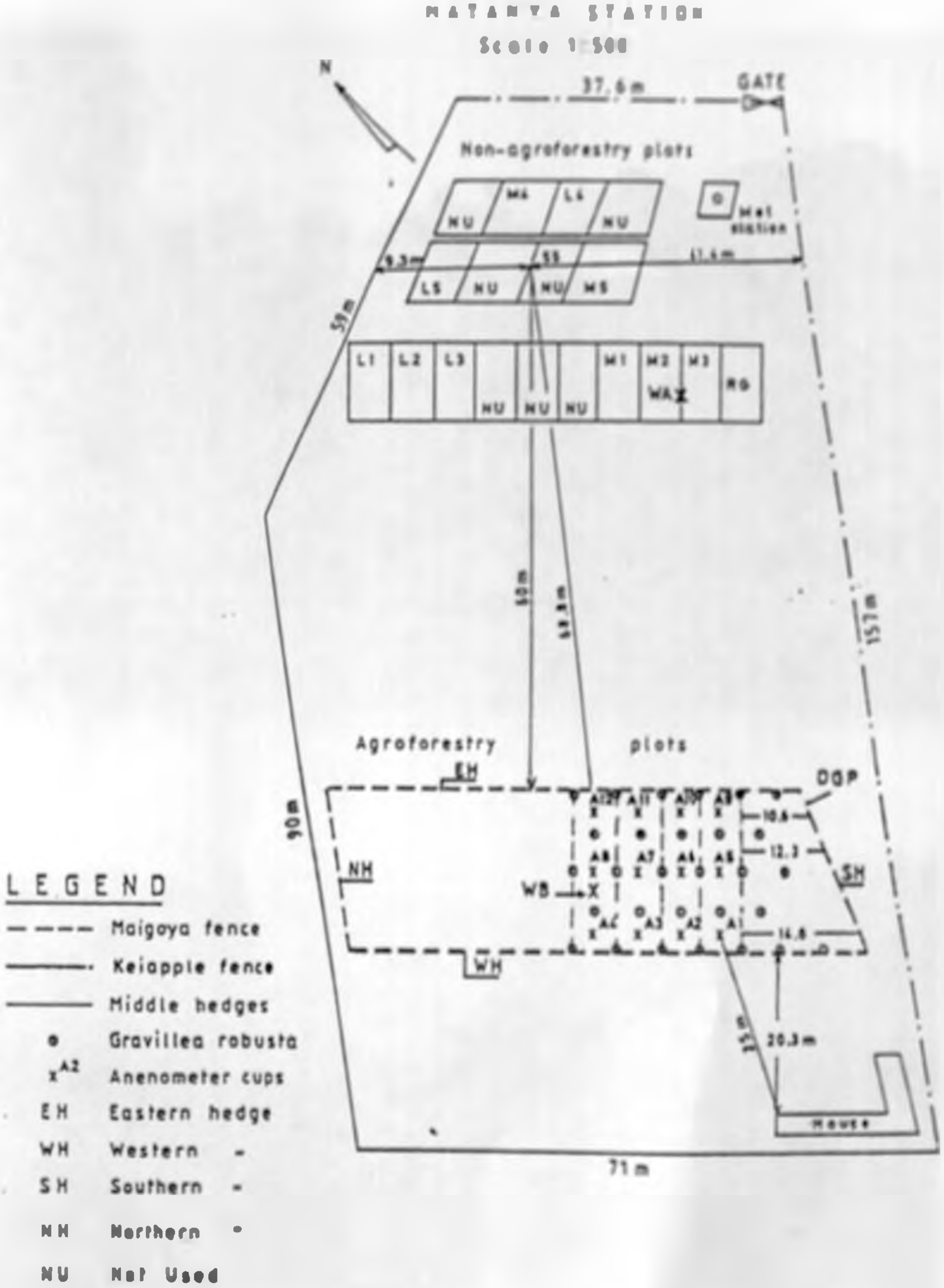


Fig. 8. Entire Matanya experimental station showing agroforestry (AF) and non- agroforestry (NAF) plots and wind measuring systems (electrical cup anemometers positions -A1, A2, ..., A12) & control electrical cup anemometer (cup 55) and Woelfle anemographs (WA in NAF and WB in AF).

Plate 3. LR92 showing diagonally opposite Mulch and Local treatments in the new control plot site. Mulched plots were minimum tilled and Local plots were deep tilled.

Plate 4. Author explaining to assistant the method of harvesting of beans on 5th Jan., 1992.

plots that previously only had pruning as difference in treatment but from LR92 onwards got our treatments. (including again pruning/ not pruning), and NAF plots that received these treatments already prior to SR91.

3.1.1 (d) Crop varieties, spacings and direction of sowing

The sowing of the maize H511 and rosecoco beans was done in the entire field along the contours and made an angle of 20° with the north and south, that is, 340° from true north (see dotted lines in Figs. 10 and 15. The spacings were: maize in 94 cm by 60 cm and beans in 94 cm by 20 cm, all with two seeds per hole.

Twenty plants in each of the plots, that is what would the following year become Local (L) control and Mulched control (M) plots and agroforestry plot (AF) were observed for phenological phases every week.

3.1.1 (e) Measurement of maize heights and grain and biomass yields of maize.

The following data were measured on weekly basis: maize plant heights and phenological phases of both maize and beans for all six seasons: Short rains of 1991 (SR91), Long rains of 1992 (LR92), Short rains of 1992 (SR92), Long rains of 1993 (LR93), Short rains of 1993 (SR93), Long rains of 1994 (LR94) and Short rains of 1994 (SR94).

Fig. 9 displays 31 maize rows numbered from 1 to 28 and TR1-TR3 and five *Grevillea robusta* tree rows (A, B(TR1), C(TR2), D(TR3), E). Three of the tree rows (B(TR1), C(TR2) & D(TR3)) are in the middle of AF plot and two (i.e. A & E) along the eastern and western sides of the live-fence. The interspaces between tree rows are given in Table 9 as A-B, B-C, C-D and D-E. There are 7 rows of maize and 7 rows of beans in each space between two rows. Fig. 9 also has two rectangles, PQRS, covering maize rows 8-12 and beans rows 9-13, on the upper (eastern) and P'Q'R'S' covering maize rows 17-21 and beans rows 20-24, on the lower (western) parts of AF. These rectangles enclose the areas where we took weekly maize height measurements as mentioned in Chapter 3. We also used these rectangles for harvesting of LR92 maize and beans biomass and beans seed yields.

Four rectangular areas running east-west in each of the treatment plots AFM1, AFL1, AFM2 and AFL2 leaving a buffer of 60 cm from the border of two adjacent plots, were used for harvesting in SR92 when we had a successful season. For LR92 we harvested total biomass per row in each plot in the two rectangular areas, in the upper (PQRS) and lower (P'Q'R'S') parts of the AF plot shown in Fig. 9. The maize rows were at the distances of 94, 188, 282, 376 & 470 cm from each of the two tree rows, B(TR1) and D(TR3), because we want to understand the nature of biomass yield differences and gradients symmetrically from two tree rows in the middle of the AF plot. For the control plots we also harvested per row totals in smaller areas of 9 m by 2 m in each plot.

Substantial maize grain and cob yields and biomass from stover were obtained only in SR92. Of the seven seasons we worked at Matanya, the remaining seasons produced only maize stover biomass yields but no grain yields. Maize grain and cob harvesting were done plant by plant in the perceived area of the high *Grevillea* influence. The four AF plots (AFM1, AFM2, AFL1 & AFL2) were harvested this way leaving four rows next to the western /lower andeastern /upper hedges. The four rows nextto the

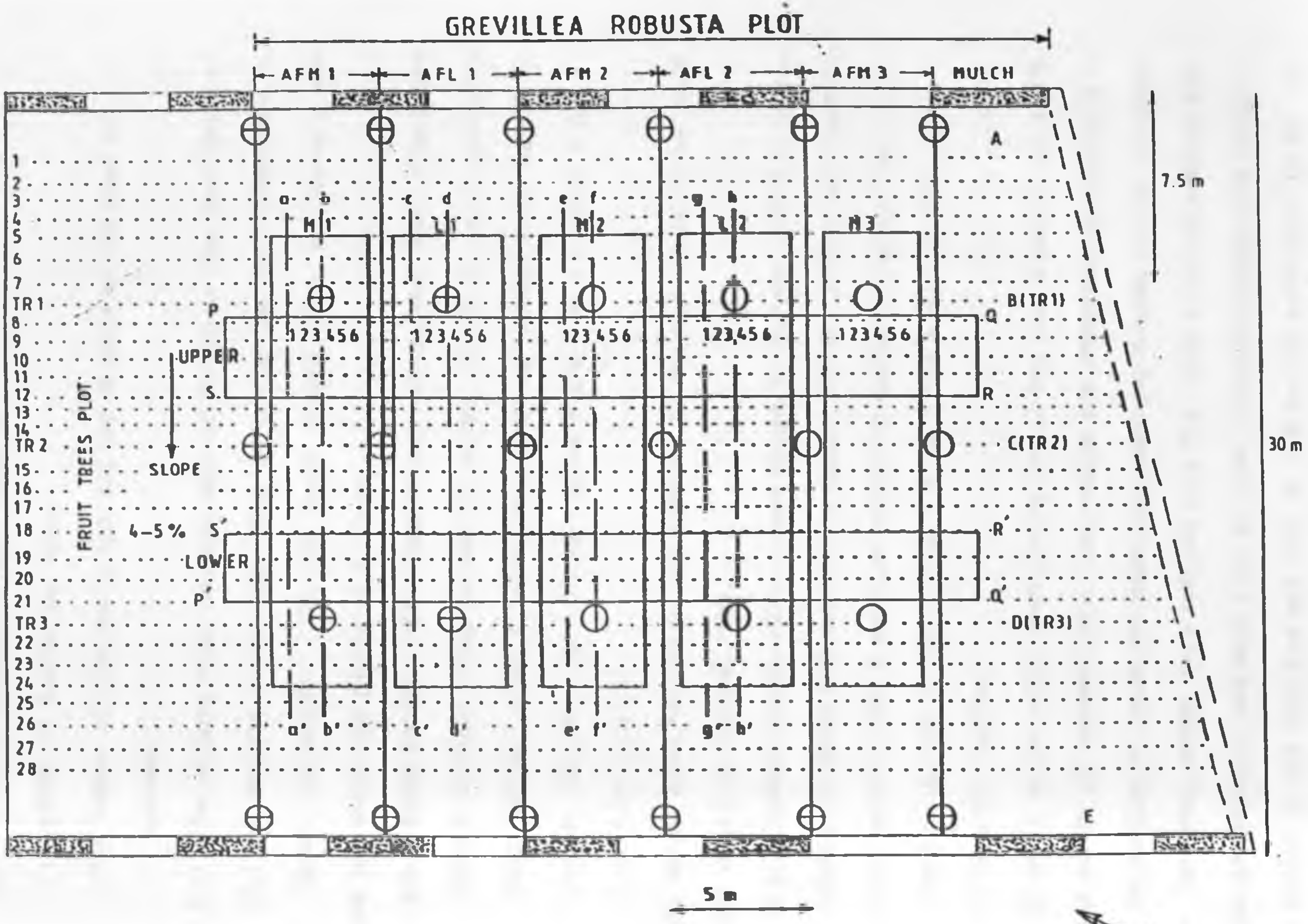


Fig. 9. Agroforestry plot showing five rows of Grevilleas (A, B(TR1); ....; E) maize rows (beans rows between maize rows are not shown) SR92 harvesting model (four E-W rectangles) and areas of maize height measurements and LR92 harvest (PQRST & P′Q′R′S′T′). Note that aa′,cc′, ee′, and are lines joining all first holes in plots AFM1, AFL1, AFM2 and AFL2 while bb′, dd′, ff′and hh′ are lines joining all fourth holes in the same plots.

hedges and the remaining parts of the crop area, including NAF, were harvested line-by-line .

The following parameters were measured:

(i) number of plants per hole,

(ii) number of cobs per plant and the weights of the same at harvest,

(iii) the weights after several days of drying in the open (sundry),

(iv) the weights of the same after 24 hrs in the oven (oven-dry).

Maize cob weight (COW) and grain weight (GOD) at oven-dry were worked out using the ratios as follows:

Cob Ovendry Weight (COW)= head weight at harvest (HW) X moisture change of heads from harvest to sundry (76.4%) X ratio of cob to head weight (21%) X moisture change of heads from sundry to ovendry (82.4%) = HW * 76.4% * 82.4% * 21% = HW * 0.764 * 0.824 * 0.21 = HW * 13.2%.

So cob weight after drying in the oven for 12 hrs was found to be 13.2% of head weight at harvest (HW).

Grain Ovendry Weight (GOD) = head weight at harvest (HW) X moisture change of heads from harvest to sundry (76.4%) X ratio of grain to head weight (79%) X moisture change of heads from sundry to ovendry (82.4%) = HW * 76.4% * 82.4% * 79% = HW * 0.764 * 0.824 * 0.79 = HW * 49.7%.

So grain weight after oven drying for 12 hrs was found to be 49.7% of head weight at harvest (HW). The results are presented in section 4.1 .

Harvesting of beans for seed and remaining biomass yields (biomass after the beans seeds were removed from the pods after harvesting and weighed separately) was done line by line, thereby giving line totals, and a buffer of one bean row was left at the end of every plot in AF. In

NAF harvesting was done within a rectangle of 2 m by 9 m in all the plots (Plate 4). It should be noted that where we mention beans biomass yields, this always means that the seeds have already been removed.

3.1.1 (f) Maize and beans intercrop experiments in two on-farm sites.

On-farm experiments were done in the seasons: SR93, LR94 and SR94 at Kiahuko-A and Kiahuko-B as explained below.

(i) Kiahuko-A on-farm

On-farm live-fence experiment was done at Kiahuko-A, about 6 km from Matanya on-station on a *Coleus barbatus* live-fence which surrounded the farm and the farmer's homestead. Three sides (northern, southern and eastern) of the live-fence and the farmer's homestead are shown in Fig. A2 (not to scale). The farmer's homestead was on the western part of the farm and therefore we could not use the western side of the live-fence (see Appendix Fig. A2). The treatments of pruning and not pruning used these three sides of the live-fence. The treatments were replicated three times, centred where access tubes had been installed, that is pruning (ALF, BLF & CLF) and not-pruning (DLF, ELF & FLF) (see appendix Fig. A2). A general control treatment (GC) around a control access tube located in the middle of the farm was used as the control. Pruning was done by digging a 30 cm deep trench at a distance of 50 cm from the live-fence.

Planting was done by the farmer at the same time as on-station using his own planting density, which we measured to be on average 100 cm by 58 cm, which was not much different from the on-station one. The entire farm was mulched and tilled by the farmer in accordance with his normal practice.

After seedlings emerged areas of 10 maize plants per row (P1...P10) in 5 maize rows (I, II, ..., IV) around access tubes replicated three times were taken for phenological, heights and yield measurements in the same way as the on-station. Yields and heights calculations were done for distances from the live-fence of 0-120, 120-300 and 300-600 cm centred around access tubes installed at 90, 180 and 360 cm from and perpendicular to the live-fence. The results are reported in Chapter 4. It should be noted that this farmer always planted maize crop in rows that were perpendicular to the live-fence on all sides, where BLF has to be seen as an extension of ELF. This is a traditional method that allows little competition for water between the live-fence and the nearby plants.

It should be noted that stover yields were obtained for the SR93 and SR94 only. The stover biomass for LR94 was incidentally taken by the farmer, to feed his livestock, before measurements. The biomass harvesting in SR93 and SR94 was done row by row. There were no grain yields from these seasons maize crops.

At Kiahuko-A beans were planted by broadcasting method which made it impossible to quantify the yields therefrom.

(ii) Kiahuko-B on-farm

On-farm agroforestry (AF) experiment was done at Kiahuko-B at 8 km from Matanya, on mostly 9 year old *Grevillea robusta* trees. The trees were planted in six rows (marked P to U in Appendix Fig. A3), with the between row spacing on the shorter side of the AF plot varying from 3.0 m to 4.8 m and the longer opposite side varying from 3.2 to 6.4 m. The

AF plot thus forms a fan-like configuration (Appendix Fig. A3). The within row tree spacings also varied in each row.

This AF experiment somewhat replicated the on-station AF experiment, but with a higher tree density. The half of this AF plot was pruned and half was left unpruned as indicated in Appendix A3. The half that was pruned was further divided into two plots, that is mulched with minimum tillage (AGM1) and Local with deep tillage (AGL1). The half that was unpruned was also divided into two plots, that is mulched with minimum tillage (AGM2) and Local with deep tillage (AGL2) as shown in Fig. A3.

An area with four control plots (NAF), that is mulched and Local replicated two times, was established 200 m away from AF plot.

Planting of maize and beans intercrop in the AF was done in the same direction as the tree rows as indicated by a sample of dotted lines in Fig. A3.

Bean yields were only obtained for LR94 at Kiahuko-B in the control plots as the heavy tree shades in AF resulted in no yields from AF plots while late planting was the main reason for total bean crop failure in SR93 and SR94. The direction of sowing in NAF was done according to the AF.

Calculations on maize and beans yields and heights were done by working out data for crop rows in these distances from tree rows, that is I for rows from tree rows till 90 cm away and II for rows between 180 and 270 cm from tree rows. These were considered to follow soil moisture gradient as monitored by the access tubes installed at 90 cm and 200 cm from the trees as shown in Fig. A3.

3.2 Soil Moisture measurements with neutron probe

3.2.1 Calibration of neutron probes (CPN 501 and CPN 503)

We did neutron probe calibration experiments for Matanya soils on 19.2.92 (for the dry calibration) and on 18.6.92 (for the wet calibration). The two calibration experiments were done to establish a calibration curve for soil moisture from count ratios (ratio of individual counts to standard count), to be corrected for the influence of bulk density, using its regression on gravimetric soil moisture.

Two neutron probes (types CPN 501 and CPN 503) were calibrated for the *Verto-luvic phaeozem* soils at Matanya. The calibration equations so developed were also used for on-farm (at Kiahuko-A and Kiahuko-B) soil, the two sites with same soil properties.

The soil layer in which the soil moisture was measured was that which could interact with the atmosphere through the soil-plant-atmosphere system. The neutron probes were calibrated against gravimetric sampling concurrently taken. The soil moisture data were collected at seven depths 18, 30, 60, 90, 120, 150 and 170 cm. The probe count rates were divided by the standard count to yield count ratios. The gravimetric data were regressed on the count ratios to produce a regression equation.

The dry calibration experiment was done on 19 February 1992 to establish the lowest point of the soil moisture scale, leading to the determination of the wilting point (Liniger, 1991). The wet calibration experiment was done on 18 June 1992 to establish the higher points that lead to the determination of the field capacity point (Liniger, 1991). The two calibration exercises were then used to determine the soil water available to the inter-crops of maize and beans and to the *Grevillea* *robusta* trees. February, being the driest month of the year in Kenya, was chosen at a time when the grass was visibly dry and the whole soil depth was at or below wilting point (WP). The maize in cropland and the grass on the unused land were completely water stressed and had actually attained or slightly passed the permanent wilting point at the time of the dry calibration.

Wet calibration was done after soaking the soil through irrigation for one and half months in order to attain field capacity. This allowed enough time for gravitational draining of the water. The following items forming the soil moisture calibration kit were used:

(a) two neutron probes (CPN 501 and CPN 503)

(b) a pre-installed aluminium access tube

(c) two soil augers.

(d) two volume sampler augers.

(e) five volume sampler rings of 5 cm diameter and 5 cm height per depth.

(f) one mattock

(g) one pick

(h) one hoe (or jembe)

(i) one knife

(j) five plastic bags per each of the seven depths sampled.

Ten standard counts were taken at the beginning and ten at the end of the experiment, with each neutron probe sensor inside the housing by placing the meter on the rim of the pre-installed access tube. Four count rates were taken at each depths of interest: 18, 30, 60, 90, 120, 150 and 170 cm before beginning to excavate around the tube to take soil samples. The five ring samples were taken from each depth around the tube after levelling the soil at these depths. The sampler rings were driven into the soil so that the middle of the ring heights coincided with the depth from which the soil was taken. The samples were taken to the LRP laboratory, where they were weighed and oven-dried at a temperature of 105°C for 24 hours. The dried samples were weighed again and differences in weight was taken as the gravimetric water content which was converted to the volumetric water content (θ) from the known volumes of the samples rings. The count ratios from each neutron probe were regressed against the volumetric water released by heating the soil samples collected. These yielded calibration curves presented in Figs. 122 and 123 in section 4.2 on soil moisture results.

The bulk densities (Bd) of the samples were obtained from the dimensions of the sampler rings and the dry weights of the soil that filled the rings. Five ring samples were collected at each depth during excavations. Each of the sampler rings was 5 cm in diameter and 5 cm high. The volume of each ring was 98.13 cc. The densities (Bd's) were calculated from the dry weights divided by this volume. The densities were regressed on the gravimetrically observed volumetric soil moisture content (% vol.) obtained during dry and wet calibrations (see Tables 45a & 45b). The calibration equations presented in Chapter 4 section 4.2 (Figs. 124-130 and Table 45) were developed by regressing Bd on observed θ at each measuring depth.

3.2.2 Correction for minimum depth to start neutron probe readings

In Matanya a standard depth of 18 cm was chosen by LRP (Liniger, 1991) as the shallowest depth to begin neutron probe measurements for both dry and wet periods and the deepest depth measured was 170 cm. This was meant to cover the rooting-depth of most crops grown in the area which included crop such as maize, beans, potatoes, agroforestry trees e.g. *Grevillea robusta* and live-fences e.g. *Coleus barbatus* (Liniger, 1991 and Moges, 1991).

The radius of sphere of importance (Q_3) of neutron probe described in chapter 2 was used to determine a minimum measuring depth at matanya. Q_3 had a maximum value of 19.1 cm during the periods of air high humidity, that is during Long Rains season. A maximum value of Q_3 was safely taken to be 20 cm as the radius of a sphere of neutrons reflected to detector of the probe (type CPN 501) during wet seasons. The equation of volume of a sphere ($V = 4\pi r^3/3$) with r taken to be 20 cm for wet seasons and 26.8 cm (at VSMC of 23.3% see Table 45a) for dry season as given by Eq. 3 was compared with the original depth of 18 cm which was being used by LRP (e.g. Liniger, 1991; Moges, 1991). It was found, using equation of volume of a sphere, that in the driest part of the wet seasons Q_3 extended by 2 cm into the open air, thereby over-estimating soil moisture by 1.9 per cent. During a dry season, when air humidity was low, Q_3 extended by 8.8 cm into the open air, thereby underestimating the soil moisture by 20.3 per cent. For these heterogeneous vertisols, it was advisable to take gravimetric samples as close to the access tubes as possible for soil moisture data that accurately compares with those taken with the neutron probe. Such a destruction within the sphere of importance may, however, create problems when tubes are at a permanent position. Hence, in our case surface gravimetric soil moisture measurements were taken at 7.5 cm depth where could no longer use the neutron probe. The results are given in chapter 4.2.

3.2.3 The layout of access tubes in agroforestry (AF) plot

Fig. 7 and Table 3 display the layout of access tubes around five root pruned *Grevillea robusta* trees marked PT1, ..., PT5 and five root unpruned trees marked UT1, ..., UT5 in the AF plots we used for our experiments. In the course of our data collection we had at one time, after LR92, excluded the access tubes installed around *Grevillea robusta* trees, PT3 and UT3, (i.e. A3, B3 and C3 around PT3 and D3, E3 and F3 around UT3), because the PT3 was in the middle of the pruned plot but on the border of Mulched (AFM1) and Local (AFL1). Similarly UT3 was

Table 3. Locations of access tubes in relation to the positions of *Grevillea robusta* trees in the AF plot at Matanya station for the six seasons (i.e. LR92, SR92, LR93, SR93, LR94 & SR94) of the experiment.

Plots with pruned trees				Plots with unpruned trees			
(i). Pruned trees Tree 1 = PT1 Tree 2 = PT2 Tree 3 = PT3 Tree 4 = PT4 Tree 5 = PT5				(ii). Unpruned trees Tree 1 = UT1 Tree 2 = UT2 Tree 3 = UT3 Tree 4 = UT4 Tree 5 = UT5			
(iii) Access tubes around pruned trees				(iv). Access tubes around unpruned trees			
Distance (cm) from trees				Distance (cm) from trees			
Tree	94	188	376	Tree	94	188	376
PT1	A1	B1	C1	UT1	D1	E1	F1
PT2	A2	B2	C2	UT2	D2	E2	F2
PT3	A3	B3	C3(=O2)	UT3	D3	E3	F3(=R2)
PT4	M1	N1	O1	UT4	P1	Q1	R1
PT5	M2	N2	O2(=C3)	UT5	P2	Q2	R2(=F3)

in the middle of the unpruned plot but on the border of Mulched (AFM2) and Local (AFL2). At that time we thought this would introduce unnecessary variability in the VSMC due to surface cover. After thoroughconsultations we decided to include these tubes. We therefore did not collect soil moisture data for the above tubes for SR92. The trees lying on the border line between pruned and unpruned plots were half pruned. The half in the pruned plot was pruned while that in the unpruned plot was not pruned. This was thought to properly influence the soil moisture regime associated with the border trees.

The access tube readings around *Grevillea robusta* trees were used to determine the following at each of the seven depths (i.e. 18, 30, 60, 90, 120, 150 and 170 cm):

i. the effect of root pruning and residue mulching on soil moisture distribution as presented by the average VSMC and deviations of the access tube readings from averages in the areas with

(a) root pruned *Grevillea robusta* trees (PT1, PT2, PT3, PT4 & PT5),

(b) root unpruned *Grevillea robusta* trees (UT1, UT2, UT3, UT4 & UT5),

(c) all access tubes in entire agroforestry plot

ii. VSMC gradients radially from pruned and unpruned *Grevillea robusta* trees.

The AF plot had seven out of sixteen (excluding of course the trees along the live-fence) *Grevillea robusta* trees root pruned at 50 cm from the tree trunks down to a depth of 30 cm, to assess the competition for soil moisture between trees and intercrops.

The influence of root pruning on soil moisture distribution was examined using individual tube readings at different depths and distances from the *Grevillea robusta* trees in their relation to the averages computed for the specific treatments, for the growing seasons LR92, SR92, LR93, SR93, LR94 and SR94.

The deviations and differences of equivalent tubes, that are tubes at equal distances from the trees, were further averaged to determine the resultant deviations and differences among equivalent tubes in each treatment (pruned and unpruned) per depth.

3.2.4 The layout of access tubes in non-agroforestry (AF) plot

One access tube was installed in the middle of each of the old control plots (L1, L2 & L3 and M1, M2 & M3) in NAF. Two access tubes (A, B) were installed in the middle of each newly opened control plots (L4 & L5 and M4 & M5) along a line parallel to the long sides of the plots. Access tubes L4A, L4B and L5A, L5B were installed Local plots marked L4 and L5 in Fig. 8. Similarly access tubes M4A, M4B and M5A, M5B were installed in Mulched plots marked M4 and M5 in Fig. 8.

3.2.5 The layout of access tubes in Kiahuko-A on-farm (Live-fence) plot

The access tubes were installed at 90, 180 and 360 cm from the root pruned (coded as ALF, BLF & CLF) and unpruned (coded as DLF, ELF & FLF) portions of the live-fence. Tubes A1, B1 and C1 were installed at 90, 180 and 360 cm respectively from ALF. Tubes A2, B2 and C2 were installed at similar distances from BLF. Tubes A3, B3 and C3 were similarly installed from CLF (see Appendix Fig. A2). Tubes D1, E1 and F1 were installed at 90, 180 and 360 cm respectively from DLF. Tubes D2, E2 and F2 were installed at similar distances from ELF. Tubes D3, E3 and F3 were similarly installed from FLF (Fig. A2 and Table 4). The on-farm naming of access tubes was meant to conform with the on-station naming for ease of comparison and interpretation.

Table 4. Access tube positions with respect to root pruned and unpruned portions of live-fence at Kiahuko-A, during SR93, LR94 and SR94.

	Distance (cm) from live-fence		
	90	180	360
(i) Pruned portions	access tubes		
ALF	A1	B1	C1
BLF	A2	B2	C2
CLF	A3	B3	C3
(ii) Unpruned portions			
DLF	D1	E1	F1
ELF	D2	E2	F2
FLF	D3	E3	F3
GC - central part of plot			

3.2.6 The layout of access tubes in Kiahuko-B on-farm *Grevillea robusta* (AF) plot

Fig. A3 displays a layout of the on-farm plot with six rows (row P, row Q, ... row U), the Mulched/Local plots, and the farmers domicile (homestead). The dotted lines indicate the direction of sowing and the double dashed lines indicate the trench dividing the pruned and unpruned plots while the single dashed lines indicate the lines separating the replication/ treatment plots.

The *Grevillea* trees on-farm AF plot was divided into: (i) pruned Mulched and minimum tilled plot (AGM1); (ii) pruned Local and deep tilled plot (AGL1); (iii) unpruned Mulched and minimum tilled plot (AGM2); and (iv) unpruned Local and deep tilled plot (AGL2). The distance between tree rows were relatively larger on the side of the plots bordering the homestead and smaller on the opposite side (see Fig. A3). The smallest distance between the tree rows was 3.0 m and the largest was 5.4. These distances allowed only two access tubes to be installed at 90 and 200 cm from each experimental tree for radial measurement of soil moisture radially from each tree.

Due to the spacing between rows of *Grevillea* trees, we could only install two access tubes at the distances of 90 and 200 cm from the *Grevillea robusta* trees of interest. In our experiment we therefore used six tubes in pruned (i.e. three in mulch and three in Local) and six in unpruned (three in mulch and three in Local) (see Table 5 and Fig. A3).

Table 5. Access tube positions with respect to pruned and unpruned *Grevillea robusta* trees at Kiahuko-B, during SR93, LR94 and SR94.

(i) Pruned	mulching plot (AGM1) dist from trees			Local plot (AGL1) dist from trees	
tree labels	90	200 (cm)	labels	90	200 (cm)
T7	A1M	B1M	R6	A1L	B1L
R8	A2M	B2M	Q6	A2L	B2L
P7	A3M	B3M	P6	A3L	B3L
(ii) Unpruned					
S2	D1M	E1M	T2	D1L	E1L
R4	D2M	E2M	S1	D2L	E2L
Q4	D3M	E3M	R2	D3L	E3L

(iii) Control plots

mulching: CTRL-MUL
Local: CTRL-LOC

3.3 Wind measurements

3.3.1 (a) Instrumentation

(i) The CR10 data-logger and WAU electrical anemometers

A CR10 data-logger (Campbell Scientific, 1990) and 15 cup anemometers were used together with two Woelfle anemographs ("WA" = Sr.

Nr. 341836 and 'WB' = Sr. Nr. 31587). The anemometers were manufactured by the Department of Meteorology mechanical Workshop/Laboratory. The former combination will be called hereafter as 'CR10'. The CR10 wind system plus its accessories at Matanya site consisted of:

(a) 15 WAU electrical cup anemometers (type WV 100R)
(b) 1 Campbell Scientific data-logger (type CR10)
(c) 1 Compaq laptop computer (type SLT 286)
(d) 13 cable reels each with 150 m long cables
(e) 13 stainless steel masts of 2.0 m long
(f) 13 mast extensions of 0.5 m long
(g) 13 arms holding the anemometers
(h) 13 connecting blocks
(i) 13 (sets of 3) soil pins, that is a pin for each mast
(j) 13 sets of 3 fixing rings and guy winders
(k) 13 sets of guys each with 3 wires
(l) There were three pegs for each mast to connect wires

Items (i) to (k) were used to erect the masts vertically and put them firmly into the ground. The WAU electrical anemometers that we used had opto-diodes consisting each of a pair of light emitting and light receiving diodes (or photo-diodes). The latter receives light from the former, interrupted by the rotating cups, and these pulses are registered as counts. As the cups revolve, these pulses are received at the rate determined by the rate of revolution, which are then converted into wind speeds from the number of revolutions using the formula $u = a + b * n$, where u is the wind speed in m/s, n is the number of counts per second (counts/s) (Campbell Scientific, 1990).

The WAU electrical cup anemometer has a threshold value (above which the rotor moves) of about 0.20 m/s, with a stalling speed which lies between 0.1 and 0.15 m/s. The threshold of an anemometer is the lowest wind speed at which the device begins to operate while the stalling speed is the wind speed at which the device stops to operate. The stalling speed is usually lower than the threshold speed. The output cable of the WAU electrical cup anemometer is 2.1 m long. The cups have a diameter of 5.0 cm and are hemispherical in form. The small arms from the cups to the centre of rotation of the instrument are 2.5 cm long. The diameter of the each cup anemometer was therefore taken as 2 * (5.0+2.5) = 15.0 cm.

(ii) The Campbell Scientific data-logger (The CR10).

The CR10 panel board could accommodate 16 electrical anemometer and 16 PT100 platinum resistance thermometer plugs. The temperature plugs were numbered from 1 to 16 and the wind plugs from 17 to 32. We used only the wind plugs 17 to 29 for 13 wind measuring points, 12 in AF and 1 in NAF. The CR10 was connected to the Compaq laptop computer with a serial interface (RS 232) cable. The programme " term log3.dld" which was modified from the original one "term log1.dld" was downloaded from the laptop to the CR10 immediately after off-loading the recorded data from the latter. We used a modified programme "edlog log3" to adjust and include the relevant calibration factors in "term log3.dld" whenever we changed an anemometer.

(iii) The wind measurements with the CR10

The CR10 was initialized using programme "term log3.dld" in the laptop to calculate and store (in random access memory (RAM) of the CR10 processor), for each of the 13 anemometers, the average wind speed over the past 15 minutes. The 15 - minute wind speed data were off-loaded weekly or fortnightly. The LOTUS import command was used to convert the CR10 data into LOTUS data and store them in 3.5 inch diskettes.

3.3.1 (b) Evaporimeter system as an auxiliary anemometer

(i) The Piche atmometer system

We attached a shaded Piche evaporimeter to each mast on which an electrical cup anemometer was installed. The open end of the Piche was adjusted to the same level as the centre of the anemometer cups. The Piches were tested for their ability to interpolate or extrapolate wind speeds. The Piches (type C.F. Casella & Co. Ltd) used consisted of a 33 cm glass tube of 1.4 cm external and 1.1 cm internal diameter filled with distilled water. Piches are hung up-side-down and its flat white circular piece of blotting paper of 3 cm diameter, backed in the centre by a metal disc of again 1.4 cm diameter, prevents the water from escaping except by evaporation through the filter paper. In this way 11.0 ± 0.04 cm^2 of evaporating wet filter paper is exposed to the environmental conditions of long wave and reflected solar radiation, temperature, wind and humidity. The metal disc is tightened by a clip to keep the blotting paper in place at the tube end. The metal disc is provided with a small hole of less than 0.2 cm for pressure equalizing purposes (eg. Stigter and Uiso, 1981; Van Zyl and De Jager, 1987 and Kainkwa, 1991). Evaporation which was read every morning at 09h00 was expressed in mm of depth of water evaporated in one hour.

(ii) The shade for the Piche atmometer

The shade for the Piche evaporimeter consists of circular plates of 25 cm diameter made of 2 cm thick tempex sand-witched between two round plates of a few mm of wood. The plates have a hole of 1.4 cm diameter at the centre, in which the Piche tube hangs with a protrusion of 7 cm at the bottom. The arm for mounting the shade system was fixed on a vertical mast. The upper surface of the shade was glued with aluminized Mylar (polyester) material, to optically reflect incident radiation with a high long-wave emission coefficient, to keep the temperature of the top surface of the shade fairly low. The surface of the shade facing the soil was painted dully white (Kainkwa, 1991, Van Zyl and De Jager, 1987). Van Zyl and De Jager (1987) found that under their conditions in Orange Free State, South Africa, their shaded Piche with a different type of shade was 1.4 times more sensitive to wind speed than the screened routine Piche. However, the main reason not to have Piches as auxiliary wind meters in the routine screen is the loss of direction independence and the influence of neighbouring instruments (Stigter, et al., 1995).

3.3.1 (c) The Woelfle anemographs

Two height adjustable Woelfle anemographs (Ser Nr. 341838 in AF and Ser. Nr. 360842 in NAF) and two other but height non-adjustable Woelfle anemographs marked 'WA' (Ser. Nr. 341836 in NAF) and 'WB' (Ser. Nr. 31587 in AF), which were fixed at 2 m height, were used to record instantaneous wind speed and direction on a strip of a monthly chart. Woelfles 'WA' Sr. Nr. 341836 and 'WB' Sr. Nr. 31587 were marked that way for the purpose of their use during calibration exercises at Embori (Plate 5), explained above. The instrument consists of (i) a wind vane to sense wind direction and (ii) a rotor with three rotating cups to measure wind run.

The vane and the rotor move due to differences in wind pressure. Each element is independently connected to worm recording rollers via separate shafts, wheels, and gears. The rollers make separate traces on a continuous mechanical clock driven strip chart from which wind run and direction were decoded. The clock was monthly wound up by hand. Each instrument was supplied with a calibration "ladder rule" by the manufacturers, to calculate average hourly wind speeds. The wind direction for a desired period, say 1 hr, could be estimated from the traces on the chart by the wind direction recording rollers. According to Lambrecht, the mechanical wind recorder can be used in the wind velocity range of 0 to 60 m/s. The threshold of the Woelfle instruments is about 0.5 m/s and the dynamic zero is unknown.

3.3.1 (d) Calibration site

Inter-comparisons of cup anemometers were conducted at a site on the Wangu Embori farm on the slopes of Mt. Kenya at an elevation of 2650 m a.s.l. The site was 45 km east of Nanyuki and 70 km east of Matanya, our main experimental site. The geographical location of the Embori site was 0° 02' N and 37° 19' E. The calibration and experimental sites at Embori and Matanya are shown in Fig. 1. This site was fairly horizontal and secure, as it was in the vicinity of a LRP observatory. It had a slope of 2-3%. About 200 m away to the east of the site there was a deep valley whose influence was later found to complicate the uniformity of the wind structure. The winds at Embori from February to March were mainly from ENE direction. The hourly wind speeds ranged from 1 to 11 m/s during this period.

The fifteen Wageningen Agricultural University (WAU) electrical cup anemometers were supplied to us with the calibration factors after they had been intercompared in a controlled laminar airflow in a wind tunnel at the Department of Meteorology, WAU-The Netherlands. The

Woelfle cup anemographs were made by Lambrecht Manufacturing Instruments (Germany).

We had to dynamically calibrate cup anemometers in a natural homogeneous (or near-homogeneous) wind field in a fairly flat (or horizontal) site. We had to do this to check their dynamical response in natural turbulent conditions in the field. It should be noted that cup anemometers integrate air movement with an angle till about 45° with the horizontal in which the cups rotate.

3.3.1 (e) Experimental set up at Embori calibration site

The first calibration experiment (Cb1) was conducted from 15 February to 8 March 1993, the second (Cb2) from 14 May to 28 May 1994 and the third (Cb3) from 25 January to 3 February 1995. Cb1 and Cb3 took place during periods of very high wind speeds while Cb2 took place during a period of low wind speeds.

(i) Comparison of anemometers in February-March 1993 (Cb1)

Four stainless steel masts of length 2.5 m each were connected to a soil pin and erected vertically at a distance of 2.4 m apart. The row formed by the anemometers was oriented in the NWW-SSE direction perpendicular to the prevailing wind direction. They were firmly held to the ground with guy wires tied to steel pegs. Some horizontal mast parts were firmly tied to each other horizontally (end-to-end) with rubber bands cut out off car tubes (as connecting blocks were not enough) to form a long horizontal mast of length 7.3 m. Sets of guys were used to adjust for verticality. Cables reels were connected to a CR10 data-logger which was 70 m from the spot where the masts were hoisted. The cable reels were rewound and connected to the anemometers. The reels were placed neatly near the CR10.

Using connecting blocks, 13 arms of a length of 0.5 m were mounted horizontally on three horizontal bars, each of 2.5 cm, connecting the masts. They were placed at a distance of 0.6 m apart, protruding 0.4 m from the long horizontal bar, their row facing the ENE wind that blew at this time of the year. At a height above the ground of 2 m, we mounted 13 anemometers (10, 11, 12, 13, 14, 15, 38, 39, 40, 41, 43, 44, 55 in that order) at a time, since we had only 13 cable reels instead of 15 to match the number of anemometers we had. We installed for comparison two Woelfles at 2 m above the ground, one at each end of the long horizontal bar made by connecting the three masts. Woelfle Ser Nr 341836 (marked 'WA') was installed at 0.7 m from cup 10 while Woelfle Ser Nr 31587 (marked 'WB') was installed at 0.7 m from cup 55. 'WA' was installed on the northern side of the bar while 'WB' was installed on the southern side. Plate 5 shows some of the details in set up with three masts which was used for Cb3.

The cup anemographs were mainly used for wind direction determinations. The substandard (cup 40) which had been kept indoors prior to this experiment was used to compare the rest. The wind speeds collected from the substandard were first intercompared with those from the Woelfles and then with other anemometers and regressions and correlations generated.

When retrieving the data of the anemometers, the Compaq computer (laptop) was connected to the Campbell Scientific CR10. The laptop was powered from a rechargeable NiCd battery (type P240-10 SLT). The battery was recharged as often as necessary using a 240 V A.C. adaptor series 2681. A solar panel (type Siemens 12 V) continuously charged the maintenance free lead acid/chloride car battery (12 V, 45 Amp), which was used to supply power to the data-logger.

(ii) Comparison of anemometers in May 1994 (Cb2)

We also conducted a second, similar comparison but with the distance over which the anemometers were installed halved, to try to exclude the influence of the valley on the structure of the wind field. The winds this time blew from a NW direction and were rather weak, ranging from 0 to 5 m/s. The electrical anemometers were now installed on a horizontal bar between 3 masts, 1.5 cm apart, separated from each other this time by a distance of 0.3 m. The distance between the last anemometers and the anemographs was now 0.7 m. The distance between the two outermost cups was therefore now 3.6 m. The distance between the horizontal connecting bar and the cup rotors was 0.35 m. Three outer anemometers were interchanged after 9 days. However, the CR10 malfunctioned and the exercise was not very successful. Cups 44 and 39 had developed problems as their photo-diodes collapsed. This necessitated the third calibration exercise (Cb3). The battery for the CR10 also malfunctioned thus affecting the flow of charges.

(iii) Comparison of anemometer in January to February 1995 (Cb3)

The second calibration (Cb2) was more-or-less a failure, so it became necessary to do a third calibration (Cb3), as already mentioned. During Cb3 we had exactly 13 WAU cup anemometers. Cups Sr. Nrs. 39 and 44 had developed problems and were removed from the field during the Cb2, as their photodiodes had malfunctioned. We therefore had no spare cup anemometer to deploy as a substandard. We had to compare each anemometer to the middle one in the sequence, cup 10, 11, 12, ..., 61, 55 and exchanged three outer cups later on. The separation between the was used to supply power to the data-logger.

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3.3.2 Materials for field measurements of wind reduction at Matanya

3.3.2 (a) Experimental site

(i) The Coleus barbatus Live-fence around Matanya AF plot

The agroforestry (AF) plot at Matanya measures 50 m by 30 m. It is surrounded by a live-fence of *Coleus barbatus* which acted as a windbreak. The eastern and the western sides measured 50 m long. The southern and the northern sides were both 30 m long. The western, the eastern and northern sides of the live-fence were planted in 1986 while the southern side was planted in 1991. The southern side was therefore the youngest. Half of the AF plot was occupied by *Grevillea robusta*. The other half was occupied by the fruit trees which bordered the Grevillea robusta plot to the north. The fruit trees (loquats, guavas etc.) and the Grevillea trees were planted in 1986. This experiment was conducted in that part of AF that was occupied by the *Grevillea robusta*. The three live-fence sides of interest were: western hedge (WH), eastern hedge (EH) and southern hedge (SH).

(ii) The *Grevillea robusta* trees in AF plot

The crowns of the Grevillea robusta trees were cone shaped with outer cup anemometers on the extreme ends of a bar was 3.6 m and between two adjacent ones it was 0.3 m. The mounting was the same as in (i) except that the middle cup anemometer (cup 38) was used for comparisons (see Plate 5). We compared each anemometer to the middle one in the sequence, cup 10, 11, 12, ..., 61, 55 and then interchanged the three outer cups on 1/2. The length of comparisons were 90 hrs in the first arrangement and 28 hrs after the interchange.

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(ii) The *Grevillea robusta* trees in AF plot

The crowns of the Grevillea robusta trees were cone shaped with the diameter (Cd) of the crown base assumed to be the diameter of the canopy. The height of the cone (Crh) represented crown height (see Appendix Fig. A1). The taller the crown height and the larger the diameter of the crown base the more effective the tree is in protection against strong winds. The *Grevillea* trees in AF here shown in Plate 7 were planted in five rows. Their geometry is given in Table A8. which presents the results of the Grevillea tree measurements made on 17/5/93 before the onset of strong winds at Matanya and on 20/8/93 when the winds had attained their full strength. It is illustrated in a diagram in Appendix Fig. A1. Figs. 7, 8, 9 and 10 show positions of *Grevillea robusta* trees in the AF plot. Fig. 9 shows that rows A & E were planted along eastern and western sides of the *Coleus barbatus* live-fence. Rows B(TR1), C(TR2) & D(TR3) were planted within the AF plot at 7.5 m, 15 m and 22.5 m from the eastern side of the live-fence while row C was planted in the middle of the plot. These Grevillea robusta trees were at a staggered spacing of 7.5 m by 5 m when viewed from an east-west direction. All the Grevilleas at the *Coleus barbatus* live-fence were root pruned. Some of the Grevilleas inside the AF plot were pruned while others were not as indicated in Table A8. The *Grevilleas* in the AF plot were playing a complementary role to the *Coleus barbatus* live-fence as scattered trees wind break. From Appendix Table A8 we see that the diameters of the Grevillea tree trunks ranged from 0.4 m to 0.6 m and had negligible wind protective effects even cumulatively downwind. We see from Appendix Table A8 that the Grevillea robusta crown heights (the difference between the whole trees length and the height of the lowest branch) for Row A averaged 4.6 ± 0.3 m with a diameter of 3.2 ± 0.6 m in May, and 4.7 ± 0.4 m with the same diameter in August. The crown height

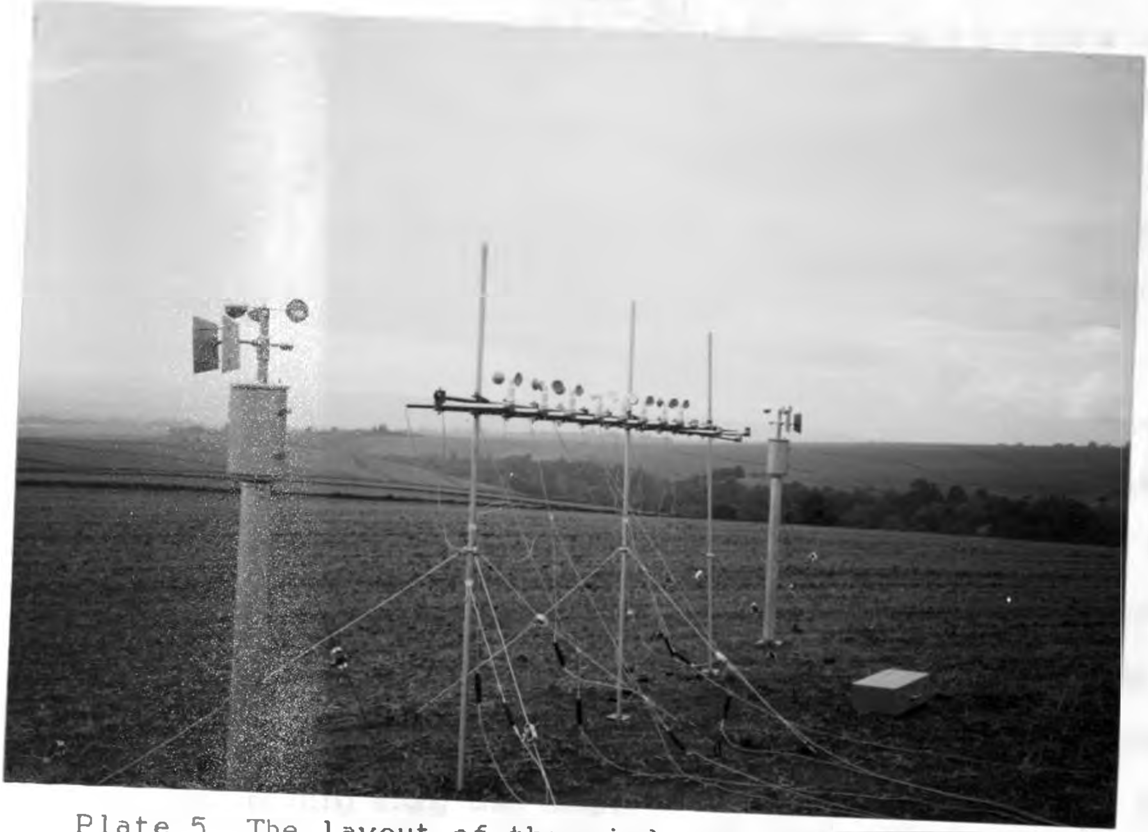

Plate 5. The layout of the wind measuring system during the calibration period (25/1/-3/2/1995) at Embori (Cb3).

Plate 6. A picture of the upper half of AF at Matanya showing electrical cup anemometers in row 3; on the background are tube solarimeters.

for row B(TR1) averaged 5.9 ± 0.5 m with a diameter of 4.0 ± 0.6 m in May and 6.1 ± 0.4 m with a diameter of 3.9 ± 0.7 m in August. The crown height for row C(TR2) averaged 4.9 ± 0.1 m with a diameter of 3.6 ± 0.6 m in May and 5.0 ± 0.1 m with a diameter of 4.1 ± 0.8 m in August. while those for row D(TR3) averaged 6.1 ± 0.1 m with a diameter of 3.3 ± 0.8 m in May and 5.7 ± 0.8 m with a diameter of 3.4 ± 0.5 m in August. The crown heights for row E averaged 5.0 ± 0.3 m with a diameter of 3.4 ± 0.4 m in May and 5.2 ± 0.3 m with the same diameter in August. From these results we observe that most wind protection may be expected in rows B(TR1) and D(TR3) and least protection in rows A and E. whose growth had been affected by competition for soil moisture and nutrients between the trees and the live-fence. from the time they were young. and by the root pruning along the hedges to exclude a combined system of *Grevilleas* and *Coleus barbatus* roots from extracting soil moisture in the cropland.

(iii) The neighbourhood of the experimental site.

A block of LRP staff houses is situated in the S.W. corner and at 10.4 m from the AF plot. Next to the house is a single Acacia tree about 6 m tall. The house is next to the boundary between the station and the southern - southwest neighbourhood. This boundary. the longest side of the main Matanya station plot. is 157 m and is marked by a planted hedge of *kale* apple thorny shrub (Fig. 8 and Plate 7).

On the other side of this hedge there is a neighbour's home with five houses. the nearest of which is about 50 m from the AF live-fence. To the southwest. that is behind LRP staff houses at about 100 m. are an assortment of tree woodlots about the age of the AF Grevillea trees. The tallest of theses trees is a eucalyptus tree about 12 m tall. To the northwest is a woodlot of old eucalyptus trees about 25 m tall at about 400 m from the AF plot. The aerodynamic influence of these old trees during June to September is directly away from the AF plot as SE/SW winds dominate. Therefore most of these features do not influence the SE to SW winds that dominate during this period, leaving the live-fence to be more exposed and making the *Coleus barbatus* live-fence all the more useful as a protective windbreak. When the SW wind blows, the southwest woodlot, the staff houses and the western part of the hedge appear to act as one continuous shelter-belt which lifts the wind making it descend somewhere in the middle of plot. This was observed from streaks of smoke from a charcoal stove placed on the roof of the staff house block.

3.3.2 (b) Experimental Layout of wind system

Figs. 8 and 9 and appendix Table A7 show the layout of wind measuring instruments in the agroforestry plot at Matanya. We installed twelve anemometers (A1, A2, ..., A12) in three rows (4 in each rows making 4 transect lines) in AF at within row spacing of 5.2 m and between row spacing of 11 m.

In row 1, which was 2H (H is height of hedge) or about 4 m from the western side of *Coleus barbatus* live-fence, we installed four anemometers, namely A1, A2, A3 and A4 (i.e. cups 10, 11, 12, and 13) at respective distances of 14.6, 19.8, 25.0 and 30.2 m from the southern side of the live-fence. In the central row (Row 2), which was 15 m from either the western or eastern live-fence sides, we installed 4 anemometers, namely A5, A6, A7 and A8 (i.e. cups 14, 15, 38 and 39) at

12.3, 17.5, 22.7 and 27.9 from the southern side of the live-fence. This row coincided with the central row of Grevillea robusta trees. The anemometers were therefore installed at the centre between two adjacent trees. Similarly in row 3, which was 4 m (almost 2H) from the eastern (or 26 m from the western live-fence) we installed 4 cup anemometers, that is A9, A10, A11 and A12 (i.e. cups 40, 41, 43 and 44) at 10.6, 15.8, 21.0 and 26.2 m from the southern side of the live-fence (see Plate 6). The above anemometers also formed transect lines composed of Line 1: anemometers A1, A5, A9 (cups: 10, 14 & 40); Line 2: anemometers A2, A6, A10 (cups: 11, 15, 41); Line 3: anemometers A3, A7, A11 (cups: 12, 38, 43) and Line 4: anemometers A4, A8, A12 (cups: 13, 39, 44) (see Fig. 10). The thirteenth anemometer, cup 55 (the control, seen in Fig. 8), was installed in NAF in the open and exposed to the undisturbed wind field at a distance of about 70 m on the eastern side of AF plot.

The anemometers were initially set at 1.0 m, at the beginning of the growing season. They were thereafter adjusted to grow with the maize crop but maintain 20 cm above the top of the highest nearby maize plant in both AF and NAF. In cases where the NAF maize plants grew faster than the AF (due to increased competition in AF between the trees and the crop during periods of low moisture availability), the anemometers in NAF were adjusted to grow with the highest maize plants in NAF and similarly those in AF were adjusted to grow with the highest maize plants in AF. Appendix Table A5 shows anemometer height adjustment in AF in the course the strong winds periods during LR93 and LR94.

3.3.2 (c) The Woelfle mechanical anemographs

The AF (WB) and NAF (WA) anemographs were installed at 2 m height to measure wind directions (see Fig. 8).

3.4. Radiation

3.4.1 Instruments for radiation measurements.

3.4.1 (a) General

We started experiments on radiation and shade measurements by comparing long tube solarimeters and Kipp solarimeters in an open area at Matanya between 20/10/91 and 31/10/91 to standardize the tube solarimeters. We used thirteen 1 m long tube solarimeters type TSL made by Delta-T Instruments ltd (Delta-T ltd., 1988; 1989) two Kipp solarimeters Sr Nr. 2091 and Sr. Nr.3080 from Delta Ltd. One of the thirteen TSL we marked as Tb was used together with the two Kipps (kp1 & kp2) solarimeters at 50 cm above the ground in an open area to act as reference radiometer. The area did not have trees nearby to cast shadows on the instruments (see Plate 8). The 12 TSLs consisted of 4 (E1, W1, S1 & N1) which were to be installed around the unpruned Grevillea robusta tree 1 (marked UT1) at 94 cm, 4 (E2, W2, S2 & N2) at 188 cm and 4 (E3, W3, S3 & N3) at 376 cm from the tree trunk (see Fig. 11). The TSLs were to be placed to the east, west, south and north of UT1 for the seasons SR91-SR93 and of PT2 for the seasons LR94 & SR94. The two trees had irregular conical canopies. They were located in AFM2 and AFL1 plots. Both of them were in tree row B(TR1) in the upper part of AF (see Figs. 15 & 7). The thirteenth tube (marked Tb) was to be placed side by side with the two Kipps in an open area throughout the experimental period, as the reference radiometers for the TSLs.

Long unfiltered detectors, namely Delta-T Tube solarimeters (Long), or TSLs, were used for spatial and temporal integration of the measured radiation (Szeicz *et al.*, 1964; Delta-T Devices Ltd., 1988). Two Kipps (kp1 and kp2) (Kipp & Zonen, 1977) and one tube (Tb) solarimeter were installed in the open and taken as the substandard instruments against which the tube solarimeters used in AF were calibrated (see Plate 8).

3.4.1 (b) Tube solarimeters (unfiltered) (TSL)-Tube pyranometers

(i) Factory specifications and calibration

The tube solarimeter sensor is made up of a copper-constantan thermopile whose junctions are embedded in a detector. The detector consists of alternate matt black and white sections which reach different equilibrium temperatures when exposed to shortwave radiation. The 60 junctions of the thermopile embedded in the black and white sections respond to the temperature differences between these two surfaces and generate a millivolt output which is directly proportional to the irradiance.

The detector measures 85.5 by 2.2 cm. It is enclosed in a pyrex borosilicate glass tube which is transparent to most of the visible and near infra-red (<2.5 µm) solar radiation. This glass is not transparent to long-wave radiation from the surrounding or the atmosphere. The pyrex glass transmits visible and infra-red radiation of wavelengths 0.35 to 2.5 µm. The pyrex glass tube has an external diameter of 2.6 cm and a thickness of 1.5 mm. The entire instrument is 97 cm long (Delta-T Devices Ltd., 1984). To ensure that the detectors were mounted horizontally, reference platforms were machined on the end of the solarimeters. Bubble levels were supplied fitted to these platforms. The levelling platform at each end was also used to check that the detector element was not twisted.

The solarimeters are supplied calibrated, with their sensitivities adjusted to 15 mV per kWm^{-2}. The TSL lack symmetry and their sensitivity solarimeter were installed in the open and taken as the substandard instruments against which the tube solarimeters used in AF were calibrated (see Plate 8).

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Plate 7. A picture of the agroforestry plot at Matanya showing part of the staff houses and some of the surrounding houses and part of the kale apple hedge.

Plate 8. The layout of tube (TSLs) and kipps (kp2) solarimeters during calibration (intercomparisons) in the open next to the solar panel which provided power for the electrical cup anemometers, in October 1991 at Matanya in Cb3 (21/4/1994).

Calibration of tube solarimeters was done to exclude inaccuracies due to:

a. moisture condensation inside the tubes;

b. erratic performance of integrators;

c. deviations from horizontality of tubes and detector elements

(iii) **Vacuum pump flushing of Tubes**

Initial flushing (or drying) of tube solarimeters was done just before SR91 on 26/9/91 at the Department of Crop Science. Field station. Kabete campus. University of Nairobi (DCS). The silica gel through which the flushing air passes was oven dried after the flushing of each tube to ensure complete drying. A vacuum pump was used to drive air through the hot silica gel and through the tube for 15 to 20 minutes. Thereafter both ends of the flushed tube were promptly sealed with the screws smeared with the silicon rubber sealant.

Subsequent flushing was done at Matanya experimental station using motor cycle tube as pump. An inflated motorcycle tube was connected to a glass tubing, through a rubber tube which was fixed with a clip to stop the air from rushing out. The tube was then immersed into the bottom of a conical (flat-bottom) flask filled with silica gel. The silica gel was again used to absorb moisture from the air which passed through it. The now dry air was then led out of the flask through another tube into the tube solarimeter. The tubes were flushed until the moisture condensation disappeared, then the clips were closed very tightly to avoid any moisture leakage.

The following materials were needed for such a field experiment (compare also Kainkwa, 1983).

- bicycle foot pump

- silica gel
- a two way flat-bottomed flask (or a conical flask)
- a motorcycle tube (modified with one way only bicycle valves)
- two right angled glass tubes
- 4 rubber tubings (diameter 0.8 cm)
- 4 clips
- 2 bicycle valves
- a screw driver

3.4.1 (c) The Kipp solarimeters

This Kipp solarimeter (also called Moll - Gorczynski pyranometer) has a 14 - junction manganin-constantan thermopile in the form of a 10 by 14 mm rectangle (HMS, 1956). The sensitivities of different Kipp solarimeters are provided by the manufacturers for resistances of approximately 10 ohms. The sensitivities of the two Kipps used at Matanya, with Tb as substandard, with which to check the rest of the TSLs were 12.3 (kp2) and 13.99 (kp1) $\mu V\ W^{-1}m^{-2}$ for Ser. Nrs. 773973 and 892505 respectively.

The blackened surface of the thermopile is covered by two concentric glass hemispheres (domes) of 3 and 5 cm in diameter. The space between the hemispheres is evacuated to limit sensible heat transfer by convection and advection. To avoid condensation on the inside of the glass domes, the interior of the solarimeter is kept dry by means of a built-in cartridge filled with silica gel pellets or other suitable drying chemicals (HMS, 1956). The Kipp has a 99% response time of about 30 s (cf. 180 s for TSL). The thermopile is not temperature compensated and has a temperature coefficient of -0.2% per deg C).

LEGEND

E1, W1, S1, N1 located at 94 cm from UT1

E2, W2, S2, N2 located at 188 cm from UT1

E3, W3, S3, N3 located at 376 cm from UT1

- - - - - direction of maize, beans and Grevillea rows.

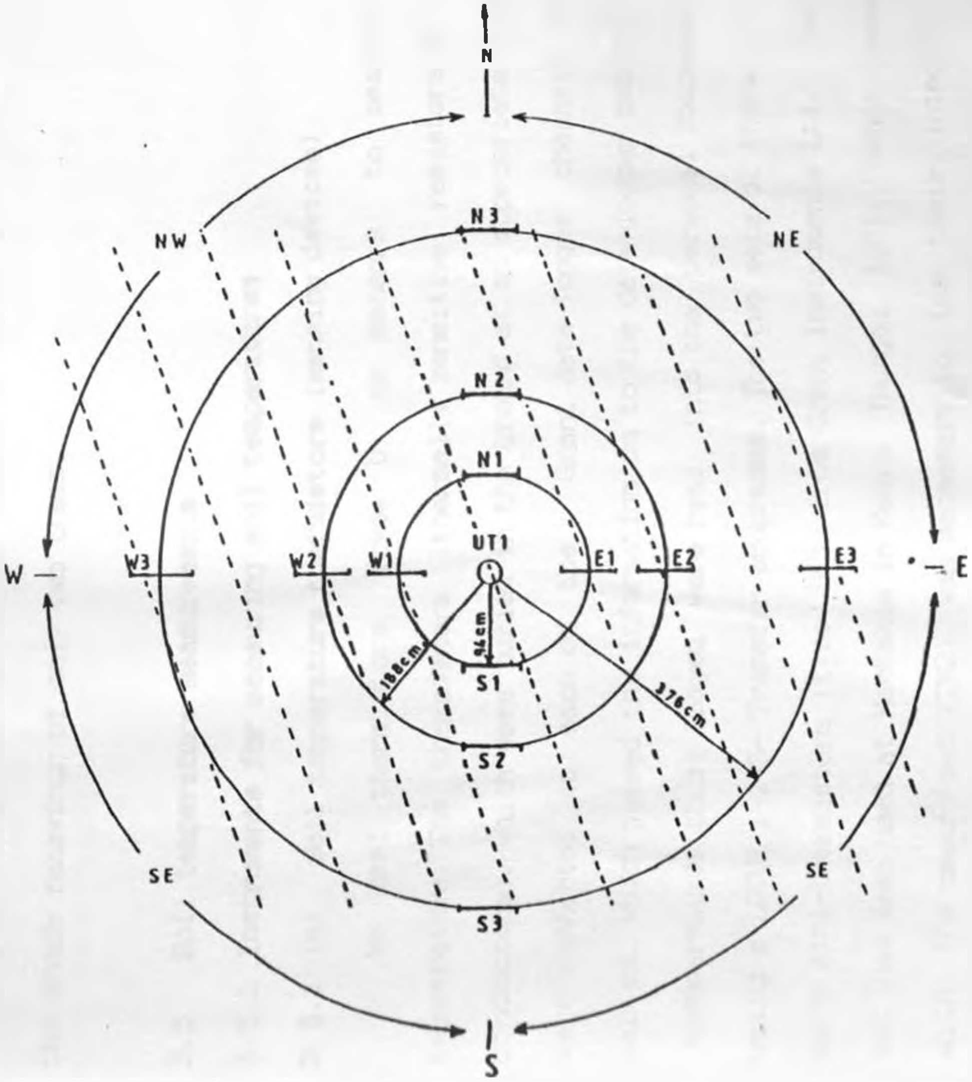


Fig. 11. A layout of tube solarimeters around one (*UT1*) of the two (UT1 & PT2) Grevillea robusta trees in AF plot whose shades were monitored.

for use as it was accidentally lost in computer during processing. Three solarimeters (two Kipps (kpi & kp2) and one tube) were installed in the open area for the experimental period. but Sr. Nr. 892505 (kp1) was later on removed because of malfunctioning.

Halverson and Smith (1974) developed a FORTRAN program that calculates the length of the shadow cast by a tree on any slope and azimuth. Quesada *et al.* (1989) developed a program written in Microsoft BASIC that plots the distribution of shadows from a specified plot of trees. Using the works of Halverson and Smith (1974) and Quesada *et al.* (1989). the shade effects of the entire AF can be quantified by knowing the shade behaviour of only two trees.

3.5 Soil temperature measurements

3.5.1 Instruments for measuring soil temperatures

3.5.1 (a) Soil temperature thermistors (sensing devices).

We used thermistors (type U) as sensors to measure soil temperature. The thermistors (thermally sensitive resistors of semi-conductors), which were buried in the ground at an appropriate depth. were connected to each of the Grant data-logger channels through cables, which passed the information on to the data-logger memory. The temperatures thus logged were read into the personal computer (PC) using a LOTUS 1-2-3- Transfer programme. The two sets of thermistors were mini-thermistors (type U") from Grant Instruments Ltd. The first set had been used at Machakos in Kenya (Mungai. 1991). hence comparison with the newer set (TM2) was necessary to test their integrity. The results are presented in section 4.5.1.

3.5.1 (b) Grant Squirrel dataloggers (logging devices)

Hourly soil temperature readings were obtained from two GRANT 8-bit 16-temperature channels. Squirrel dataloggers (type SQ32-16U) for three plots (agroforestry (AF), non-agroforestry (NAF) and a 2 m by 2 m bare soil plot (BS)). One Grant (Sr Nr 7317), with a reading range of 10°-80°C, was used in AF and the other (Sr Nr 11402) with a reading range of 0°-50°C, in NAF and BS. The Grant dataloggers were housed in two wooden boxes lined with polythene sheets to protect them from rain and other weather vagaries. Insulating materials, that is cotton wool and small pieces of paper, were laid on the bases to protect them from very low temperatures that sometimes occurred at night.

Plate 9. The layout of TSLs on wooden stands under an experimental Grevillea robusta tree in the AF (UT1) plot.

3.5.2 Calibration of soil thermistors in a Temperature-Humidity Chamber at the Kenya Meteorological Department (Nairobi).

Calibration of thermistors was carried out before they were deployed in the field for SR91. The sensors were calibrated in the Temperature-Humidity Chamber of the Kenya Meteorological Department, Dagoretti-Corner, Nairobi. The first set of fifteen soil thermistors (TM1) was calibrated on 4 & 5/6/91 while the second set (TM2) of eighteen which were received later from The Netherlands, were calibrated on 17/9/91. The almost 1:1 regression lines of TM2 on TM1 (Fig. 332) and the thermistors response to chamber temperature curves obtained during calibration exercises in the Temperature-Humidity chamber are presented in Chapter 4 section 4.5.

3.5.3 Experimental layout

3.5.3 (a) Agroforestry plot (AF)

Fig. 12 presents the soil temperature thermistor layout in the agroforestry plot (AF). Like NAF, the agroforestry thermistors (ATMs and BTMs) in AF were installed at two depths of 7.5 cm and 15 cm. Eight of the sixteen thermistors (ATMs) were installed at a distance of 94 cm from the Grevillea trees (four at each of the 7.5 cm and 15 cm depths). Similarly, the remaining eight (BTMs) were installed at a distance of 376 cm from the Grevilleas (again four at each of the 7.5 cm and 15 cm depths). There were four different plots in the AF. Each plot had two trees centered along its longitudinal line. The Grevillea trees in two of these were root-pruned and the other two had unpruned trees. One of the pruned and one of the unpruned plots were mulched. The other two were unmulched.

Two pruned (PT1 and PT2) and two unpruned (UT4 and UT5) Grevilleas had thermistors (ATMs and BTMs) installed at the distance of 94 cm and 376 cm from the tree trunks. It was expected that the soil structural and textural gradients that occur from higher to lower parts of the AF as given by its slope will be reflected, together with the influences of treatments, in the behaviour of soil temperatures.

3.5.3 (b) Non-agroforestry plot (NAF)

The entire NAF plots where soil temperature readings were taken measured 13.5 m by 25 m. This was divided into eight 12 m by 3 m replication plots, four of which were not used by us (see section 3.1.1 (c)). The other four had the maize (H511)/ bean (rosecoco) intercrop. We installed soil temperature sensors in intercropped plots only as shown in Fig. 13. Fourteen thermistors (TMs) were installed in NAF, two at each site at the depths of 7.5 and 15 cm, along the diagonals of each plot making four per plot with the 7.5 cm depth in position AM5 and one at 15 cm depth in position BM5, exception of plot M5 (positions AM5 and BM5) which had one thermistor each. Thermistors TM15 and TM16 which would have been used in these NAF plots were deployed in the bare soil plot (BS).

During the preparatory experiment in 1991, a short preliminary measurement period was conducted, prior to March 1992, in the old control plots (L1, L3, M1 & M3), before we moved all thermistors to new plots.

3.5.3 (c) Bare soil plot (BS).

A bare soil plot, measuring 2 m by 2 m, was set aside for measuring the effect of unimpeded solar heating on the soil temperatures

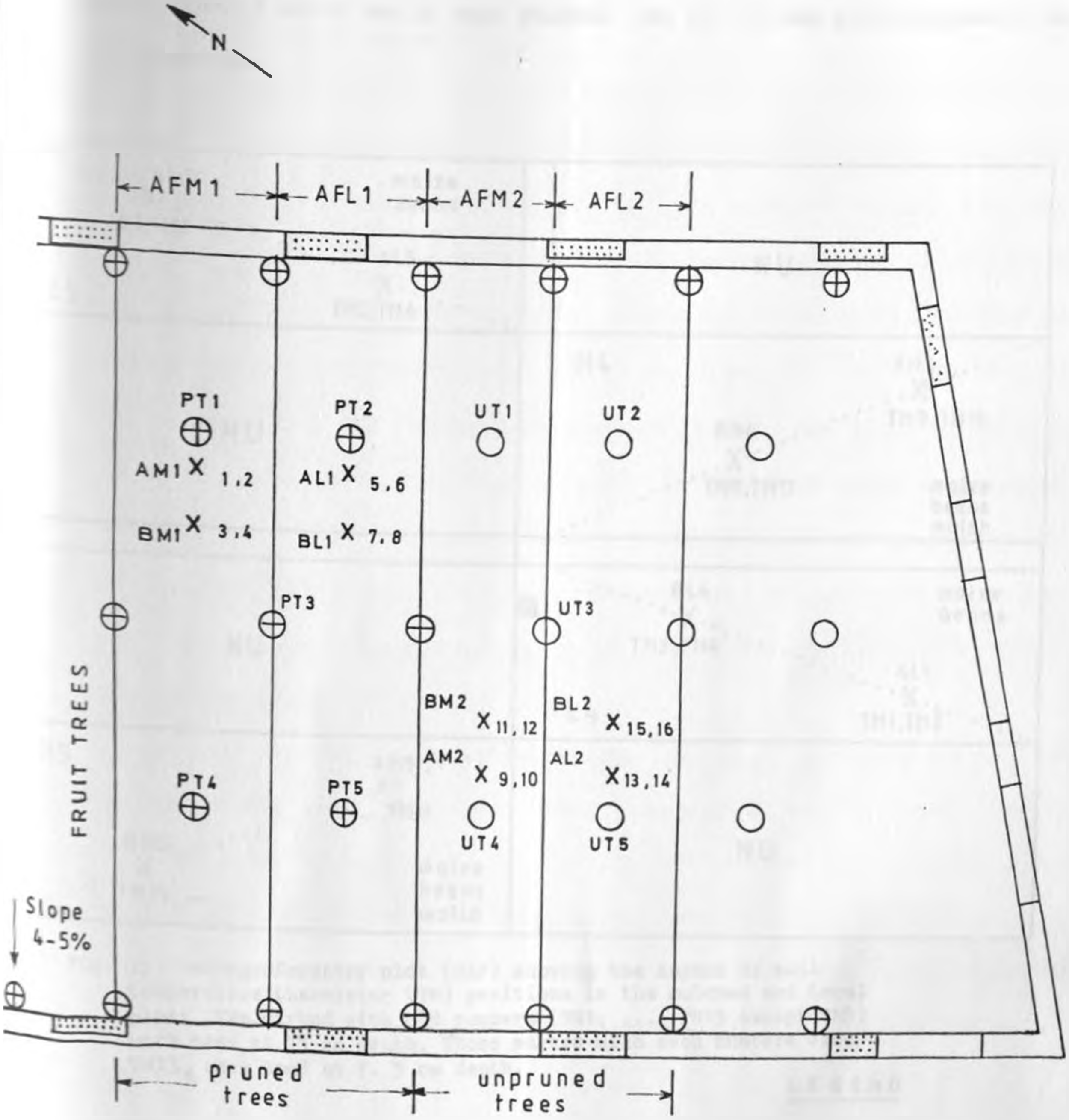


Fig. 12. Agroforestry plot at Matanya showing the layout of soil temperature thermistor (ATM) positions installed at 94 and 376 cm distances from *Grevillea robusta* trees. Note that thermistors marked with odd numbers were used to measure soil temperatures at 15 cm depth and those with even numbers at 7.5 cm depth.

at the two depths (7.5 and 15 cm). The thermistors were installed at the centre of the BS plot. The bare soil plot was on an open site far from high objects which would cast shadows on it. It was kept extremely bare all the time.

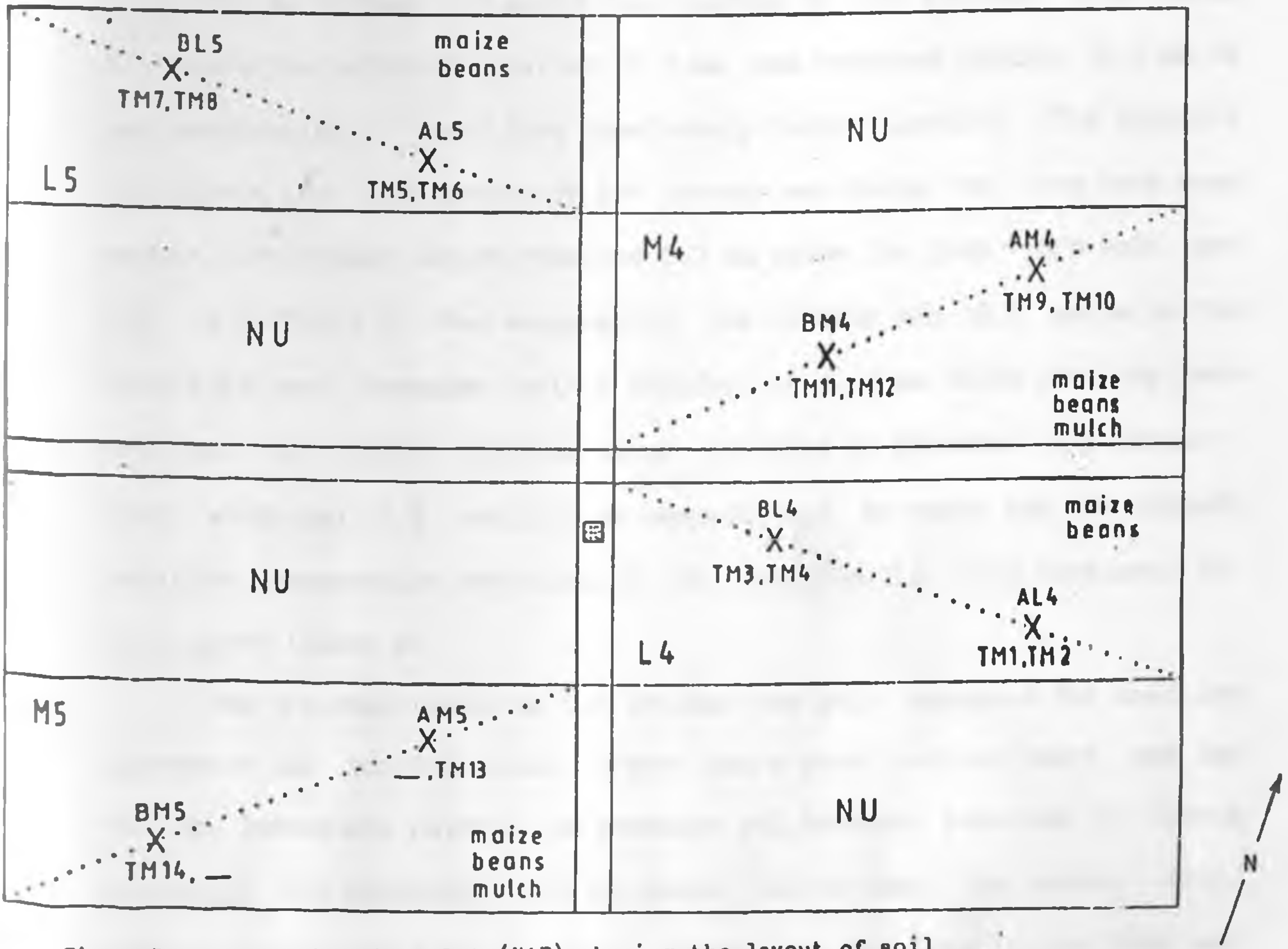


Fig. 13. Non-agroforestry plot (NAF) showing the layout of soil temperature thermistor (TM) positions in the mulched and Local plots. TMs marked with odd numbers (TM1; ...; TM15 except TM13) were used at 15 cm depth. Those marked with even numbers except TM13, were used at 7. 5 cm depth.

LEGEND

▦ instrument pox
X position of thermistors
...... diagonals of sub-plots
NU not used

CHAPTER FOUR

4. Results and discussion

4.1 Results on maize and beans intercrops

4.1.1. Short Rains season 1991

4.1.1 (a) Rainfall and evaporation climate during growing season

The maize/bean intercrop was planted on 15th October. 1991, after a cumulative rainfall total of 30.3 mm was received against 22.5 mm of pan evaporation in the 4 days immediately before planting. The rainfall throughout the four months of the season was below the long term mean except for October, which received 8.7 mm above its long term mean (see Fig. 14 & Table 6). Pan evaporation for October was 18.5 mm below the long term mean. November, with a rainfall of 43.9 mm below its long term mean had the highest negative value followed by December and January, 1992, which had 29.8 and 16.6 mm respectively. November had the highest positive evaporation deviation of 31.8 mm from its long term mean for that month (Table 6).

The rainfall received in October was only adequate for seedling emergence and initial growth. There was a good initial start and bad ending. Inadequate rainfall in November and December resulted in plants attaining the permanent wilting point fairly fast, by January 1992. Beans were harvested on 5/2/92 and maize that remained in the field was drying quite fast. The plants did not attain their optimum height of 2 m this season.

4.1.1 (b) Maize and beans phenology and soil fertility variation

Of the plants 15% in the plots that would the following year become Local control (L) and in the plots that would the following year become Mulched control plot (M), as well as 20% in agroforestry (AF).

Table 6. Seasonal monthly rainfall (mm) and pan evaporation rates (mm) for 1991-1994 Short Rains growing seasons and deviations from their long term averages.

	monthly		long term (1942-94)		actual deviations from long term means	
	rainf	evapo	rainf	evapo	rainf	evapo
SR91						
Oct	88.0	137.4	79.3	155.9	8.7	-18.5
Nov	91.4	147.1	135.3	115.3	-43.9	31.8
Dec	50.6	148.6	80.4	133.7	-29.8	14.9
Jan'92	35.7	158.2	52.3	151.2	-16.6	5.0
SR92						
Oct	48.5	159.6	79.3	155.9	-10.8	3.7
Nov	137.6	120.6	135.3	115.3	2.3	5.1
Dec	146.8	122.8	80.4	133.7	66.5	-10.9
Jan'93	204.7	105.2	52.3	151.2	152.4	-46.0
SR93						
Oct	65.2	168.2	79.3	155.9	-14.1	12.3
Nov	117.2	115.8	135.3	115.3	-18.1	0.5
Dec	48.3	174.7	80.4	133.7	-32.1	41.0
Jan'94	3.1	172.5	52.3	151.2	-49.2	21.3
SR94						
Oct	98.0	137.0	79.3	155.9	18.7	-18.9
Nov	155.2	95.2	135.3	115.3	19.9	-20.1
Dec	60.3	115.3	80.4	133.7	-20.1	-18.4
Jan'95	13.9	167.9	52.3	151.2	-38.4	16.7

Table 7. Seasonal monthly rainfall (mm) and pan evaporation rates (mm) for 1991-1994 Long Rains growing seasons and deviations from their long term averages.

	monthly		long term (1942-94)		actual deviations from long term means	
	rainf	evapo	rainf	evapo	rainf	evapo
LR92						
March	49.8	166.6	60.6	160.6	-10.8	6.0
April	99.7	141.7	122.2	138.3	-22.5	3.4
May	18.1	170.8	46.6	158.0	-28.5	12.8
June	5.2	180.9	47.5	154.3	-42.3	26.6
LR93						
March	38.6	145.6	60.6	160.6	-22.0	-15.0
April	84.7	138.2	122.2	138.3	-37.5	-0.1
May	90.4	154.4	46.6	158.0	43.8	-3.6
June	32.3	146.1	47.5	154.3	-15.2	-8.2
LR94						
March	29.5	177.0	60.6	160.6	-31.1	16.4
April	190.5	154.0	122.2	138.3	68.3	15.7
May	73.7	148.2	46.6	158.0	27.1	-9.8
June	47.5	131.0	47.5	154.3	0.0	-23.3

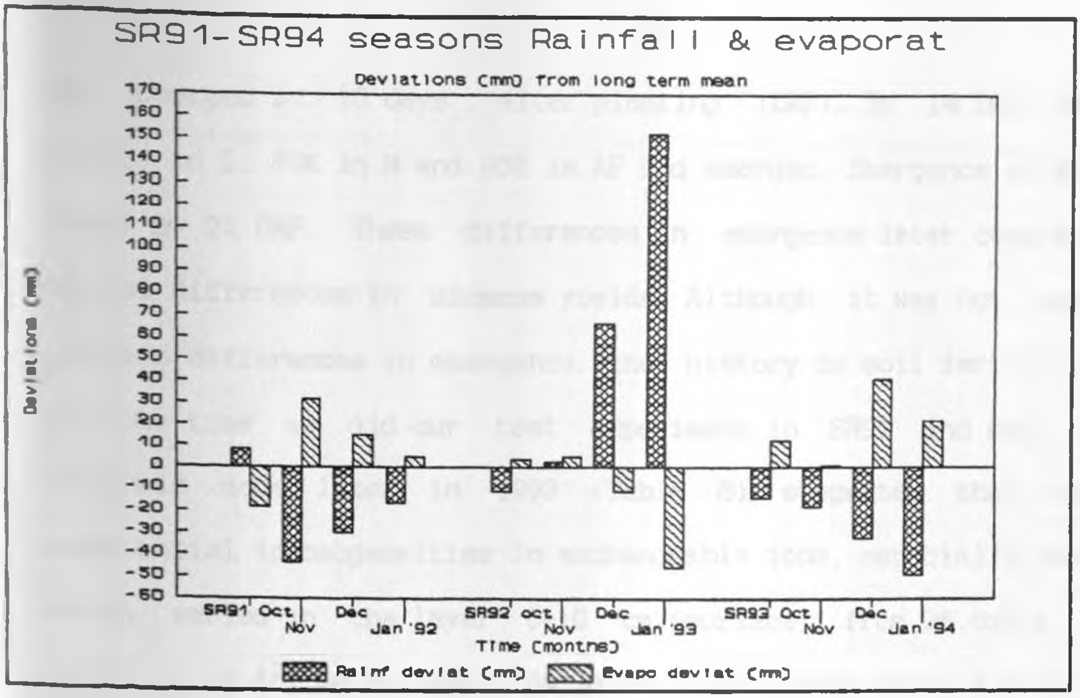


Fig. 14. Deviations (in mm) of three seasons of Short Rains (1991-1995) monthly seasonal rainfall and evaporation from long term means at Matanya.

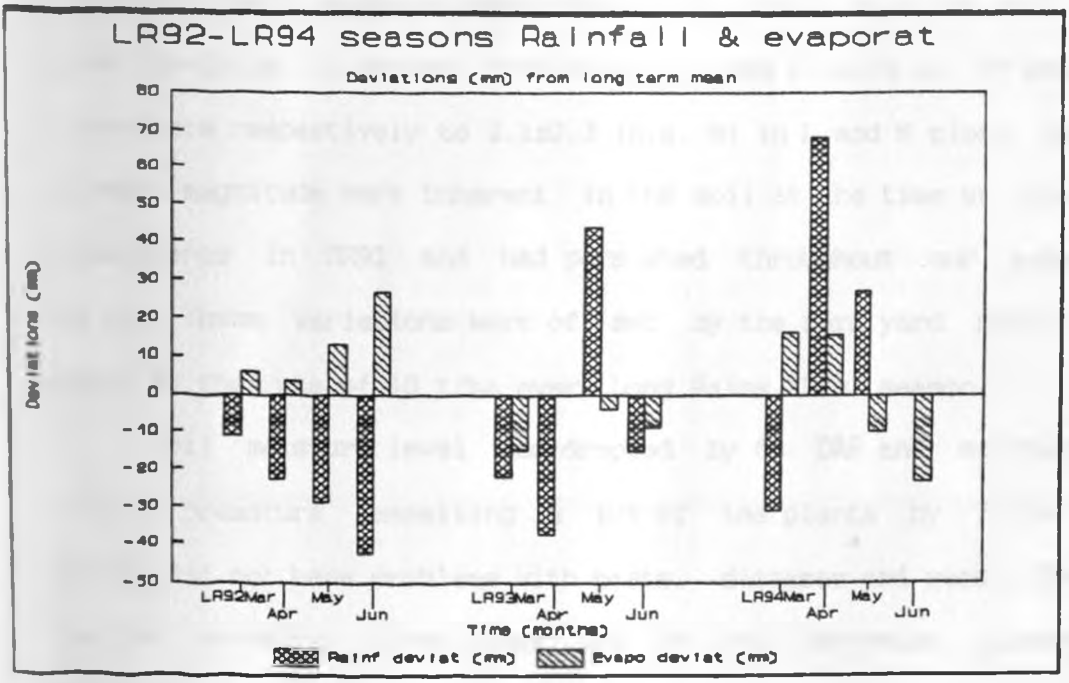


Fig. 15. Deviations (in mm) of three seasons of Long Rains 1991-1995 monthly seasonal rainfall and evaporation from long term means at Matanya.

had emerged by 10 days after planting (DAP). By 14 DAP 80% of the plants in L, 90% in M and 85% in AF had emerged. Emergence attained 100% level by 21 DAP. These differences in emergence later contributed to marked differences in biomass yields. Although it was not possible to explain differences in emergence, the history on soil fertility levels at the time we did our test experiment in SR91 and soil chemical analysis done later in 1993 (Table 8) suggested that there were substantial inhomogeneities in exchangeable ions, especially phosphorus, which varied in the layer 0–10 cm (surface) from 96.8±5.5 in L to 40.7±2.0 in AF. We can see from Table 8 that these soils are acidic with a pH of about 6.3±0.3 in the surface layers. Variations were observed in K, Mn and Mg. At the surface (0–10 cm of the soil) Mg, for example, varied from 4.1±1.1 and 5.9±1.5 in the centre of AF and in the areas closer to the live-fence respectively to 1.8±0.2 (m.e. %) in L. In the layer 20–30 cm it varied from 5.6±0.8 and 6.0±1.8 in AF and closer live-fence respectively to 2.1±0.3 (m.e. %) in L and M plots. Variations of such magnitude were inherent in the soil at the time we started our experiments in SR91 and had persisted throughout our experimental period. These variations were off set by the farm yard manure that we added at the rate of 10 t/ha every Long Rains (LRs) season.

Soil moisture level had dropped by 63 DAP and moisture stress induced premature tasselling in 10% of the plants by 78 DAP. Maize plants did not have problems with pests, diseases and weeds. The plants started drying up after tasselling. We only harvested biomass and no grain yields from the intercrop.

Table 8. Soil chemical composition at Matanya of examples taken during study period.

(a) Chemical composition in the layer 0-10 cm depth

	local	Mulch	Agrof	Livefe	average
pH. soil	6.3±0.5	6.6±0.2	6.1±0.1	6.0±0.5	6.3±0.3
Na m.e. %	1.1±0.3	0.9±0.1	0.9±0.1	1.0±0.3	1.0±0.2
K m.e. %	2.1±0.8	1.9±0.2	1.8±0.4	1.5±0.6	2.2±0.5
Ca m.e. %	11.9±0.9	9.8±0.2	7.9±1.4	9.4±3.1	9.8±1.4
Mg m.e. %	1.8±0.2	2.1±0.2	4.1±1.1	5.9±1.5	3.5±0.8
Mn m.e. %	0.8±0.2	0.8±0.1	1.3±0.2	1.2±0.0	1.0±0.1
P p.p.m.	96.8±5.5	53.3±33	40.7±2.0	88±71	69.7±27.4
N %	0.3±0.1	0.2±0.0	0.3±0.2	0.2±0.1	0.3±0.1
C %	2.4±0.5	1.4±0.1	1.1±0.2	1.5±0.3	1.6±0.3

(b) Chemical composition in the layer 20-30 cm depth

	local	Mulch	Agrof	Livefe	average
pH. soil	5.5±0.2	6.5±0.2	6.3±0.3	6.1±0.6	6.1±0.3
Na m.e. %	1.2±0.2	0.8±0.2	0.9±0.1	1.0±0.3	1.0±0.2
K m.e. %	2.4±0.7	1.5±0.2	1.6±0.1	1.5±0.6	1.8±0.4
Ca m.e. %	11.6±0.9	8.5±0.8	9.8±2.5	8.8±1.5	9.7±1.4
Mg m.e. %	2.1±0.3	2.1±0.2	5.6±0.8	6.0±1.8	4.0±0.8
Mn m.e. %	0.8±0.1	0.7±0.1	1.0±0.1	0.9±0.1	1.0±0.1
P p.p.m.	86.5±0.6	28.5±9.0	42.0±6.0	96±90	63.3±26.4
N %	0.2±0.1	0.4±0.5	0.2±0.0	0.2±0.1	0.3±0.2
C %	1.7±0.2	1.4±0.1	1.8±0.3	1.1± 0.1	1.5±0.2

NB:

ph, soil- degree of acidity or alkalinity;
Na, K, Ca, Mg & Mn m.e. % - per cent molar equivalent of these chemicals in the soil;
P p.p.m. - parts per million of phosphorus in the soil;
N & C % - per content in the soil.

By 14 DAP, 85% of the beans in L and AF and 100 % in M plots had emerged. By 44 DAP, 10% of the beans in L and AF and 20% in M plots had flowered. Flowering was completed by 49 DAP. The plants started wilting by 77 DAP due to lack of moisture and by 83 DAP they were drying *en masse*. Again there were no problems associated with pest, diseases, and weeds before soil moisture level dropped.

The biomass and seed yields from beans were harvested on 110 DAP (2/2/92). We here therefore present the following results for this season: (i) maize heights in control (L and M) plots and AF; (ii) grain and biomass yields in each of these plots.

4.1.1 (c) Maize heights

Fig. 16 displays growing maize heights during SR91 in the those plots that would in the following year become Local (L) and in the those plots that would in the following year become Mulched (M) and AF plots. The time scale adopted here is the julian day (i.e. successive number of days in a year (DOY) : 1-365 days), which we will use for most parts in this thesis. The maize heights were measured in centimetres.

We see from Fig. 16 that the plants in the Mulched plots had outgrown those in the AF and Local respectively. However, the whole picture of Fig. 16 indicated that plants were growing at uniform rate within ±15 cm. Although the final differences remain small (±7-8 cm, if agroforestry is taken up as the average), the difference between Mulched and Local future plots, is largest. Given the equal treatment in SR91, a small inherent fertility difference (explained in Table 8) due to previous seasons, with mulch application may be behind this difference, because that may not fully vanish by deep tillage.

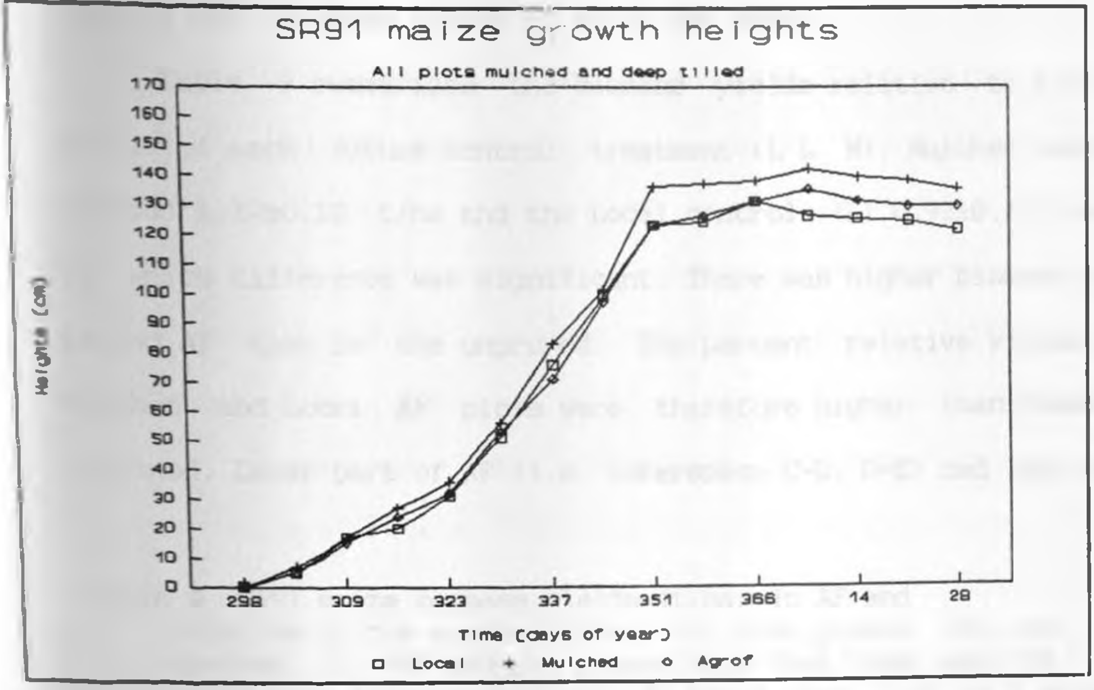


Fig. 16. SR91 maize heights for three plots: Local, Mulched and agrofrestry at Matanya, equally treated (deep tilled plus mulching).

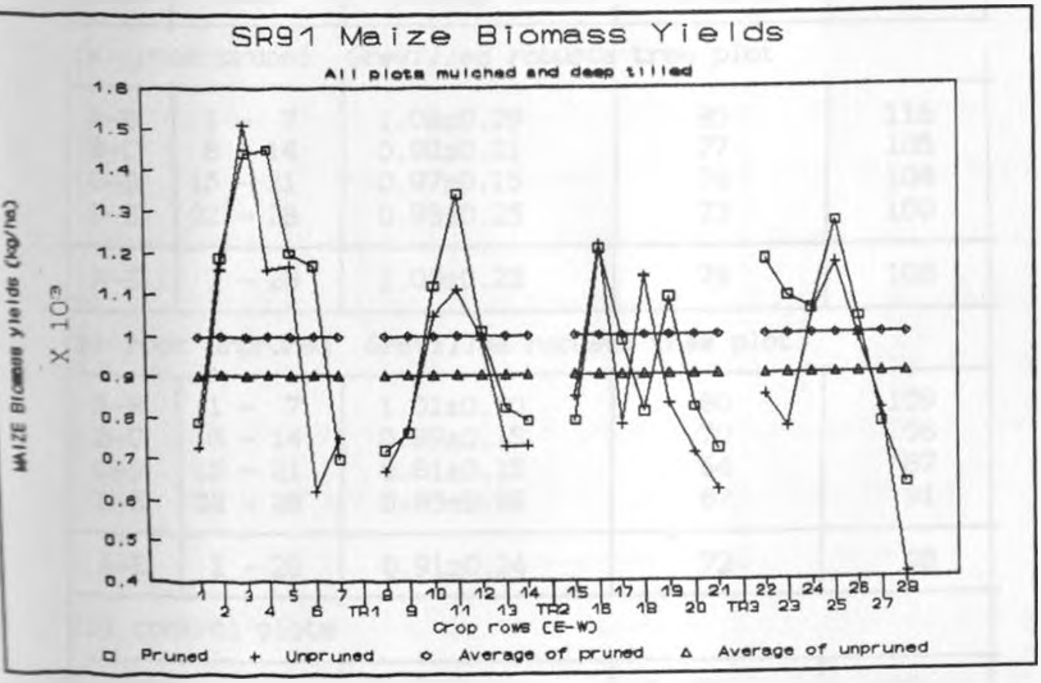


Fig. 17. Average SR91 maize biomass yields per row in equally treated (deep tilled plus mulching) pruned and unpruned plots in the AF, and mean yields for all pruned and unpruned plots respectively (horizontal lines).

4.1.1 (d) Biomass yields of maize and beans

Table 9 summarizes the biomass yields relative to the average yields of each future control treatment (L & M). Mulched control (M) yielded 1.27±0.10 t/ha and the Local control (L) 0.93±0.19 t/ha (Table 9), which difference was significant. There was higher biomass yield in pruned AF than in the unpruned. The percent relative yields in both Mulched and Local AF plots were therefore higher than those in the unpruned. Lower part of AF (i.e. interspace C-D, D-E) had less actual as

Table 9. SR91 maize biomass yields (t/ha) in AF and relative to the control plots. (a) root pruned, (b) root unpruned, (c) NAF control plots. Note that there were 28 maize rows intercropped with 32 beans rows, that is 7 maize was in the space (interspace) between two *Grevillea robusta* tree rows. This layout was used for all seasons except LR92.

Between tree rows	Between maize rows	average maize yields (t/ha)	% of M	% of L
(a) root pruned *Grevillea robusta* tree plot				
A-B	1 - 7	1.08±0.29	85	116
B-C	8 - 14	0.98±0.21	77	105
C-D	15 - 21	0.97±0.15	76	104
D-E	22 - 28	0.93±0.25	73	100
A-E	1 - 28	1.00±0.23	79	108
b) root unpruned *Grevillea robusta* tree plot				
A-B	1 - 7	1.01±0.30	80	109
B-C	8 - 14	0.89±0.15	70	96
C-D	15 - 21	0.81±0.15	64	87
D-E	22 - 28	0.85±0.28	67	91
A-E	1 - 28	0.91±0.24	72	98
(c) control plots				
Local (L)		0.93±0.19	73	100
Mulched (M)		1.27±0.10	100	137

well as percentage relative yields than the upper part (i.e. A-B. B-C).

A comparison of pruned versus unpruned plots indicate the yields were higher in the former than in the latter byabout 10% (Fig. 17 and Table 9). The root pruning somewhat reduced competition for soil moisture between the trees and the maize in the intercrop, resulting in more biomass yields in the pruned portion of the AF. Termites had built their nests in the lower part of AF (< 2% of AF plot), thereby affecting the soil homogeneity, root penetration and hence crop growth and resultant biomass yields. This area was excluded from further analysis.

Figs. 18 & 19 show the beans biomass and seed yields for the SR91 in pruned and unpruned plots. Bean rows were not shown in Fig. 9, only maize rows were shown. Also bean rows did not coincide with the tree rows in the intercrop but maize rows did. The gaps in the graphs therefore denote positions of the tree rows relative to the bean rows. The results of the beans biomass and seeds yields are also presented as the row averages in pruned and unpruned plots.

According to Fig. 18 there were only small differences in average biomass yields between the pruned and unpruned plots, although the former appeared to have somewhat more. In the lower half of the AF, the unpruned had more biomass than the pruned, although the overall average yield for the pruned plot was 6.7% higher than for the unpruned plots. These higher biomass yields in this part of the unpruned AF were probably due to more soil moisture in the surface layers of this part than in the pruned part of the plot, which bordered the fruit trees whose roots might partially have colonized this part of the plot. The bean plants have shallow roots and may also have been affected less by termite nests in deeper layers of the soil than the maize plants with deeper roots. Hence maize biomass yields were lower than bean biomass

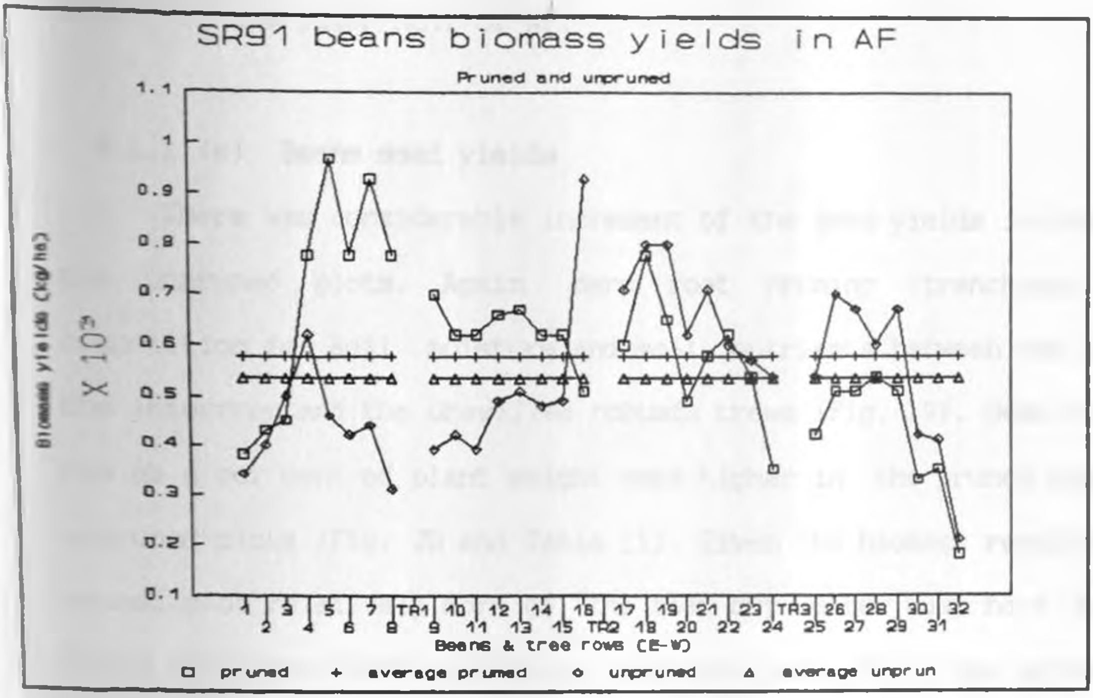


Fig. 18. Average SR91 beans biomass yields per row in equally treated (deep tilled plus mulching) pruned and unpruned plots in the AF, and mean yields for all pruned and unpruned plots respectively (horizontal lines).

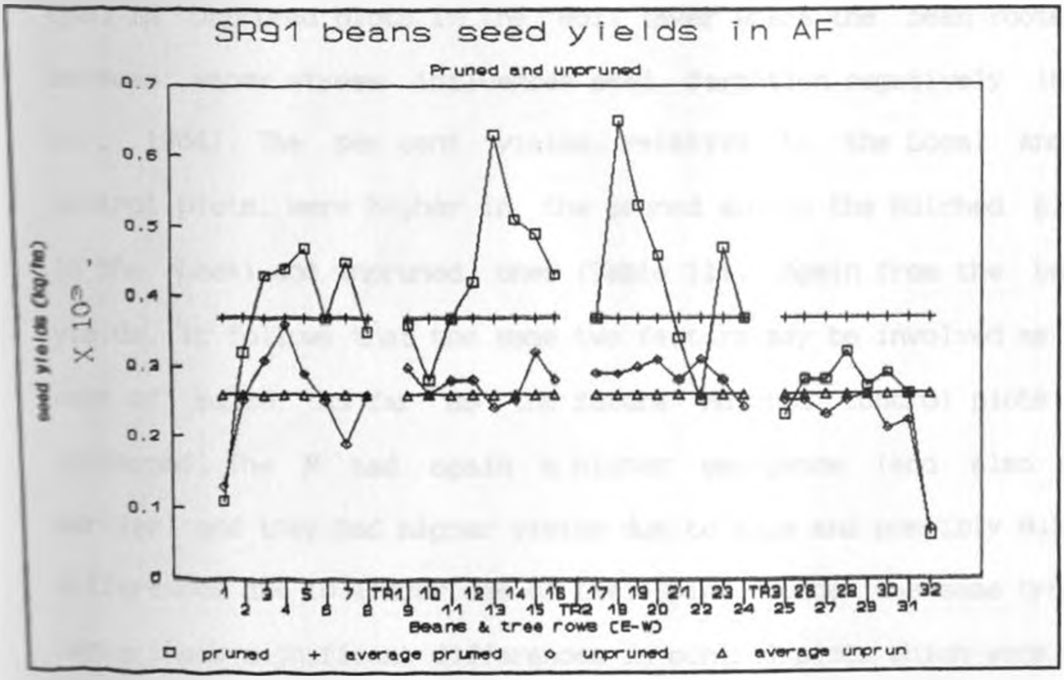


Fig. 19. Average SR91 beans seed yields per row in equally treated (deep tilled plus mulching) pruned and unpruned plots in the AF, and mean yields for all pruned and unpruned plots respectively (horizontal lines).

yields in the lower half of AF.

4.1.1 (e) Beans seed yields

There was considerable increment of the seed yields in pruned over the unpruned plots. Again here root pruning (trenching) reduced competition for soil moisture and soil nutrients between the beans in the intercrop and the *Grevillea robusta* trees (Fig. 19). Seed yields per row as a per cent of plant weight were higher in the pruned than in the unpruned plots (Fig. 20 and Table 11). Given the biomass results for the pruned plot relatively more of the bean dry matter must have gone into seeds under the SR91 conditions than into pods. Seeds are agronomically more important than the remaining dry matter although pod residues may be used as fodder (!). The average seed yield as percentage of plant weight was 38.9% in the pruned and 27.4% in the unpruned (Tables 10 & 11). This might have been due to higher soil moisture in pruned plots than in unpruned plots in the soil layer where the bean roots ramify, because water stress influences seed formation negatively (Norman et al., 1984). The per cent yields, relative to the Local and Mulched control plots, were higher in the pruned and in the Mulched plots than in the Local and unpruned ones (Table 11). Again from the beans seed yields, it follows that the same two factors may be involved as in the case of maize, as far as the future Mulched control plots (M) is concerned. The M had again a higher emergence (and also flowered earlier) and they had higher yields due to this and possibly Mulch/Local differences due to longer use of these plots under the same treatments. Hence these significant differences in control plots which were observed in maize biomass yields, (Table 9) and in beans biomass yields (Table

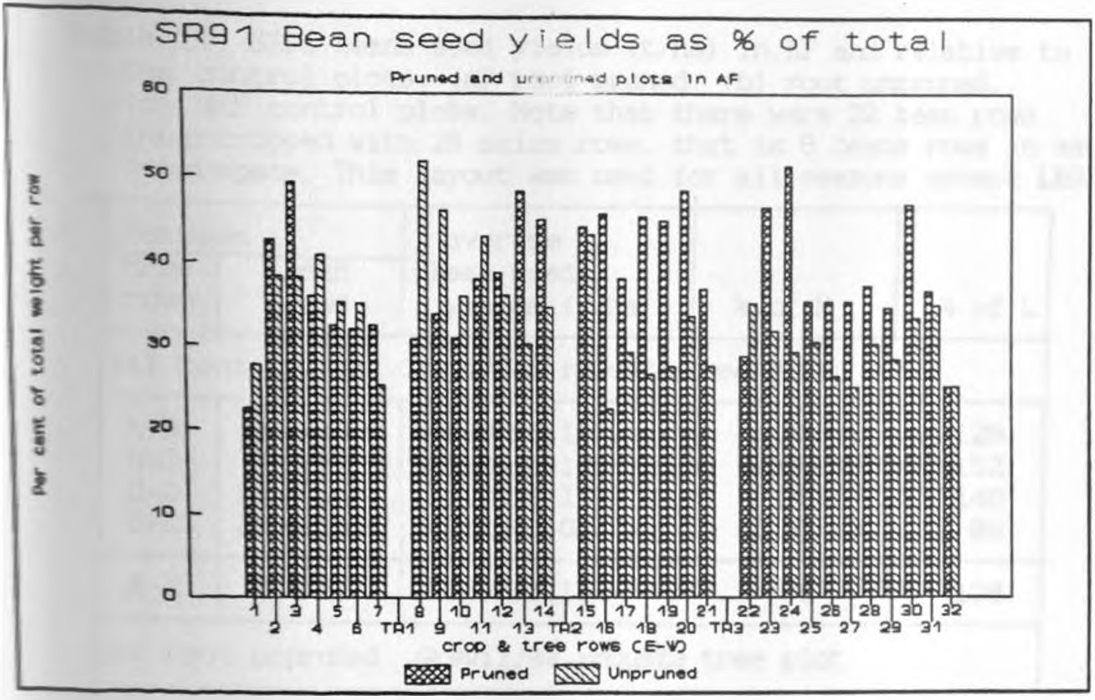


Fig. 20. SR91 beans seed weight as a percentage of total plant weight per row in the same pruned and unpruned plots in the AF of Fig. 17.

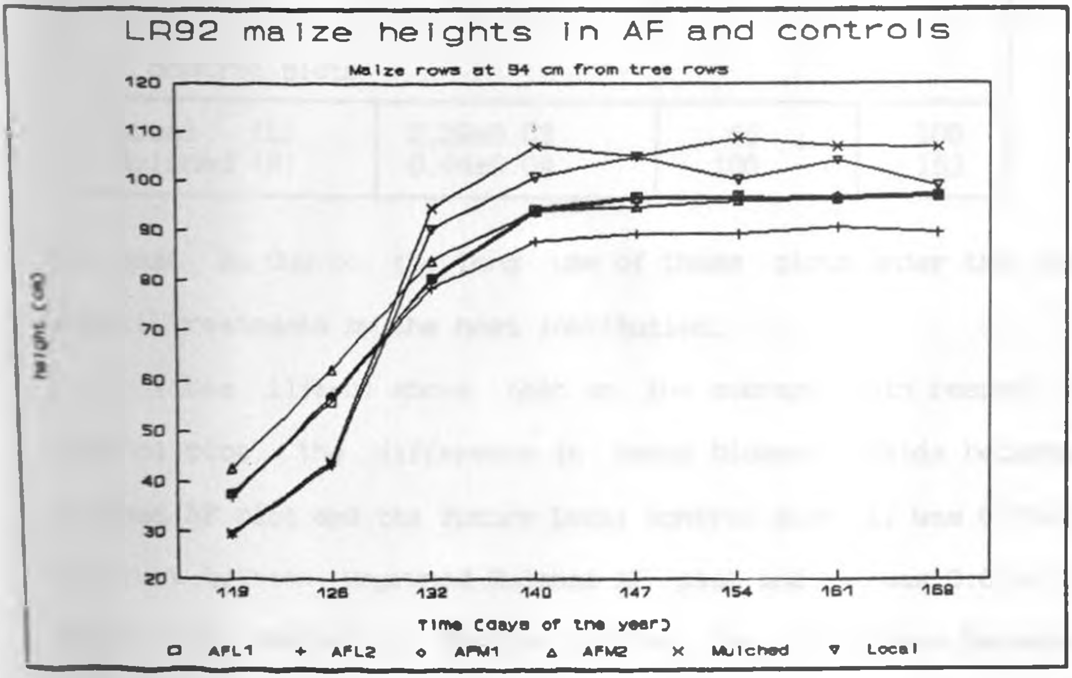


Fig. 21. Maize heights at 94 cm from *Grevillea robusta* row (row 1 of maize) in AF plots for LR92, for four differently treated series of plots (pruned and unpruned Local and Mulched) and the control plots.

Table 10. SR91 beans seed yields (t/ha) in AF and relative to the control plots. (a) root pruned. (b) root unpruned. (c) NAF control plots. Note that there were 32 bean rows intercropped with 28 maize rows, that is 8 beans rows in each interspace. This layout was used for all seasons except LR92.

Between		average bean seed yields (t/ha)	% of M	% of L
tree rows	bean rows			
(a) root pruned *Grevillea robusta* tree plot				
A–B	1 - 8	0.37±0.11	84	128
B–C	9 - 16	0.44±0.10	100	152
C–D	17 - 24	0.43±0.12	98	148
D–E	25 - 32	0.25±0.02	57	86
A–E	1 - 32	0.37±0.13	84	128
(b) root unpruned *Grevillea robusta* tree plot				
A–B	1 - 8	0.26±0.07	59	90
B–C	9 - 16	0.28±0.02	64	97
C–D	17 - 24	0.29±0.02	66	100
D–E	25 - 32	0.22±0.06	50	76
A–E	1 - 32	0.26±0.05	59	90
(c) control plots				
Local (L)		0.29±0.03	66	100
Mulched (M)		0.44±0.04	100	152

10) must be due to the long use of these plots under the same Mulch /Local treatments by the host institution.

Table 11(a–c) shows that on the average with respect to Local control plot, the difference in beans biomass yields between pruned Mulched AF plot and the future Local control plot (L) was 0.06±0.22 t/ha and that between unpruned Mulched AF plot and L was 0.02±0.21 t/ha, while with respect to Mulched control, the difference between pruned Mulched AF plot and the future Mulched control plot (M) was 0.12±0.29 t/ha and that between unpruned Mulched AF plot and M was 0.16±0.28 t/ha.

Table 11. SR91 beans biomass yields (t/ha) in AF. (a) root pruned. (b) root unpruned. (c) control

interspace	(a) pruned	(b) unpruned
A - B	0.69±0.22	0.44±0.07
B - C	0.63±0.05	0.51±0.16
C - D	0.58±0.12	0.67±0.09
D - E	0.42±0.12	0.58±0.16
A - E	0.58±0.17	0.54±0.16

(c) control

Local (L)	0.52±0.05
Mulched (M)	0.70±0.12

These differences were much smaller than their error margins and therefore should be considered agronomically irrelevant.

4.1.2 Long Rains season 1992

4.1.2 (a) Rainfall and evaporation climate during growing season

The intercrop of maize and beans for the Long Rains 1992 (LR92) growing period was planted on 23th March, 1992 after a total rainfall of 24.3 mm was received in 9 days against pan evaporation of 33.2 mm prior to the sowing date at Matanya station. An additional rainfall amount of 13.4 mm was obtained on the day of planting. Seedling emergence and establishment was very poor. There were few seed yields for beans and no grain yields for maize during LR92. There were some biomass yields for maize and beans albeit in reduced tonnage per hectare. The maize did not reach the tasselling and silking phases.

The rainfall totals for March, April, May and June (LR92) were way below their long term means (see Fig. 15 & Table 7). Increasing/ negative deviations were experienced from the beginning to the end of the season. The months of May and June received 28.5 and 42.3 mm respectively below their long term means. March and April at the beginning of the season received 10.8 and 22.5 mm respectively below their long term mean values. The actu deviations of pan evaporation were all positive in the four months. The highest deviation, of 26.6 mm above the long term mean, was experienced in June and the minimum of 3.4 mm in April. Matanya received a total moisture deficit of 487.2 mm for the four months of these Long Rains. The rainfall therefore fell short of that expected to support crop production.

4.1.2 (b) Maize and beans phenology

By 30th March (i.e. 7 DAP) 30% of the maize seedlings in the AF and 20% in the other treatments (control plots) had emerged. Emergence of 100% was attained by 15 DAP. The soil moisture level had dropped soon after emergence. although the plants had survived for some time before starting to wilt. The wilting began by 57 DAP before tasselling and silking phases were reached. We assessed the general conditions as unsatisfactory on 56 DAP.

By 7 DAP 20% of the beans bean seedlings in the control plots and 30% in the AF emerged. Emergence of the beans seedlings reached 100% by 15 DAP. 50 DAP complete flowering had been achieved. Plants started experiencing water stress by 64 DAP. Ripening was completed at the same time as the plants were drying up. by 85 DAP. Due to water stress and attack by fungal diseases, mainly smut, the plants were in unsatisfactory condition. Both the seeds and biomass were harvested on 7-9th July, 1992 (near the 105 DAP).

Like for the SR91, we present results of maize heights and biomass yields for both maize and beans, and seeds for beans alone. in the intercrop in the (i) Mulched and Local control and AF plots. (ii) four AF sub-plots with pruned and unpruned *Grevillea robusta* trees. There were no grain yields for maize.

4.1.2 (c) Maize heights

Fig. 21 presents maize heights at 94 cm from Grevillea rows (i.e row 1) in the AF plots. The plants in the pruned Local at day 147 and beyond were about 8 cm or less taller than those in the unpruned Local. The plants in the pruned Mulched plot had a slow initial growth compared to those in the unpruned Mulched plots in the beginning but attained and remained at the same height by day 140. In fact 140 days onwards, in the AF plots only unpruned Local showed a difference with the others. The plants in rows 188 cm from tree rows grew at the same rate from DOY 119 till 132 when those in AFL2 remained behind and from DOY 140 the AFM2 plants overtook the rest (Fig. 22). The plants in the rows at 282 cm from the tree rows (i.e. row 3, Fig. 23) had an initial head start in the pruned Local plot but were from day 147 onwards overtaken by those in pruned Mulched plot. Particularly the final differences between unpruned and pruned Mulched plots, in order of 20 cm from day 147 onwards, is striking. In the Local plots this difference was less than 10 cm at maximum.

Fig. 24 presents the average heights for plants in rows 4 at 376 cm from tree rows. We can see here that the plants in unpruned Local (AFL2) plot, had initial head start, reaching 10 cm more at maximum and remained ahead throughout. They were followed by those in pruned Local (AFL1) and then by those in AFM2, but these differences are even smaller.

A comparison of AF sub-plots with the control plots (Figs. 21-24) reveals that for all the distances plants in both control treatments (Mulched control and Local control) had slow initial growth but they overtook the others towards the end of the season by DOY 132. Plants in Mulched NAF plots were must often the tallest in three cases immediately

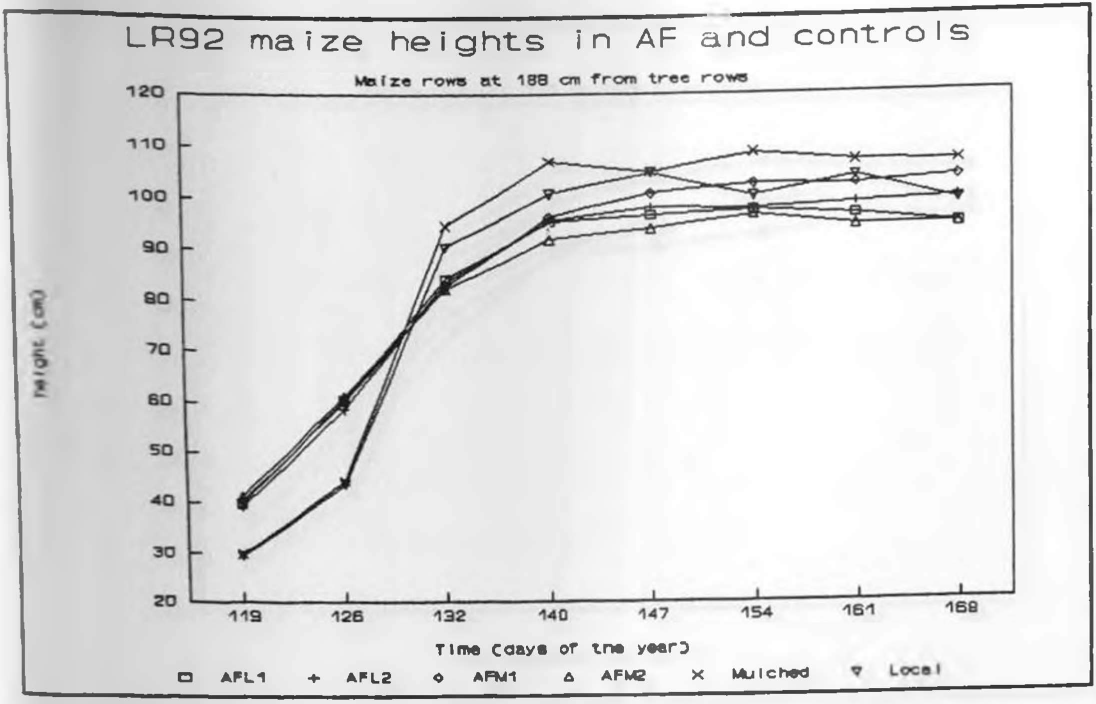


Fig. 22. Maize heights at 188 cm from *Grevillea robusta* row (row 2 of maize) in the same AF plots as in Fig. 21 for LR92.

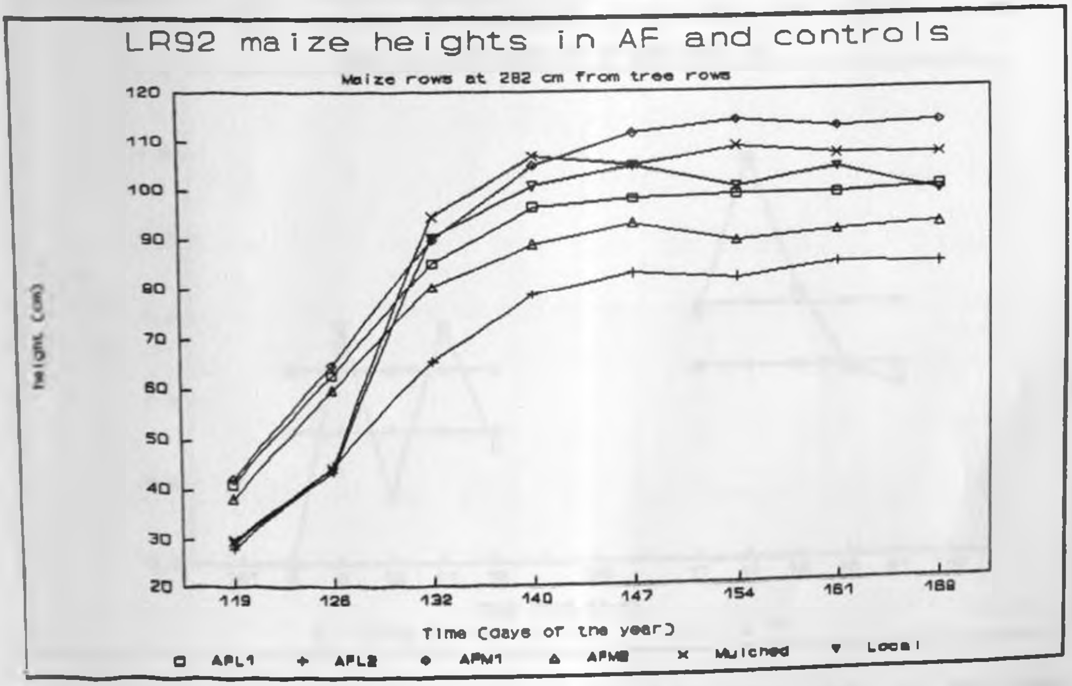


Fig. 23. Maize heights at 282 cm from *Grevillea robusta* row (row 3 of maize) in the same AF plots as in Fig. 21 for LR92.

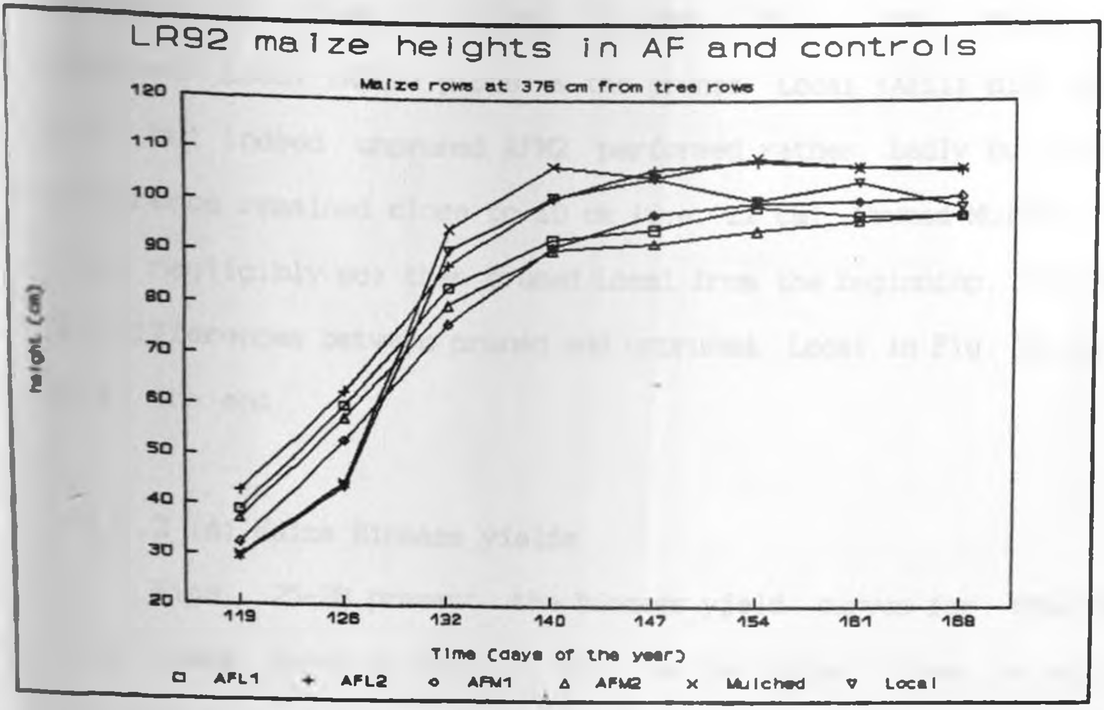


Fig. 24. Maize heights at 376 cm from *Grevillea robusta* row (row 3 of maize) in the same AF plots as in Fig. 21 for LR92.

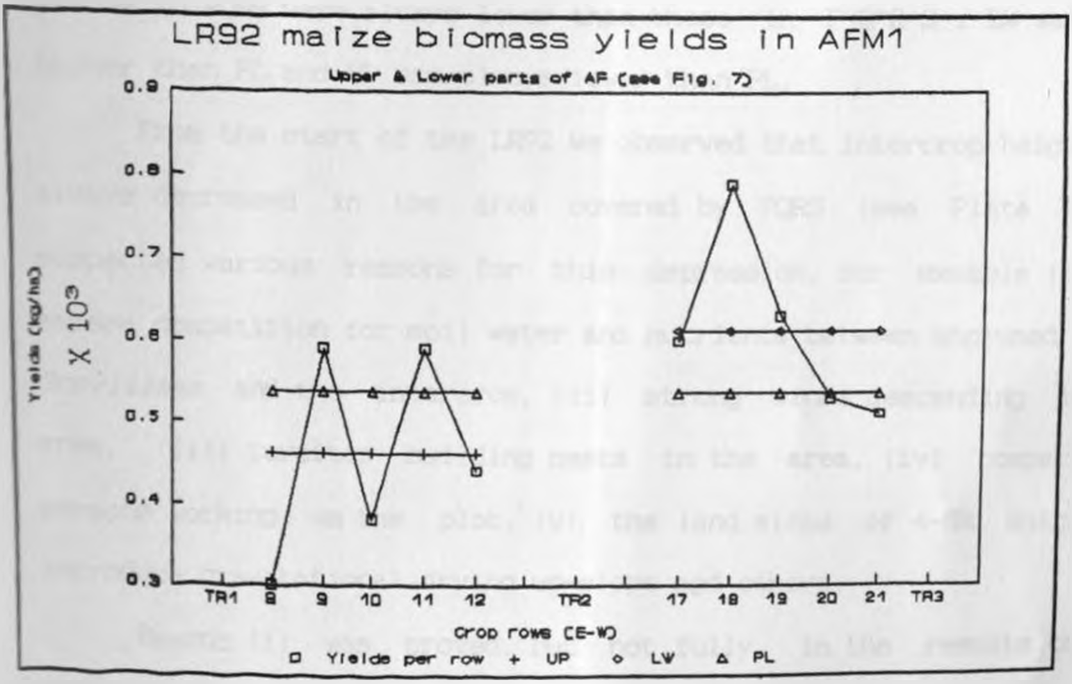


Fig. 25. Average LR92 maize yields per row in Mulched pruned (AFM1) plot. LW and UP are respectively average yields in the lower (rows 17-21) and upper (rows 8-12) parts of AFM1. PL is average yield for entire AFM1 plot.

followed by those in pruned Mulched (AFM1). Local control and the unpruned Local (AFL2) plots & the pruned Local (AFL1) did not differ much but indeed unpruned AFM2 performed rather badly but the height difference remained close to 10 cm (i.e. 12 cm). Pruned Mulch is higher (but negligibly so) than pruned Local from the beginning, till day 132. The differences between pruned and unpruned Local in Fig. 23 is also 20 cm at the end.

4.1.2 (d) Maize Biomass yields

Figs. 25-28 present the biomass yield curves for the upper and lower areas shown in Fig. 9. The two horizontal lines in each graph indicate an overall average (PL) for each treatment plot (AFM1, AFM2, AFL1 & AFL2) and one average for the upper (UP) and another for lower (LW) areas. We observe from each of these curves that the average yields in PQRS were always lower than those in P'Q'R'S'. LW was always higher than PL and UP was always lower than PL.

From the start of the LR92 we observed that intercrop heights were always depressed in the area covered by PQRS (see Plate 10). We suspected various reasons for this depression, for example (i) more severe competition for soil water and nutrients between unpruned *Grevilleas* and the intercrop, (ii) strong winds descending into the area, (iii) termites building nests in the area, (iv) compaction by persons working on the plot, (v) the land slope of 4-5% which would introduce gravitational drying up-slope and others.

Reason (i) was proved, but not fully, in the results on soil moisture in section 4.2. The possibility of strong winds descending into the area affecting plant growth, reason (ii), was investigated by Figs.

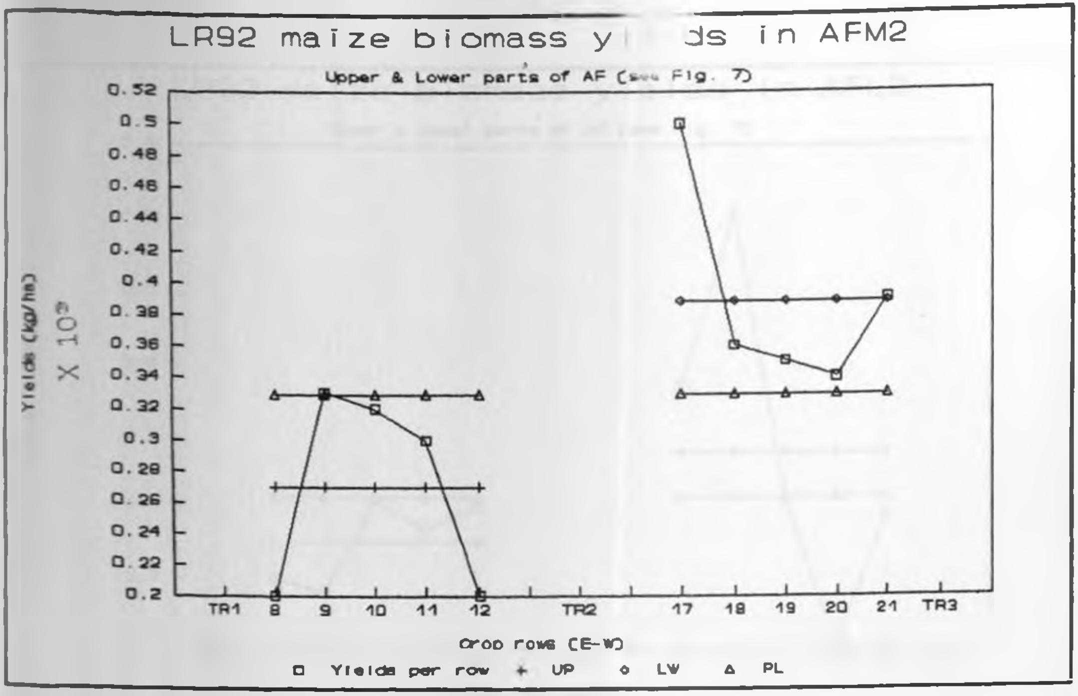


Fig. 26. Average LR92 maize yields per row in Mulched unpruned (AFM2) plot. LW and UP are respectively average yields in the lower (rows 17-21) and upper (rows 8-12) parts of AFM2. PL is average yield for entire AFM2 plot.

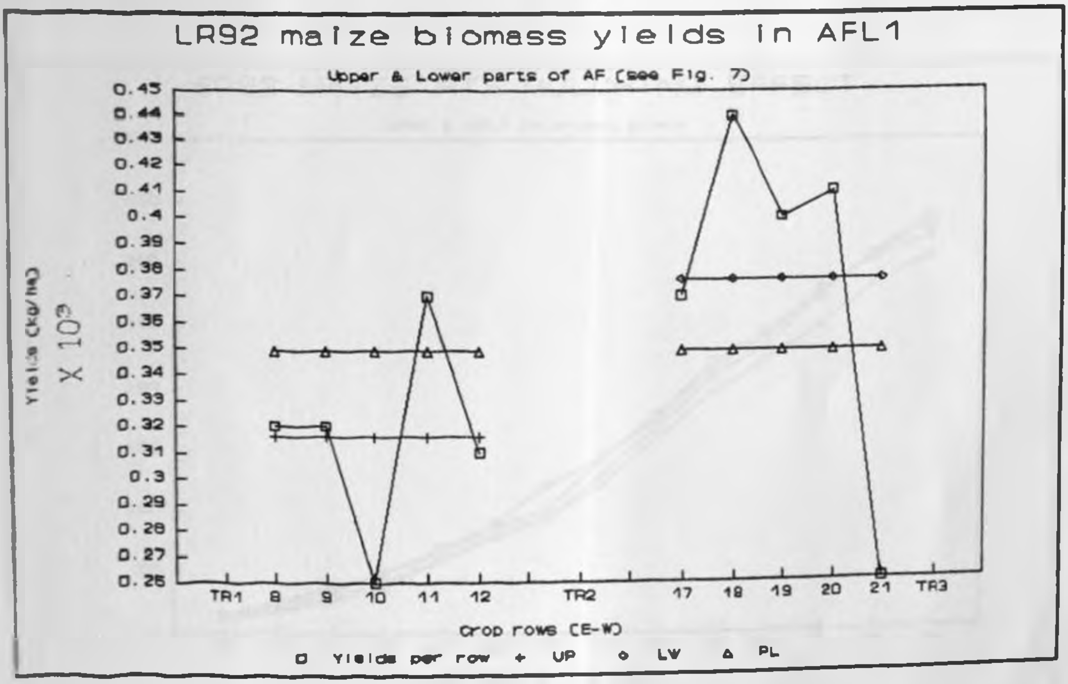


Fig. 27. Average LR92 maize yields per row in Local pruned (AFL1) plot. LW and UP are respectively average yields in the lower (rows 17-21) and upper (rows 8-12) parts of AFL1. PL is average yield for entire AFL1 plot.

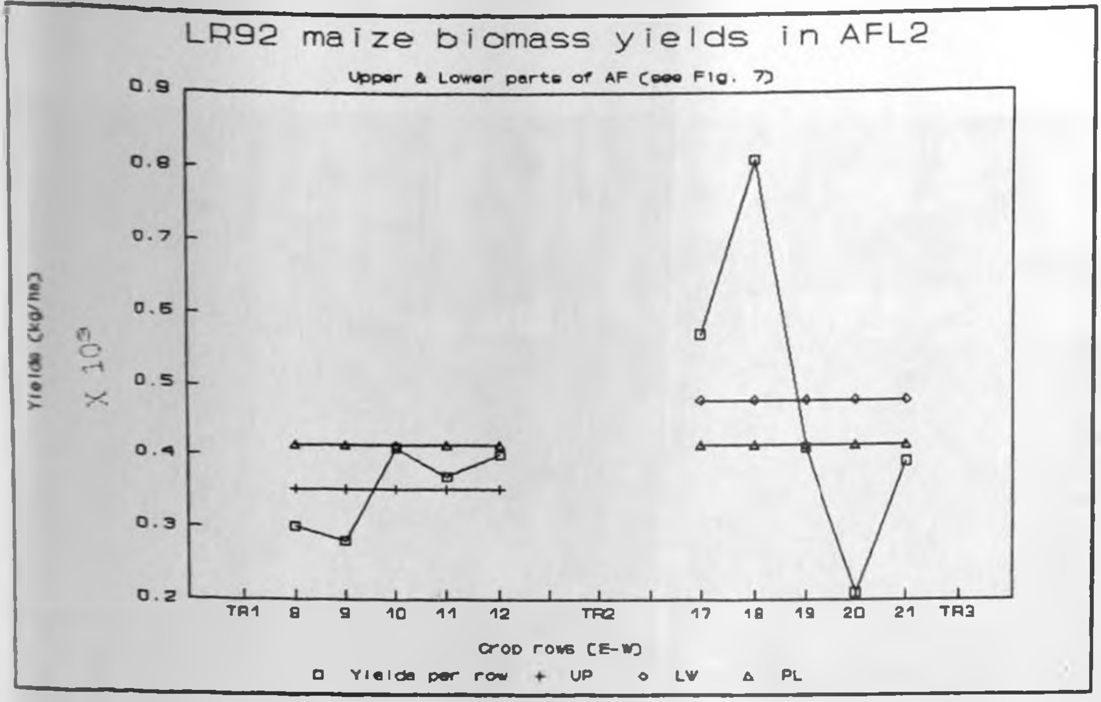


Fig. 28. Average LR92 maize yields per row in Local unpruned (AFL2) plot. LW and UP are respectively average yields in the lower (rows 17-21) and upper (rows 8-12) parts of AFL2. PL is average yield for entire AFL2 plot.

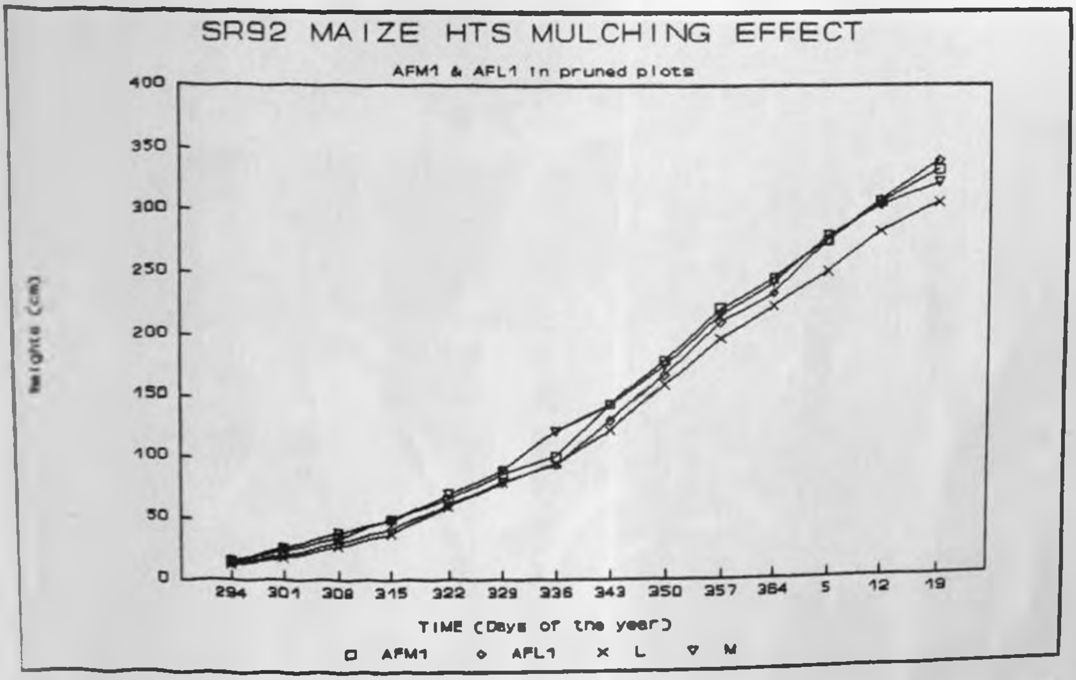


Fig. 29. Maize heights in pruned Mulched (AFM1) and pruned Local (AFL1) plots in AF and controls (M & L) for SR92.

Plate 10. SR92 harvesting of the only maize crop in the seven seasons of field work at Matanya. a smile accompanies such a harvest.

Plate 11. A picture of young maize/beans intercrop in AF showing positions of depressed plants heights.

placing a charcoal stove on the roof of the staff house in Fig. 8. There was marked subsidence in the area as demonstrated by smoke streaks, making us believe that wind down-wash could after all be most affecting the yields in the AF. For reason (iii) termites were eradicated by mixtures of insecticides but this action did not improve crop growth in this area. Reason (iv) infiltration experiments were done all over the station to try and identify any extraordinary infiltration rates. Apart from high rates in cracks in Vertic soil, infiltration rates were uniform throughout the area including AF. Reason (v) the gravitational drying up-slope was identified in soil moisture results but not per se concentrated in the area of our concern. We had therefore only reason (ii) as the major causative factor for this problem. This is because of thigmo-morphogenetic responses of plants to mechanical stimuli (Stigter, 1985) which was due to the descending winds over the nearby buildings and neighbouring high trees onto the AF plot as studied by the smoke trails. Very little is known about such thigmo-morphogenetic responses (i.e. plants response to wind: wind stressed-plants becoming more resistant to wind injury as the plants become stunted in growth) in plant growth to mechanical stimuli (e.g. Stigter, 1985; Grace, 1988), is very common in areas surrounded by structures such as buildings.

Figs. 25-28 also would show the influence of tree rows (rows B(TR1) & D(TR3)) on the maize biomass yields especially in unpruned plots (Figs. 26 & 28). Looking at the two to three maize rows closest to the trees this is especially the case in unpruned Local conditions, but the average there is higher.

Table 12 presents maize biomass and how they relate to the average yields in each of the control treatments (Local & Mulched). We see from Table 12 that the Mulched pruned plot (AFM1) had on the average the

Table 12. LR92 maize biomass yields (t/ha) in AF and relative to the control plots. (i) - (iv) and (M & L).

Between tree maize rows	average yields (t/ha)	% of L	% of M
(a) Agroforestry plot (AF)			
(i) Pruned Mulched (AFM1)			
PQRS 8 - 12	0.46±0.12	92.7	125.7
P'Q'R'S' 17 - 21	0.61±0.10	123.4	167.2
Average	0.54±0.13	108.1	146.5
(ii) Unpruned Mulched (AFM2)			
PQRS 8 - 12	0.27±0.06	54.4	73.8
P'Q'R'S' 17 - 21	0.39±0.06	78.2	106.0
Average	0.33±0.08	66.3	89.9
(iii) Pruned Local plot (AFL1)			
PQRS 8 - 12	0.32±0.03	63.7	86.7
P'Q'R'S' 17 - 21	0.38±0.06	75.8	102.7
Average	0.35±0.06	69.8	94.5
(iii) Unpruned Local plot (AFL2)			
PQRS 8 - 12	0.35±0.05	71.0	96.2
P'Q'R'S' 17 - 21	0.48±0.20	96.4	130.6
Average	0.42±0.16	83.7	113.4
(C) control plots			
Local (L)	0.50±0.11	100.0	135.5
Mulched (M)	0.37±0.08	73.8	100.0

highest per cent yields relative to the yields in each of the controls.

The positive effect of mulching on the yields could be realized yields in all the four treatments, but the that of effect of pruning could not easily be discerned as the unpruned Local (AFL2) had higher relative yields than unpruned Mulched (ii) or but lower than pruned Local (iii) plots although the differences remained small. The thigmo—morphogenetic effects as mentioned above affected mostly the AFM2 plot resulting in lower yields there than in AFL2. However, we can clearly see that a combination of mulching with minimum tillage and pruning was beneficial to the maize biomass (dry matter) accumulation.

A comparison of controls themselves shows that Local (0.50 ±0.11 t/ha) yielded more biomass than the Mulched (0.37 ±0.08 t/ha) plots (Table 12). This as earlier mentioned could be attributed more to a longer use of these plots under the same mulch /Local treatments and to variations in soil nutrients in newly opened up plots, as seen in Table 8, than in soil moisture availability .

4.1.2 (e) Beans biomass yields

Table 13 presents beans biomass yields for LR92 in the AF and control plots. As we have indicated above, the beans performance was unsatisfactory. The *Grevillea robusta* root pruned Mulched plot with

Table 13. Long Rains 1992 beans biomass yields (t/ha) compared to the controls.

(a) Agroforestry plots

Between tree rows	beans rows	average biomass yields (t/ha)	% of L	% of M
(i) unpruned Mulched (AFM2)				
PQRS	9 - 13	0.16±0.03	84.2	48.5
P'Q'R'S'	20 - 24	0.20±0.05	105.0	60.6
Average		0.18±0.04	94.7	54.5

(ii) pruned Mulched (AFM1)			
PQRS 9 - 13	0.26±0.04	136.8	78.8
P'Q'R'S' 20 - 24	0.21±0.04	110.5	63.6
Average	0.24±0.04	126.3	72.7
(iii) unpruned Local (AFL2)			
PQRS 9 - 13	0.20±0.03	105.0	60.6
P'Q'R'S' 20 - 24	0.25±0.03	131.6	75.8
Average	0.23±0.03	121.1	69.7
(iv) pruned Local (AFL1)			
PQRS 9 - 13	0.24±0.01	126.3	72.7
P'Q'R'S' 20 - 24	0.26±0.04	136.8	78.8
Average	0.25±0.03	131.6	75.8
(b) Control			
(i) Local (L)	0.19±0.02	100.0	57.6
(ii) Mulch (M)	0.33±0.07	173.7	100.0

minimum tillage (AFM1), which was our best bet for the maize biomass yields, was the worst for the beans biomass yields, although differences are small and error limits overlap. The two unpruned plots (AFM2 & AFL2) had higher yields compared to the two pruned ones (AFL1 & AFM1), but for the Local treatment the difference was negligible. The M control plot had the highest biomass yield of 0.33±0.07 t/ha while L had a biomass yield of 0.19±0.02 t/ha.

The poor performance of the pruned plots (AFM1 & AFL1) must have been due to invasion of the crop land by the neighbouring fruit tree roots in the absence of the Grevillea tree roots which were restrained by pruning. This invasion was not foreseen. The fruit trees comprising loquats and guavas bordered the pruned Mulched plot (AFM1) on one long side and the pruned Local (AFL1) was on its other side. We demonstrated this influence by digging during land preparation for the subsequent LR93. We dug 50 cm deep trenches at the borders between AFM1 and the fruit trees and between AFL1 and AFM2 to exclude the roots from the *loquat* and *guava* fruit trees and unpruned Grevilleas in the adjacent plots from invading the pruned *Grevilleas* area of the AF plot.

In an agroforestry system, tree roots from farms or woodlots may cause interference in neighbouring farms. For soil water conservation measures to succeed. one should try to exclude the threat of invasion of tree roots from the neighbouring plots.

Table 14 presents LR92 bean seed yields. Like the biomass yields. we had the highest seed yields from the Mulched unpruned plot (AFM2). The other yield differences in AF were overall very small. The Local control had clearly the lowest average yield of all. 0.03±0.03. while the Mulched control had 0.14±0.04 t/ha. of which the error limits overlap all AF averages.

4.1.3 Short Rains season 1992

4.1.3 (a) Rainfall and evaporation climate during growing season

SR92 was the most successful season of the seven seasons we worked in Laikipia district when a good harvest was obtained (see Plate 11). The Short Rains came early. on 29th September 1992. The SR92 maize/beans intercrop was planted on 4th October 1992 after a total amount of rainfall of 74.3 mm was received against evaporation of 34.5 mm. On the sowing day a rainfall amount of 4.9 mm was received.

From there on and throughout October and November rainfall occurrences were quite few. Rainfall amounts for SR92 were above the long term means for November and December, 1992, and January, 1993, by

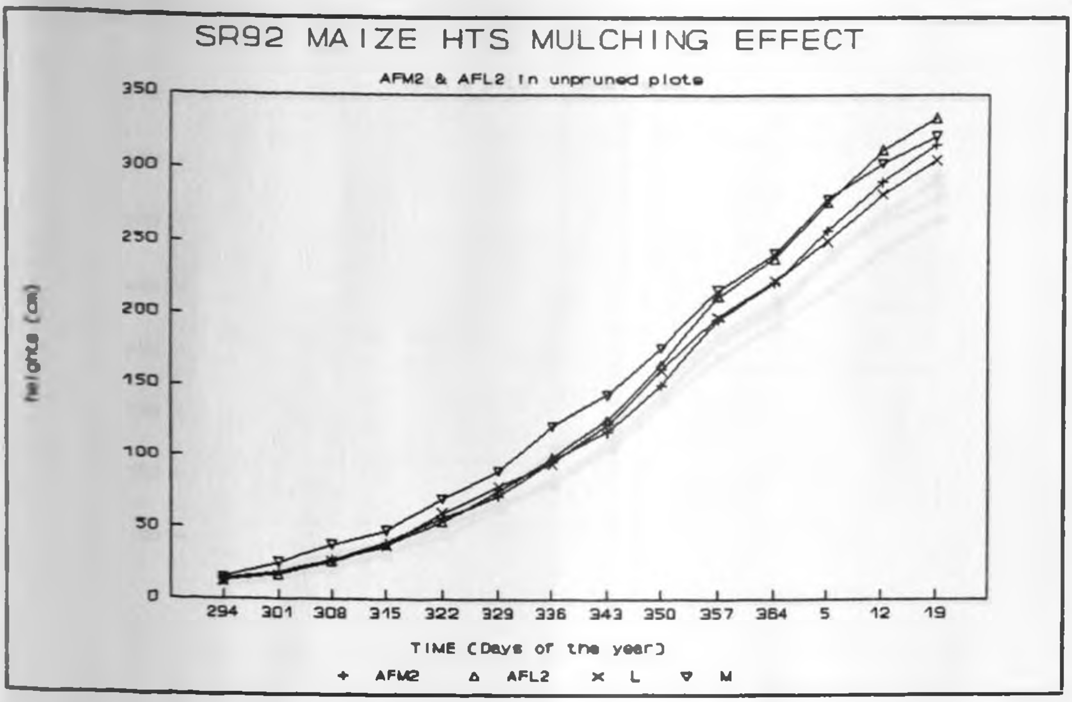


Fig. 30. Maize heights in unpruned Mulched (AFM2) and unpruned Local (AFL2) plots in AF and controls (M & L) for SR92.

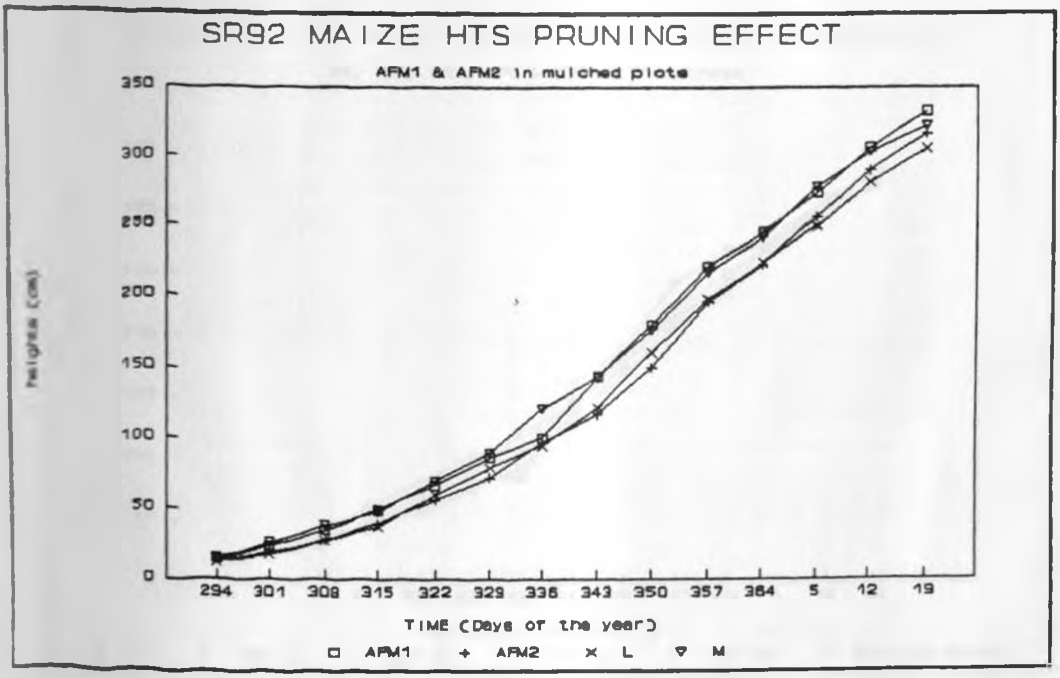
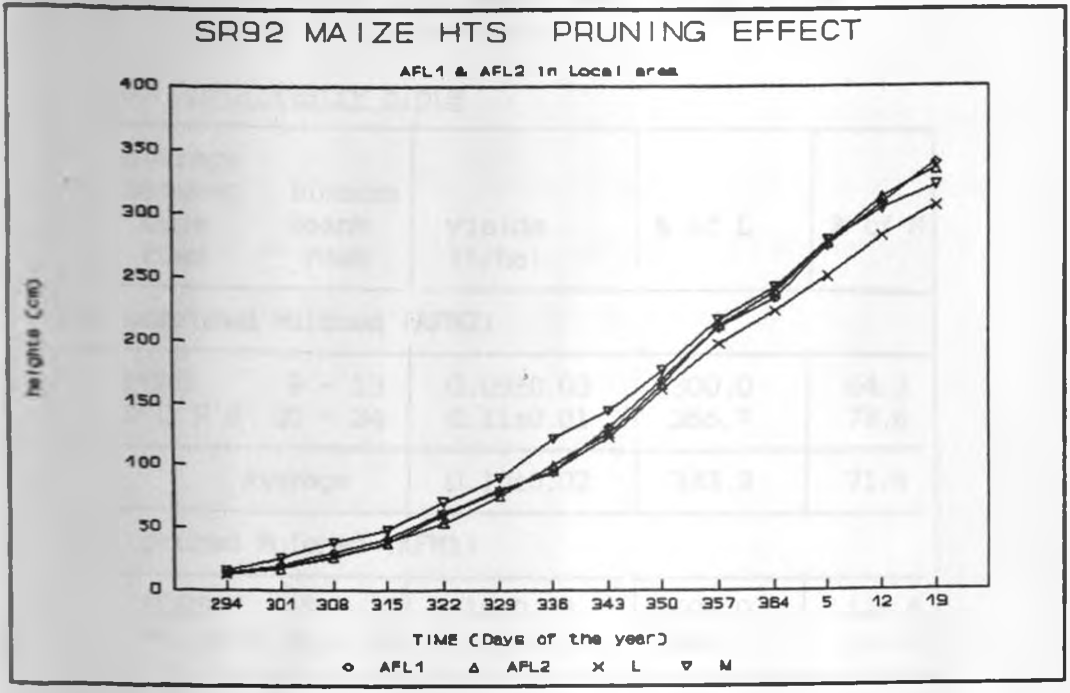


Fig. 31. Maize heights in pruned Mulched (AFM1) and unpruned Mulched (AFM2) plots in AF and controls (M & L) for SR92.



Fi4. 32. Maize heights in pruned Local (AFL1) and unpruned Local (AFL2) plots in AF and controls (M & L) for SR92.

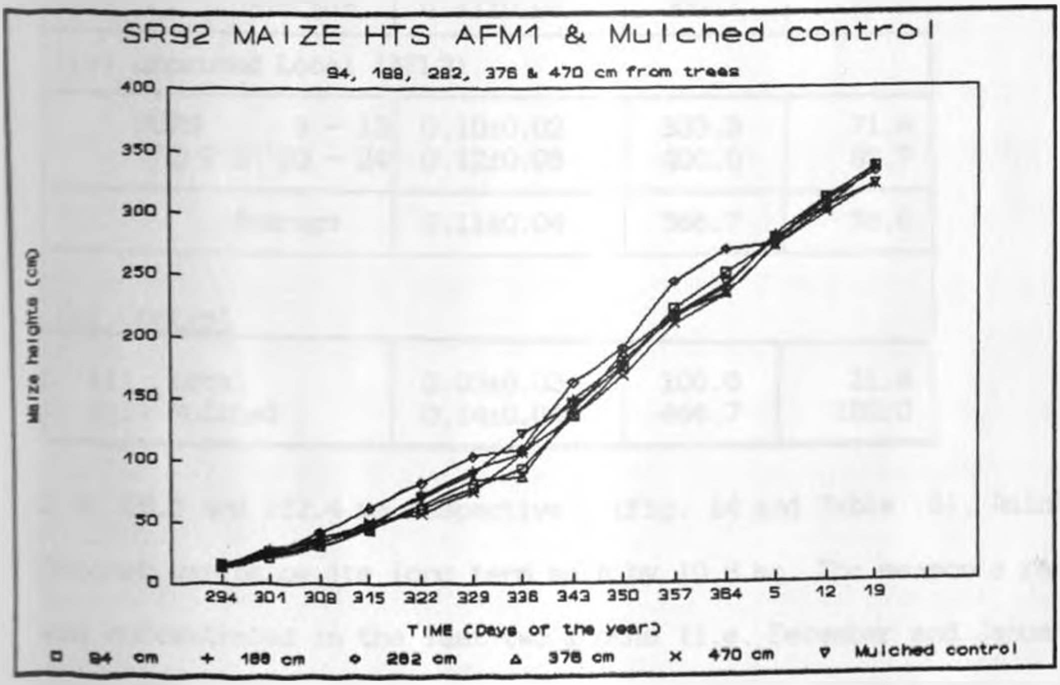


Fig. 33. Maize heights in different rows of pruned Mulched (AFM1) plots in AF and Mulched control (M) for SR92.

Table 14. Long Rains 1992 beans seed yields (t/ha) relative to the controls.

(a) Agroforestry plots

average between tree rows	biomass beans rows	yields (t/ha)	% of L	% of M
(i) unpruned Mulched (AFM2)				
PQRS	9 - 13	0.09±0.03	300.0	64.3
P'Q'R'S'	20 - 24	0.11±0.01	366.7	78.6
	Average	0.10±0.02	333.3	71.4
(ii) pruned Mulched (AFM1)				
PQRS	9 - 13	0.18±0.03	600.0	128.6
P'Q'R'S'	20 - 24	0.14±0.02	466.7	100.0
	Average	0.16±0.03	533.3	114.3
(iii) pruned Local (AFL1)				
PQRS	9 - 13	0.10±0.02	333.3	71.4
P'Q'R'S'	20 - 24	0.12±0.02	400.0	85.7
	Average	0.11±0.02	366.7	78.6
(iv) unpruned Local (AFL2)				
PQRS	9 - 13	0.10±0.02	333.3	71.4
P'Q'R'S'	20 - 24	0.12±0.06	400.0	85.7
	Average	0.11±0.04	366.7	78.6
(b) Control				
(i) Local		0.03±0.03	100.0	21.4
(ii) Mulched		0.14±0.04	466.7	100.0

2.3, 66.5 and 152.4 mm respectively (Fig. 14 and Table 6). Rainfall for October was below its long term mean by 10.8 mm. The season's rainfall was concentrated in the last two months (i.e. December and January).

The evaporation rates were consequently somewhat higher than their long term means during October and November but lower during December and especially January. The average for the January evaporation rate was 46.0 mm below its long term mean. This was the lowest for all the seven seasons. During SR92 Matanya received a moisture surplus over evaporation of 331.6%. The actual monthly rainfall of 137.6, 146.8 and 204.7 mm for November, December and January respectively were quite high (but the value for November is normal).

4.1.3 (b) Maize and beans phenology

By 12th October (i.e. 8 DAP) 30% of the maize seedlings in the AF and 28% in the other treatments (control plots) had emerged. Emergence of 100% was attained by 16 DAP (20th October 1992). Due to less rainfall in the months of October and early November, seedling emergence and early growth did not well. Nevertheless the rainfall in December and came at the right time, just before the critical phases of maize tasselling and silking (Todorov, 1977) and rescued what otherwise would have been a crop failure. There was a lot of rain in January, 1993 which delayed attainment of maturity as the ground as very wet and the air was very cold. By 92 DAP (4th January, 1993) complete (100%) tasselling was attained and by 97 DAP (10th January, 1993) complete silking (100%) phase was reached. We assessed the general conditions as excellent on 110 DAP. Wax ripeness (soft grain, milky sap oozing out when pressed) was reached on 121 DAP and full ripeness (hard grain) was attained on 142 DAP. Harvesting of maize grain, cob splint and biomass were carried out on 176 DAP (29th March 1993).

By 7 DAP 32% of the beans seedlings in the AF plots and 26% in the control (NAF) had emerged. Emergence of the beans seedlings was completed (100%) that is 8 days later on 19th October (i.e. 15 DAP). By 55 DAP (28th November, 1992) complete flowering had been reached. We assessed the plants on 71 DAP and found them to be in very satisfactory condition. Ripeness was completed and complete dryness od the bean seeds were reached by 90 DAP (2nd January, 1993). Both the seeds and biomass were harvested on 20th January, 1993 (on 108 DAP).

4.1.3 (c) The effect of mulching and root pruning on maize heights

Intercomparisons were made of the effect of mulching (Figs. 29 & 30) and of *Grevillea* root pruning (Figs. 31 & 32) on the growth of maize heights in AF and control plots for SR92.

The plants in the pruned Mulched plot (AFM1, Fig. 29) and the pruned Local plot (AFL1, Fig. 29) in the AF plot had grown taller than those in the control plots (L & M), in particular for the Local treatment. The plants in the unpruned Local plot (AFL2, Fig. 30) in the AF plot were taller than those in the control and unpruned Mulched (AFM2) plots. This suggested that plants in AFM2 were more affected by thigmo-morphogenetic responses to turbulent subsiding air mass than in AFL2, which reduce their growth rate (see chapter 5). Plants in the Mulched NAF (control) grew taller than those in the Local NAF.

We observe the effect of pruning in Figs. 31, 32 & 33. Intercomparisons of plants in the Mulched plots (AFM1 & AFM2) show that the pruned Mulched (AFM1) had grown somewhat taller than the unpruned Mulched (AFM2) (Fig. 31). This was also the case with the Local plots (AFL1 & AFL2) where the pruned Local (AFL1) had grown a very bit taller than the unpruned Local (AFL2) (Fig. 32), but only towards the very end of the season. Of the Mulched plots presented in Fig. 33, we observe that by DOY 315 till 364 the Local control had grown taller by about 10 cm than any of maize rows in distances to trees in Mulched pruned plot

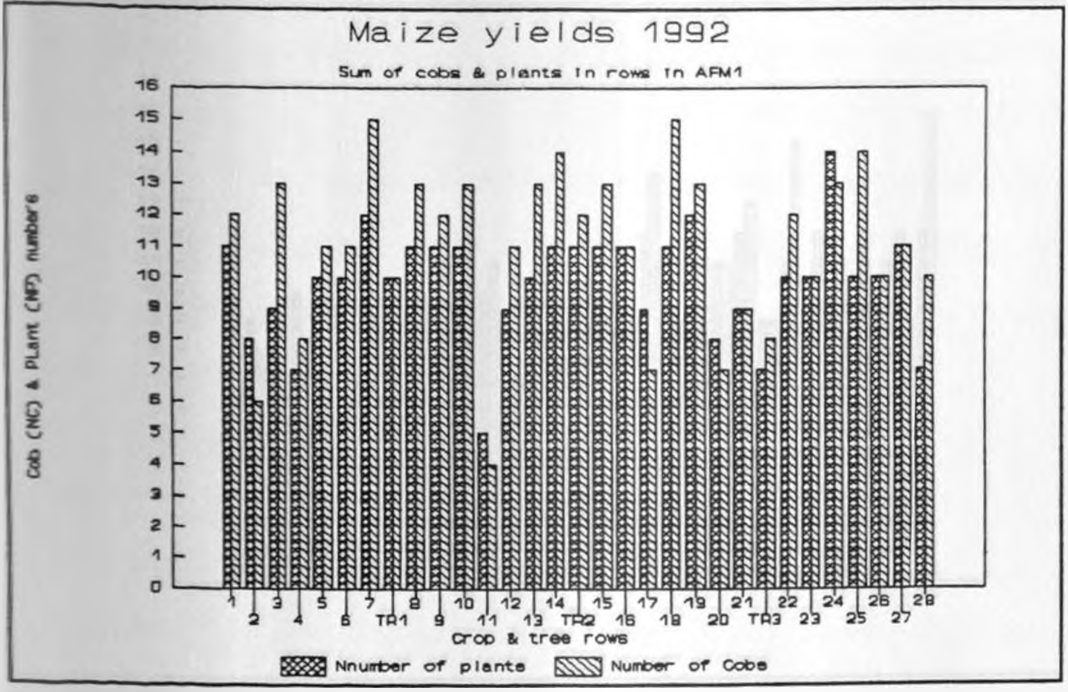


Fig. 34. The total number of plants and cobs per row in the AFM1 plot for SR92.

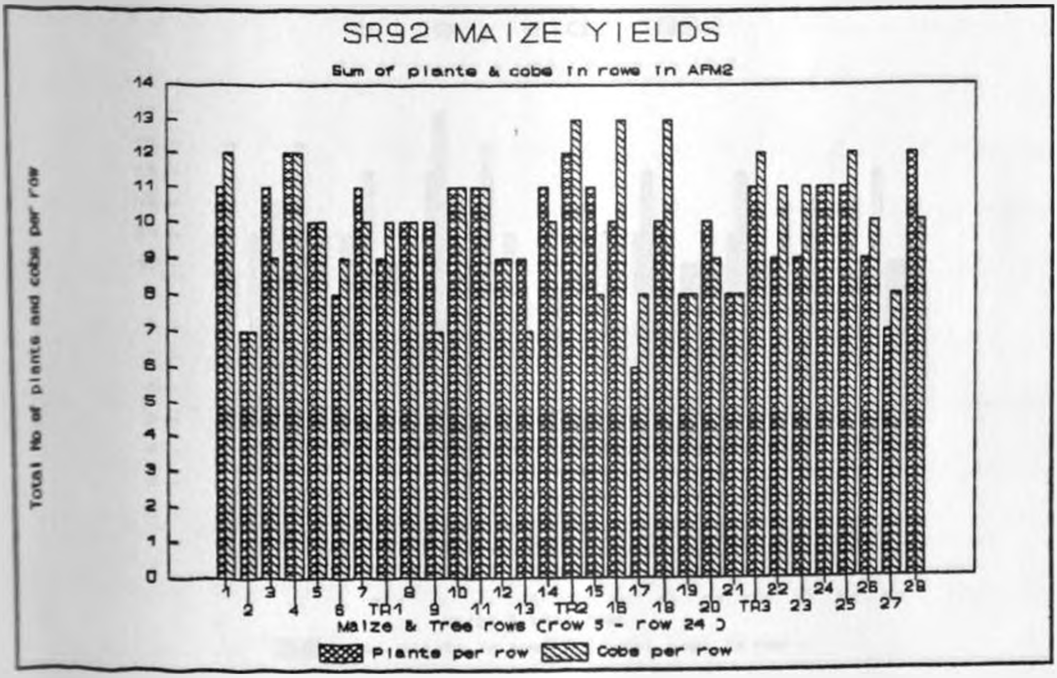


Fig. 35. The total number of plants and cobs per row in the AFM2 plot for SR92.

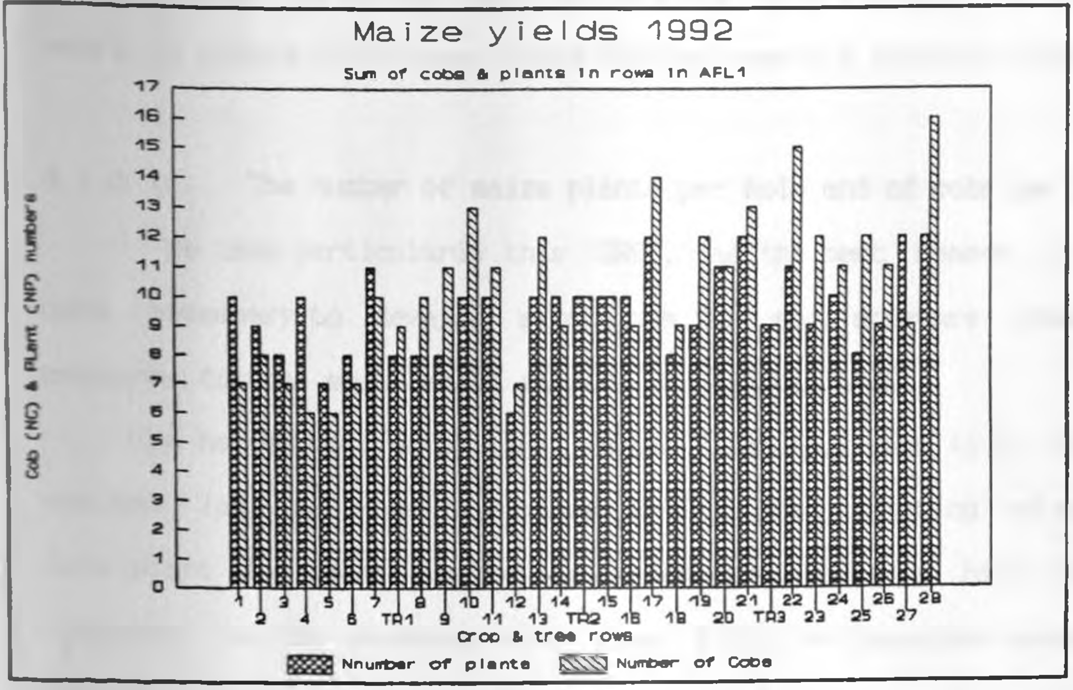


Fig. 36. The total number of plants and cobs per row in the AFL1 plot for SR92.

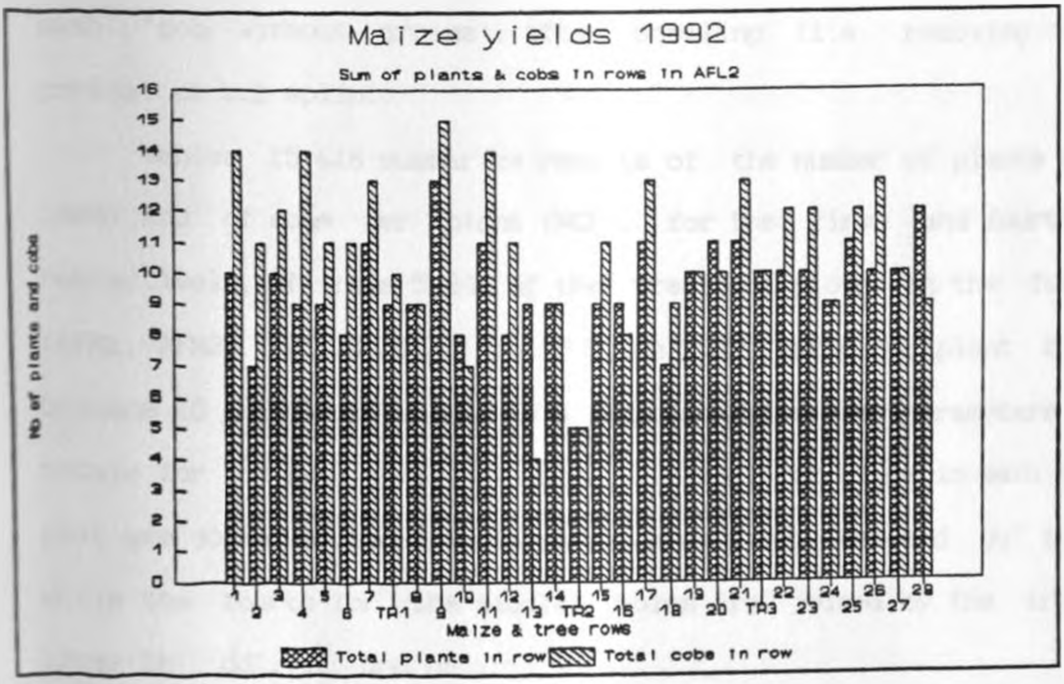


Fig. 37. The total number of plants and cobs per row in the AFL2 plot for SR92.

(AFM1). Fig. 33 proves that differences with distance to trees are small in pruned conditions. those further away are somewhat depressed.

4.1.3 (d) The number of maize plants per hole and of cobs per plant

We used particularly this SR92, as the best season, to collect data necessary to develop strategies for soil moisture conservation measures for the small scale farmers in Laikipia ASAL.

We harvested line by line in the first four rows (i.e. rows 1-4) and the last four rows (i.e. rows 25-28). The harvesting of maize was done plant by plant in the area perceived to have high *Grevillea* influence on the intercrop (i.e. rows 5-24). We therefore present here the results on maize on: (i) the number of plant per hole. (ii) the number of cobs per plant, (iii) the cob plus grain weights per plant and (iv) the total biomass yields. In this work we refer to 'cob' to mean 'cob without grains', after shelling (i.e. removing of maize grains) or cob splint.

Tables 15 &16 summarize results of the number of plants per hole (NPH) and of cobs per plant (NCP), for the first and fourth holes respectively, of rows 5-24 of the treatment plots in the four plots (AFM1. AFM2. AFL1 & AFL2) in AF which were harvested plant by plant. Columns 10 and 11 of Tables 15 & 16 present the same parameters as row totals for the same area (see Fig. 9). The first holes in each row per plot are joined by the transverse lines aa', cc', ee' and gg' in Fig. 9 while the fourth (or the middle) holes are joined by the transverse lines bb', dd', ff' and hh'.

The NPH was considered as an indicator for the spatial plant establishment (i.e. seedling emergence) and the number that attained maturity to produce cobs. The NCP was used as a measure of growth vigour for individual plants when moisture did not limit plant growth. Planting was done with two seeds per hole. Three plants per hole came about as the result of a third seed dropping in a hole by mistake and managing to germinate because moisture was adequate. Only two rows had two plants with 3 cobs each.

We observe in Table 15 row 13 and tree row TR3 in AFM1 and row 12 in AFL1 did not have plants in the first holes. In a comparison of number of plants per hole in the first hole of every plot in AF, we learn from Table 15 that of 23 rows in each plot, five rows in AFM1: 11 rows in AFL1: 7 rows in AFM2 and 4 rows in AFL2 had one plant per first hole. AFL2 had the fewest rows with single plants per first hole while AFM2 had the most. The cases of single plants per hole in AFM1 are found at the upper edge around tree TR2 and around TR3. It is evident that tree row TR2 might have affected emergence of the plants around it. Of the 23 maize rows displayed in Table 15 we see that 16 rows in AFM1, 11 rows in AFL1, 16 rows in AFM2 and 19 rows in AFL2 had two or more plants per first hole. These indicate that only 4 rows in AFL2 did not have all plants at the time of harvest. More plants at the time of harvest were found in the lower part of AF in rows 15-24 and in rows 7-12 and 16-21 of AFM1. In AFM2 all plants at the time of harvest were found in rows 7-11 and 14-20. AFL1 had least plants per row. All plants in the four plots in AF had one cob each, except in few cases where one plant had two or none. This showed that each seedling that emerged and reached maturity had a cob, when rainfall was adequate.

Comparison of number of plants per hole in the fourth (middle) hole of every plot in AF, (see Table 16) show that of out 23 rows in each plot, 9 rows in AFM1: 8 rows in AFL1, 5 rows in AFM2 and 9 rows in

AFL2 had one plant per hole. Here AFM2 had the fewest rows with single

Table 15. SR92 number of plants per hole (NPH) and of cobs NCP) per plot plant for the first hole (aa', cc', ee' and gg').

Plant row	AFM1		AFL1		AFM2		AFL2		Total	
	NPH	NCP	NPH	NCP	NPH	NCP	NPH	NCP	NPH	NCP
5	1	1	1	0	2	2	2	2	6	5
6	1	2	2	1	1	1	1	1	5	5
7	2	2	2	2	2	3	2	1	8	8
TR1	2	1	1	1	2	3	2	2	7	7
8	2	2	2	3	2	1	1	1	7	7
9	2	2	2	3	2	2	2	2	8	9
10	2	3	1	1	2	2	3	1	8	7
11	2	1	1	1	2	2	2	3	7	7
12	2	2	0	0	1	1	2	3	5	6
13	0	0	1	1	1	1	2	1	4	3
14	1	2	1	1	2	2	1	1	5	6
RT2	2	2	1	1	2	2	1	1	6	6
15	1	1	2	3	2	2	2	4	7	10
16	2	3	2	3	2	3	2	1	8	10
17	2	2	2	3	2	2	2	3	8	10
18	2	3	1	1	2	2	2	2	7	8
19	2	3	1	2	2	2	2	2	7	9
20	2	1	2	2	2	3	2	2	8	8
21	2	2	2	2	1	1	2	2	7	7
TR3	0	0	2	2	2	1	2	2	6	5
22	1	1	1	1	1	1	2	4	5	7
23	2	2	2	4	1	1	2	2	7	8
24	2	2	1	2	1	1	2	1	6	6

plants per hole in the fourth holes while AFM1 and AFL2 had the most. The single plants per hole cases in AFM1 are again found at the upper edge near the eastern live-fence (rows 5-TR1) and west of TR2. Fewer plants at harvest were found around tree row TR3 in AFM1. The interspace between tree rows TR2 and TR3 till maize row 22 seemed to have been affected by the trees. Of the 23 maize rows shown in Table 16 we see that 12 rows in AFM1, 15 rows in AFL1, 17 rows in AFM2 and 13 rows in AFL2 had two or more plants per fourth hole in each plot. This shows that AFM1 was last with respect to the number of plants found at harvest in each middle hole in per row. In AFM1, AFM2 and AFL2 number of plants found at harvest matched the seeds that were planted but in AFL1 more plants were found between maize rows 13 and 18. Again all plants that emerged in the four plots in AF had one cob each, except in few cases where one plant had two or none.

The middle (hole 4) holes of AFM1, AFM2 and AFL2 respectively did not have plants in rows 21 and TR3, TR1 and TR2. Row 24 had 3 plants per hole and 4 cobs per plant.

Figs. 34-37 present the total number of cobs and plants per row obtained by harvesting row by row instead of plant by plant. We notice that the number of plants was small in rows 2, 4, 11, 20, 21 and 22.

The total number of cobs were more than that of plants in 15 out of 28 rows in AFM2 (Fig. 35). In AFL1 15 out of 24 rows had more cobs per row than the number of plant (Fig. 36). There was a bigger proportion of plants with more than one cob in AFL2 compared with single cobbed plants (Fig. 37). The middle holes in each row of AFL2 (rows 13-18) had few cobs per plant.

From the foregoing we can infer that in seasons with adequate rainfall, which are very rare, water conservation measures may not be necessary for good maize yields. This can be seen from the fact that during SR92 unpruned treatments AFM2 & AFL2 with less water conservation measures had more plants per hole with more cobs per plant than pruned treatment, AFM1, which had all necessary measures (see Chapter 5).

4.1.3 (e) Maize yields for SR92

Figs. 38-45 and Tables 17-21 present some of the results on biomass yields, oven-dry weights of grain and cobs (after shelling) per hole per row in each treatment plot (i.e. AFM1, AFM2, AFL1 & AFL2) in the AF. Fig. 38 shows that cobs from Mulched pruned plot (AFM1)

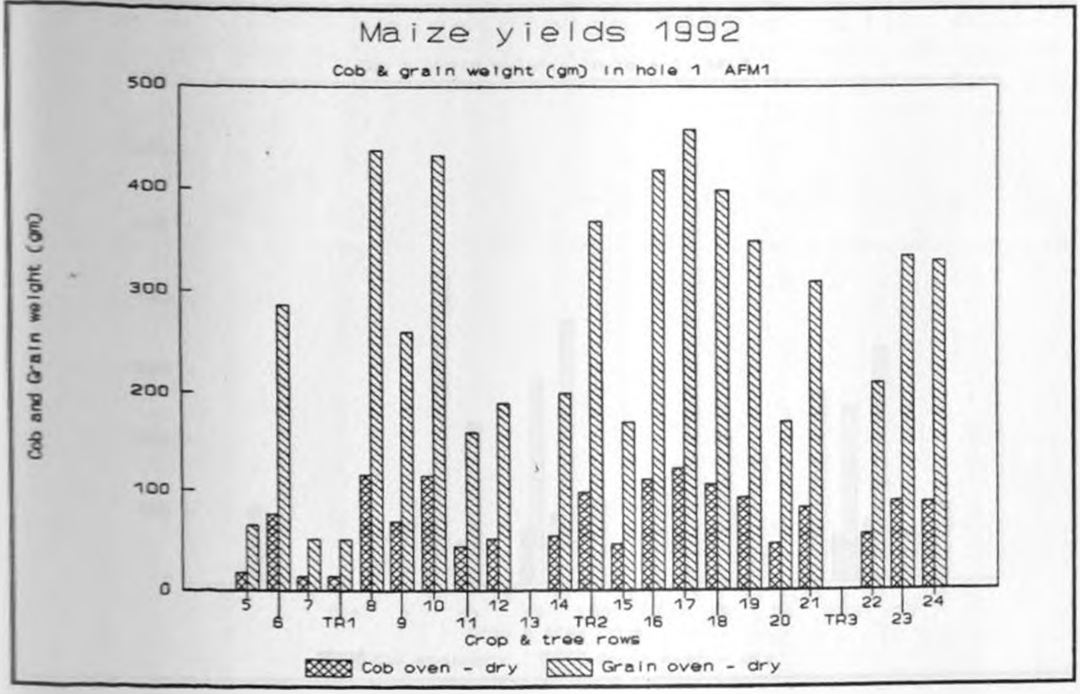


Fig. 38. Shelled cob (cob splint) and grain weights in first hole (hole 1) per row in AFM1 for SR92.

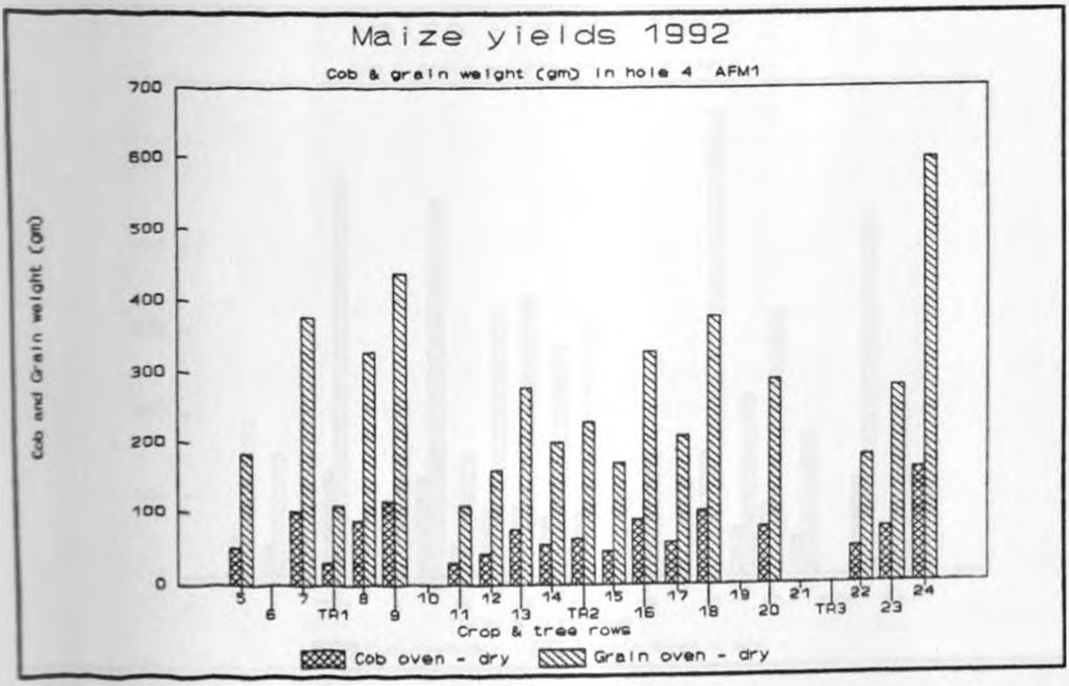


Fig. 39. Shelled cob (cob splint) and grain weights in middle hole (hole 4) per row in AFM1 for SR92.

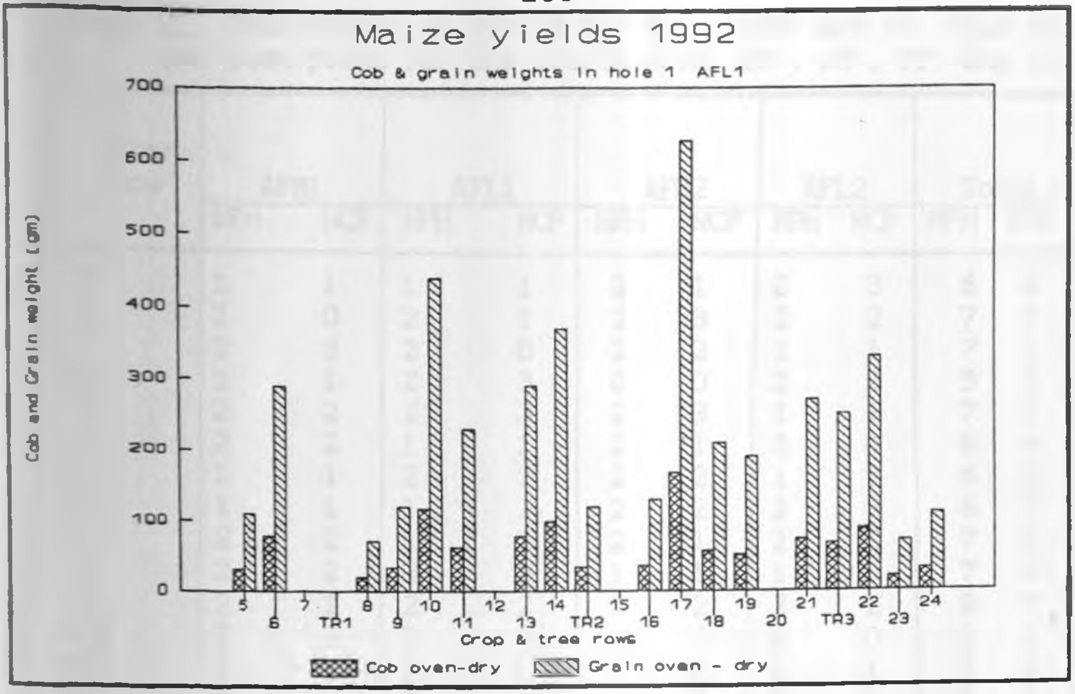


Fig. 40. Shelled cob (cob splint) and grain weights in first hole (hole 1) per row in AFL1 for SR92.

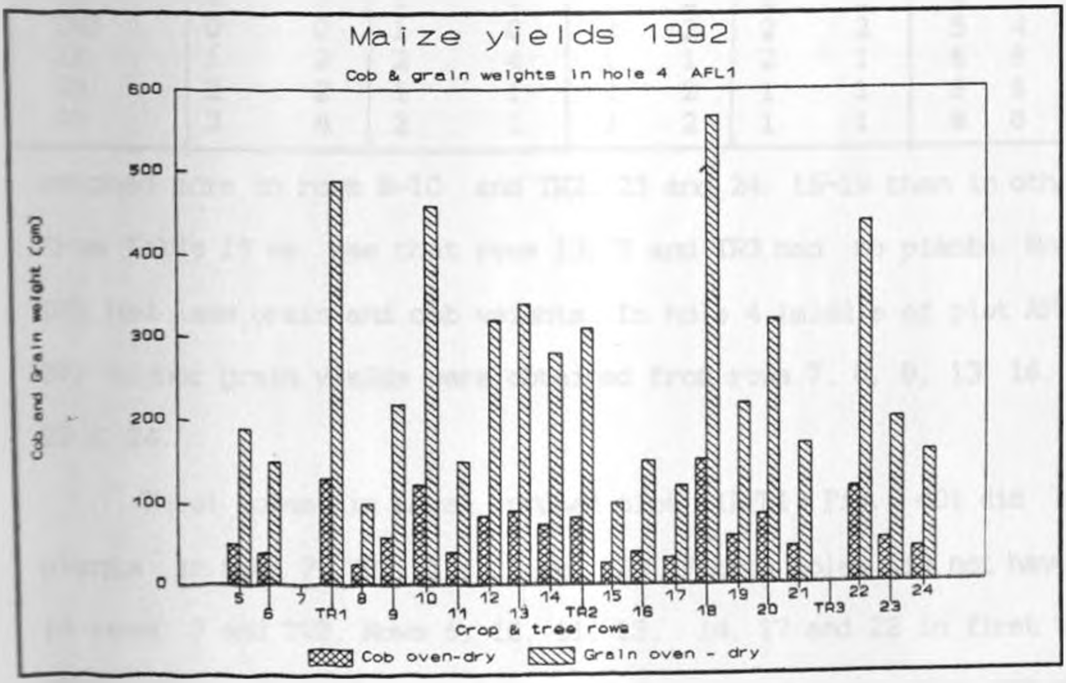


Fig. 41. Shelled cob (cob splint) and grain weights in middle hole (hole 4) per row in AFL1 for SR92.

Table 16. SR92 number of plants per hole (NPH) and of cobs NCP) per plot plant for the fourth hole (bb', dd', ff' and hh')

Plant row	AFM1		AFL1		AFM2		AFL2		Total	
	NPH	NCP	`NPH	NCP	NPH	NCP	NPH	NCP	NPH	NCP
5	1	1	1	1	2	1	2	3	6	6
6	1	0	2	1	2	3	2	2	7	6
7	2	3	2	0	2	2	1	1	7	6
TR1	1	1	2	3	0	0	2	2	5	6
8	2	2	2	3	2	3	1	1	7	9
9	2	2	1	1	2	1	3	4	8	8
10	1	1	2	3	2	2	1	2	6	8
11	1	1	1	1	2	2	2	3	6	7
12	2	2	1	2	2	1	2	3	7	8
13	2	2	3	3	1	1	1	0	7	6
14	2	1	2	2	2	2	2	2	8	7
RT2	2	2	2	2	2	2	0	0	6	6
15	1	1	2	1	2	1	1	1	6	4
16	1	2	2	1	2	3	1	1	6	7
17	2	1	2	2	1	2	2	2	8	7
18	2	3	2	3	1	1	1	1	6	8
19	1	0	1	1	2	1	2	2	6	4
20	2	2	2	2	2	2	2	1	8	7
21	0	0	1	1	1	2	2	2	4	5
TR3	0	0	1	0	2	2	2	2	5	4
22	1	2	2	4	1	1	2	1	6	8
23	2	2	1	1	2	2	1	1	6	6
24	3	4	2	1	2	2	1	1	8	8

weighed more in rows 8–10 and TR2. 23 and 24. 16–19 than in other rows. From Table 15 we see that rows 13. 7 and TR3 had no plants. Rows 5 and TR1 had less grain and cob weights. In hole 4 (middle of plot AFM1. Fig. 39) higher grain yields were obtained from rows 7. 8. 9. 13. 16. 18. 20. 23 & 24.

First holes in Local pruned plot (AFL1. Fig. 40) did not have plants in rows 7. TR1. 12. 15 and 20. Fourth holes did not have plants in rows 7 and TR3. Rows 6. 10. 11. 13. 14. 17 and 22 in first holes of AFL1 (Fig. 40) had proportionately much more grain than cob weights. although it was true for all rows. Low weights were generally observed in rows 5. 8. 9. TR2. 16. 23 & 24 in plot AFL1 (Fig. 40).

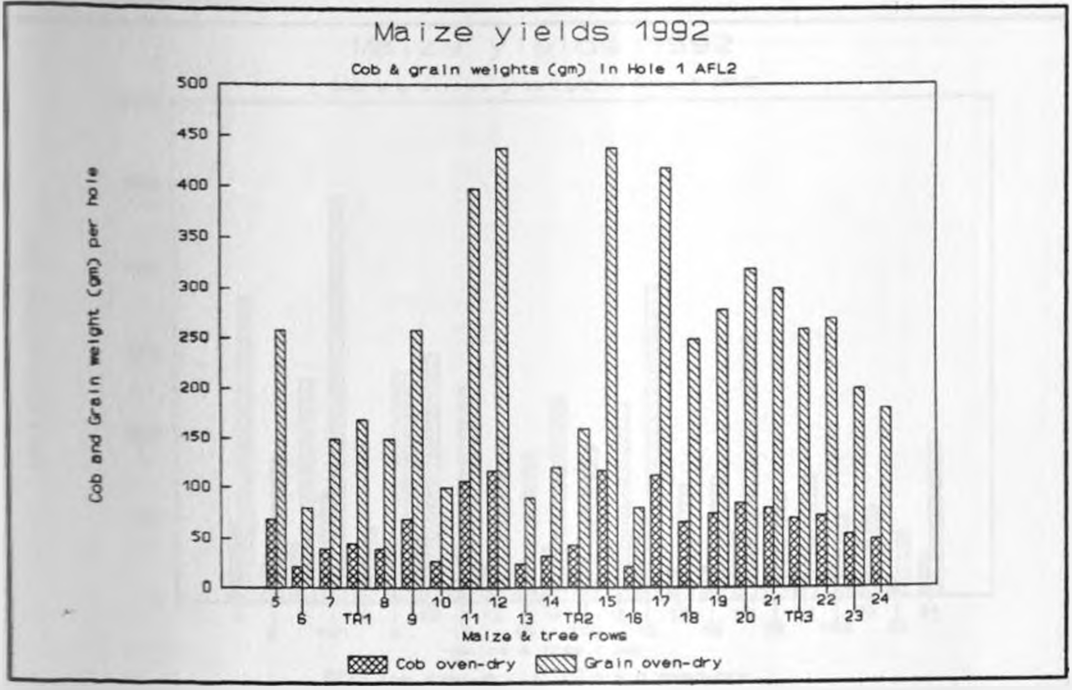


Fig. 42. Shelled cob (cob splint) and grain weights in first hole (hole 1) per row in AFL2 for SR92.

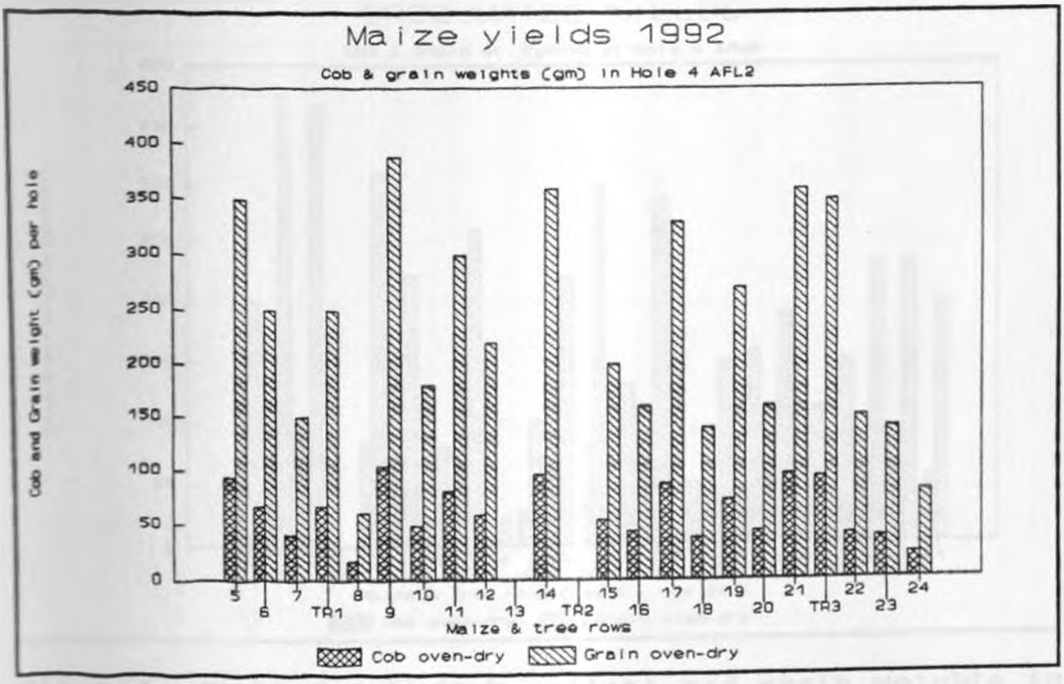


Fig. 43. Shelled cob (cob splint) and grain weights in middle hole (hole 4) per row in AFL2 for SR92.

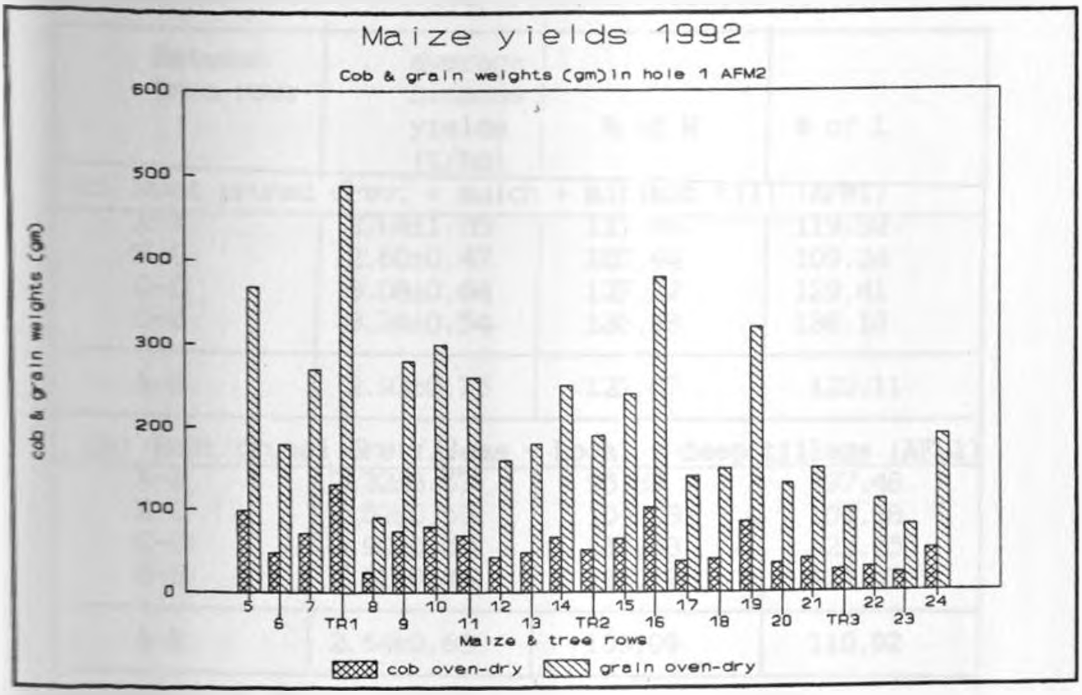


Fig. 44. Shelled cob (cob splint) and grain weights in first hole (hole 1) per row in AFM2 for SR92.

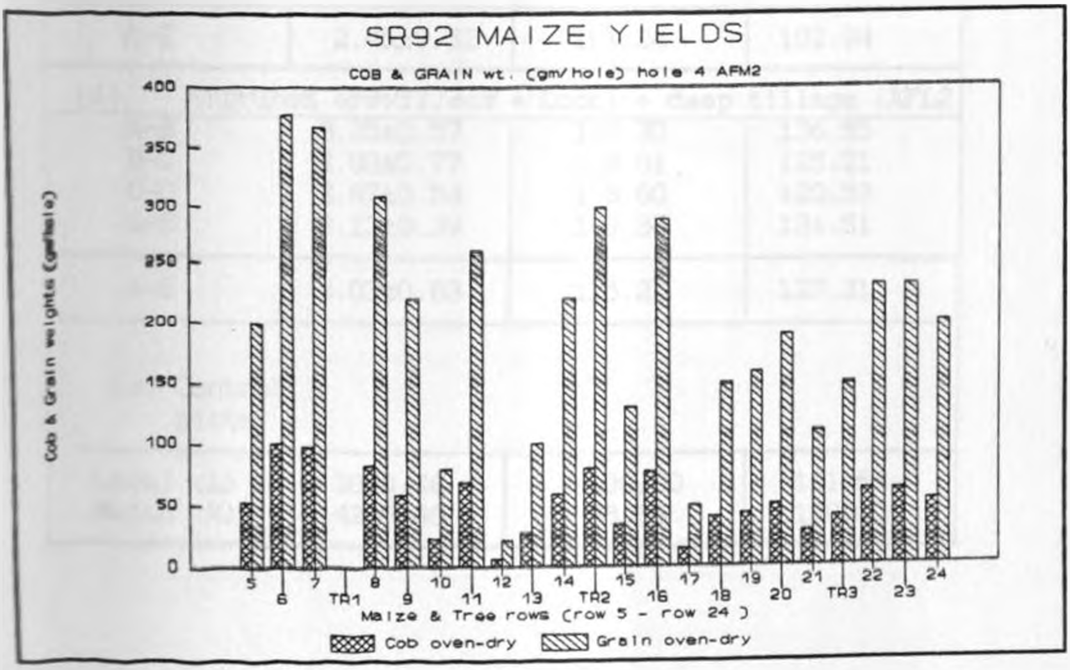


Fig. 45. Shelled cob (cob splint) and grain weights in middle hole (hole 4) per row in AFM2 for SR92.

Table 17. SR92 maize biomass (stover BOD) yields in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average biomass yields (t/ha)	% of M	% of L
(a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A-B	2.84±1.05	117.36	119.32
B-C	2.60±0.47	107.44	109.24
C-D	3.08±0.64	127.27	129.41
D-E	3.24±0.54	133.88	136.13
A-E	2.93±0.75	121.07	123.11
(b) Root pruned *Grevilleas* + Local + deep tillage (AFL1)			
A-B	2.32±0.57	95.87	97.48
B-C	2.52±0.59	104.13	105.88
C-D	2.90±0.59	119.83	121.85
D-E	2.81±0.46	116.12	118.07
A-E	2.64±0.60	109.09	110.92
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	2.34±0.78	96.69	98.32
B-C	2.15±0.61	88.84	90.34
C-D	2.42±1.31	100.00	101.68
D-E	2.90±0.36	119.83	121.85
A-E	2.45±0.52	101.24	102.94
(d) Unpruned *Grevilleas* + Local + deep tillage (AFL2)			
A-B	3.25±0.57	134.30	136.55
B-C	2.88±0.77	119.01	125.21
C-D	2.87±0.54	118.60	120.59
D-E	3.13±0.39	129.34	131.51
A-E	3.03±0.63	125.21	127.31
(e) Control plots			
Local (L)	2.38±0.46	100.00	101.68
Mulch (M)	2.42±0.40	98.35	100.00

Table 18. SR92 maize grain (GOD) yields in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average grain yields (t/ha)	% of M	% of L
(a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A–B	1.33±1.35	83.10	102.30
B–C	1.60±0.46	100.00	123.10
C–D	1.46±0.38	91.30	112.30
D–E	1.82±0.14	113.80	140.00
A–E	1.54±0.39	96.30	118.50
(b) Root pruned *Grevilleas* + Local + deep tillage (AFL1)			
A–B	0.99±0.25	61.90	76.20
B–C	1.46±0.30	91.30	112.30
C–D	1.67±0.30	104.40	128.50
D–E	1.57±0.35	98.10	120.80
A–E	1.42±0.40	88.80	109.20
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A–B	1.31±0.32	81.85	100.77
B–C	1.22±0.30	76.30	93.90
C–D	1.00±0.20	62.50	76.90
D–E	1.19±0.22	74.36	91.34
A–E	1.18±0.26	73.75	90.77
(d) Unpruned *Grevilleas* + Local + deep tillage (AFL2)			
A–B	1.47±0.20	91.90	113.10
B–C	1.15±0.46	71.90	88.50
C–D	1.32±0.28	82.50	101.50
D–E	1.26±0.24	81.30	100.00
A–E	1.30±0.33	81.30	100.00
(e) Control plots			
Local (L)	1.30±0.34	100.00	81.25
Mulch (M)	1.60±0.37	123.00	100.00

Table 19. SR92 maize cob (COW) yields in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average biomass yields (t/ha)	% of M	% of L
(a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A–B	0.35±0.09	87.50	109.40
B–C	0.42±0.12	105.00	131.30
C–D	0.39±0.10	97.50	121.90
D–E	0.48±0.04	120.00	150.00
A–E	0.41±0.10	102.50	128.10
(b) Root pruned *Grevilleas* + Local + deep tillage (AFL1)			
A–B	0.26±0.07	65.00	81.30
B–C	0.39±0.08	97.50	121.90
C–D	0.44±0.08	110.00	137.50
D–E	0.42±0.09	105.00	131.30
A–E	0.38±0.11	95.00	118.80
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A–B	0.36±0.08	90.00	112.50
B–C	0.32±0.08	80.00	100.00
C–D	0.27±0.05	67.50	84.40
D–E	0.34±0.06	85.00	106.30
A–E	0.32±0.08	80.00	100.00
(d) Unpruned *Grevilleas* + Local + deep tillage (AFL2)			
A–B	0.39±0.05	97.50	121.90
B–C	0.31±0.17	77.50	96.90
C–D	0.35±0.07	87.50	109.40
D–E	0.33±0.06	82.50	105.10
A–E	0.35±0.09	87.50	109.40
(e) Control plots			
Local (L)	0.32±0.08	100.00	125.00
Mulch (M)	0.40±0.09	80.00	100.00

In AFL2 (Figs. 42 & 43) low cob and grain weights were obtained from around TR3 which extended to 470 cm on either side the tree row. We also harvested low grain and cob weights around TR1. Higher grain weights in hole 1 of AFL2 were obtained from rows 11, 12,15 and 17 with relatively light cobs. Hole 4 of AFL2 had plants missing in rows 13 and TR2 (Fig. 43). Here again the rows within 470 cm from TR2 had lighter cobs and less grain weight. SR92 had enough rainfall evenly distributed in the later half of the season. This evened out any factors that would tend to retard plant growth, such as competition for water between tree roots and crops.

In Figs. 44 & 45 the cob weights in hole 1 of plot AFM2 were generally low in rows 13-16 with exception of rows 15 in hole 1 and row 14 in hole 4. This suggests that the unpruned *Grevillea* trees did compete for resources with the maize. The rows close to the unpruned *Grevillea* trees had low cob and grain weights, except rows 5-TR1. Rows 9-18 had generally low cob weight in hole 1 except row 14, TR2 & 16 ((Fig. 45).

Tables 17-19 present respectively SR92 maize biomass (stover), Maize grain and maize cob yields in the AF and NAF. We can see from Table 17 that the lower half of AFM1, AFL1 and AFM2 had higher maize stover yields than the upper part, but in AFL2 the two parts obtained approximately the same yields. All the plots had higher stover yields than the controls. Unpruned Local had the highest stover yields because the depression that one observes in the upper half of the other AF plots (Plate 10) did not occur here. Mulched pruned plot (AFM1) was next. Therefore only in good rainy season did AF do better than NAF.

Table 18 presents SR92 maize grain yields in pruned and unpruned AF plots. Like in the case of maize stover yields (Table 17), the lower half of AFM1, AFL1 and AFM2 plots produced higher maize grain yields than the upper half. Again like Table 17 the lower and upper halves of

AFL2 nearly had the same yields. Of course Table 18 is more important than Table 17 because grain yield is the most important yield component. In the upper half of AF. large grain yield depression could only be observed in the Local pruned plot. Being unpruned appears of most importance for overall grain yield depressions. In the depressed pruned parts mulching does particularly help in the upper half of the plot. There was more maize grain in the Mulched control than in the Local control. which was not the case with stover yields.

In respect to maize cob (cob splint) yields (Table 19), the differences were relatively unimportant, certainly given that this is the least interesting yield component. Nevertheless, there was a tendency for higher cob yields in AFM1 and AFL1 than for AFM2 and AFL2.

4.1.3 (f) Maize weight components

Figs. 46–49 and Table 20 show the per cent yield components of maize (i.e. cob. grain and biomass weights) and their averages for every replication in AF (AFM1. AFL1, AFM2 and AFL2) and the same in the control plots. We observe a ratio of per cent weight of cob. grain and biomass in the total weights produced per row to be nearly 1:3:6 for all four diagrams (Figs. 46–49). The per cent component weights tend to fluctuate around this ratio in all the treatments/replications. The fluctuations around this ratio occur in the opposite direction between the per cent biomass on one hand and the per cent grain and cob weights on the other. The per cent cob and grain weights are directly related to each other and inversely related to the per cent biomass weights. An increase in per cent stover biomass tend to result in corresponding reduction in per cent cob and grain parts. The cob weights tend to be more stable around their mean values than the grain and biomass weights.

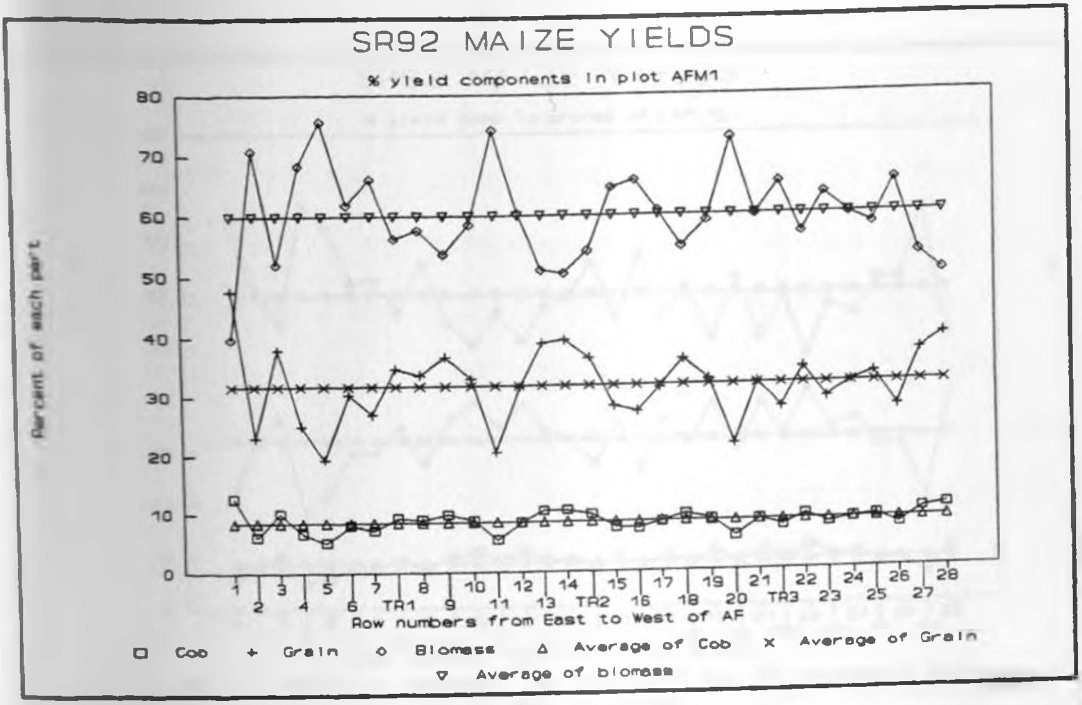


Fig. 46. Weights of maize cob splints, grains and biomass as percentages of total dry matter weight of maize in pruned Mulched plot (AFM1) for SR92.

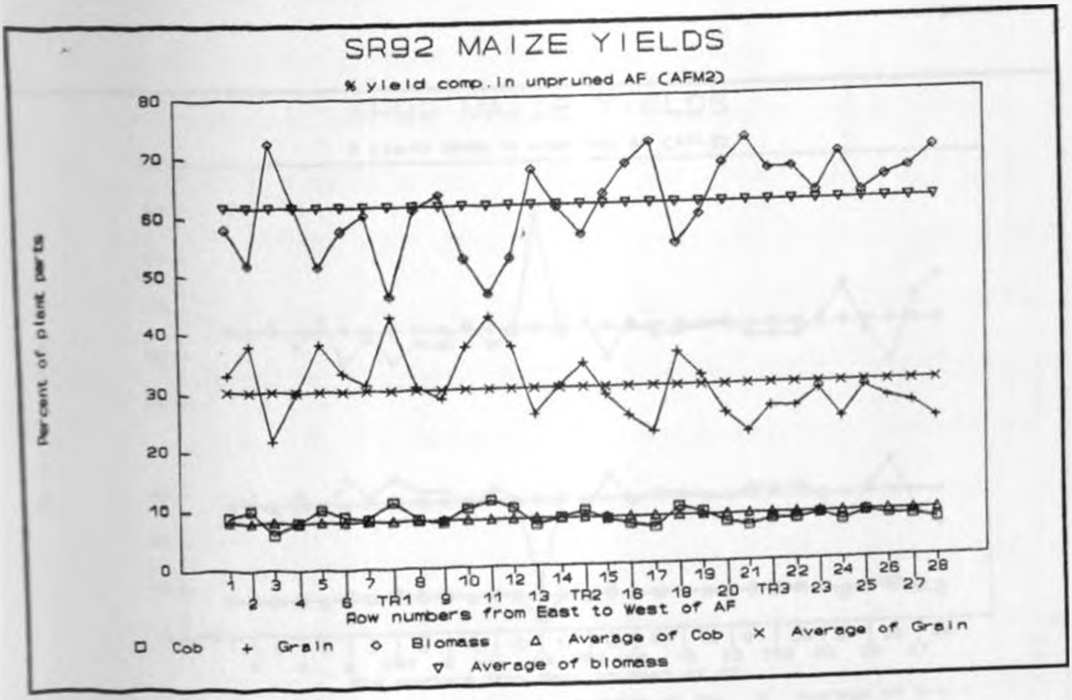


Fig. 47. Weights of maize cob splints, grains and biomass as percentages of total dry matter weight of maize in unpruned Mulched plot (AFM2) for SR92.

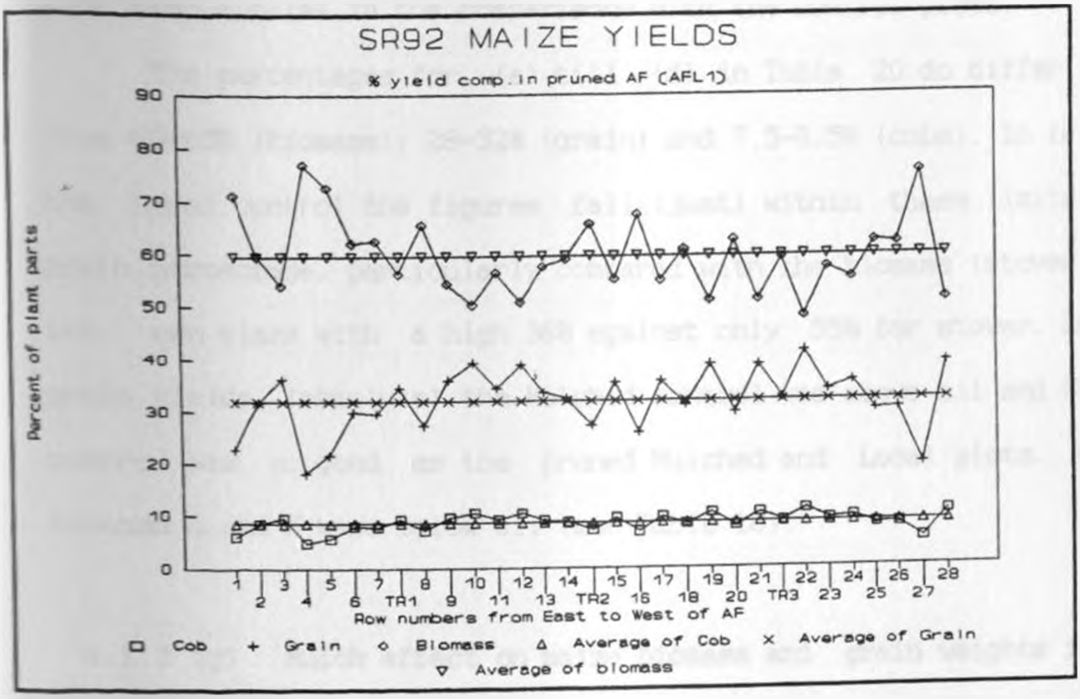


Fig. 48. Weights of maize cob splints, grains and biomass as percentages of total dry matter weight of maize in pruned Local plot (AFL1) for SR92.

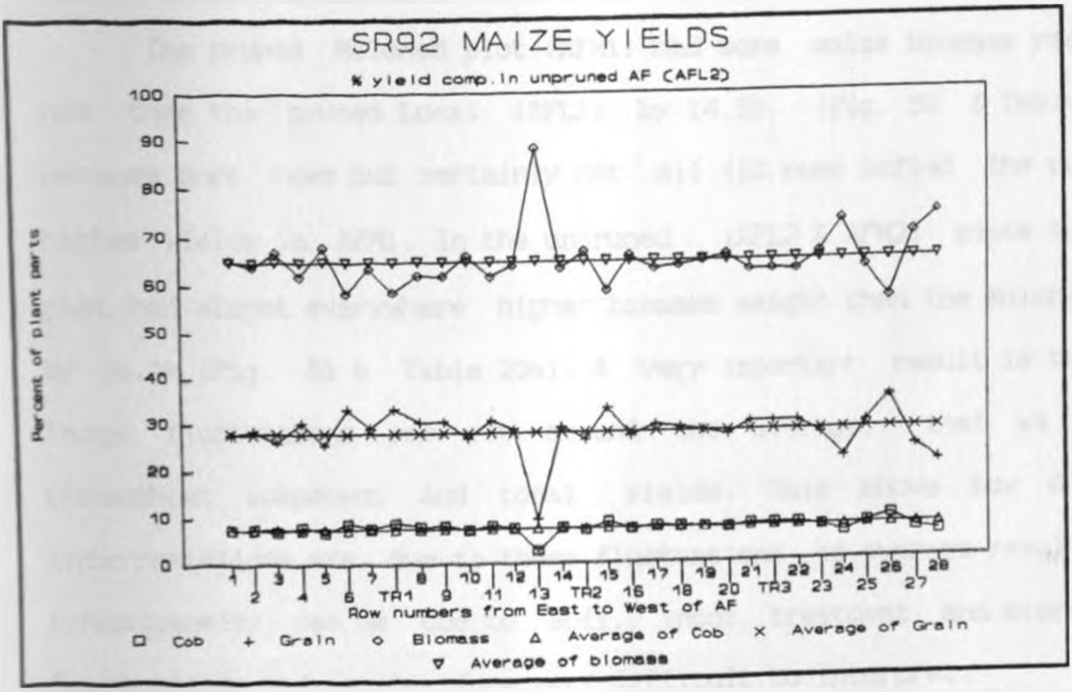


Fig. 49. Weights of maize cob splints, grains and biomass as percentages of total dry matter weight of maize in unpruned Local plot (AFL2) for SR92.

which means that stover and grain fluctuates in opposite directions. This also applies in the comparisons with the control plots.

The percentages for (a) till (d) in Table 20 do differ roughly from 60-65% (biomass); 28-32% (grain) and 7.5-8.5% (cobs). In (e) for the Local control the figures fall (just) within these limits but the grain percentage, particularly compared with the biomass (stover), is of its own class with a high 36% against only 55% for stover. Indeed in grain yields (absolute) the Mulched control was above all and the Local control was no good as the pruned Mulched and Local plots, while in biomass L and M were below all (see Table 18).

4.1.3 (g) Mulch effect on maize biomass and grain weights in pruned and unpruned tree plots

Figs. 50 & 51 and Table 21a compare the effects of mulching on the maize biomass weights in each row respectively the total of the pruned (AFM1, AFL1) and unpruned (AFM2 & AFL2) plots.

The pruned Mulched plot (AFM1) had more maize biomass yields per row than the pruned Local (AFL1) by 14.5%. (Fig. 50 & Table 21a), because more rows but certainly not all (10 rows defied the rule) had higher yields in AFM1. In the unpruned (AFL2 & AFM2) plots the Local plot had almost everywhere higher biomass weight than the Mulched plots by 18.1% (Fig. 51 & Table 20a). A very important result is the very large fluctuations per row around the average, that we observe throughout component and total yields. This shows how difficult interpretations are, due to these fluctuations of average results. This inhomogeneity can be due to soil, input, treatment and microclimate fluctuations and is therefore very difficult to interpret.

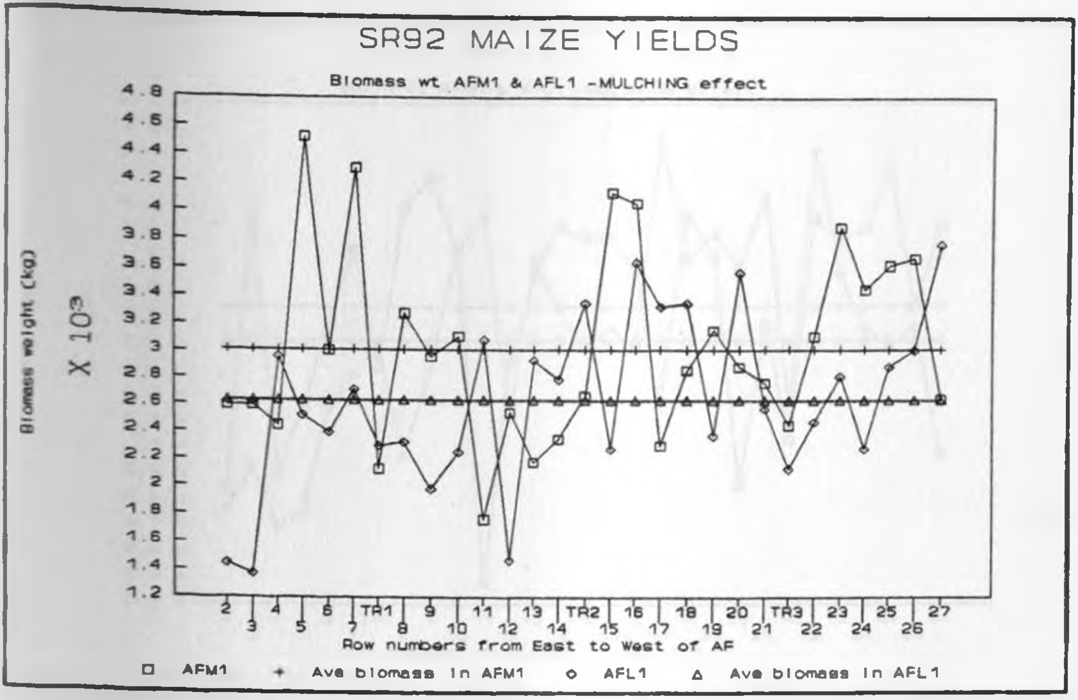


Fig. 50. Average maize biomass yields per row in pruned Mulched (AFM1) and pruned Local (AFL1) for SR92.

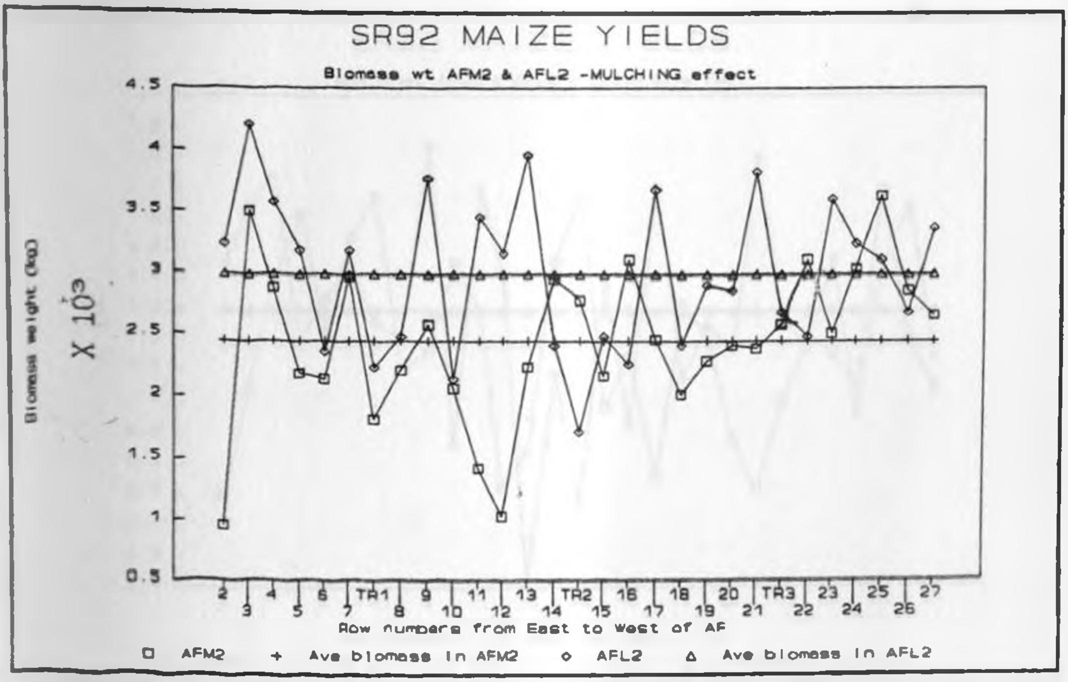


Fig. 51. Average maize biomass yields per row in unpruned Mulched (AFM2) and unpruned Local (AFL2) for SR92.

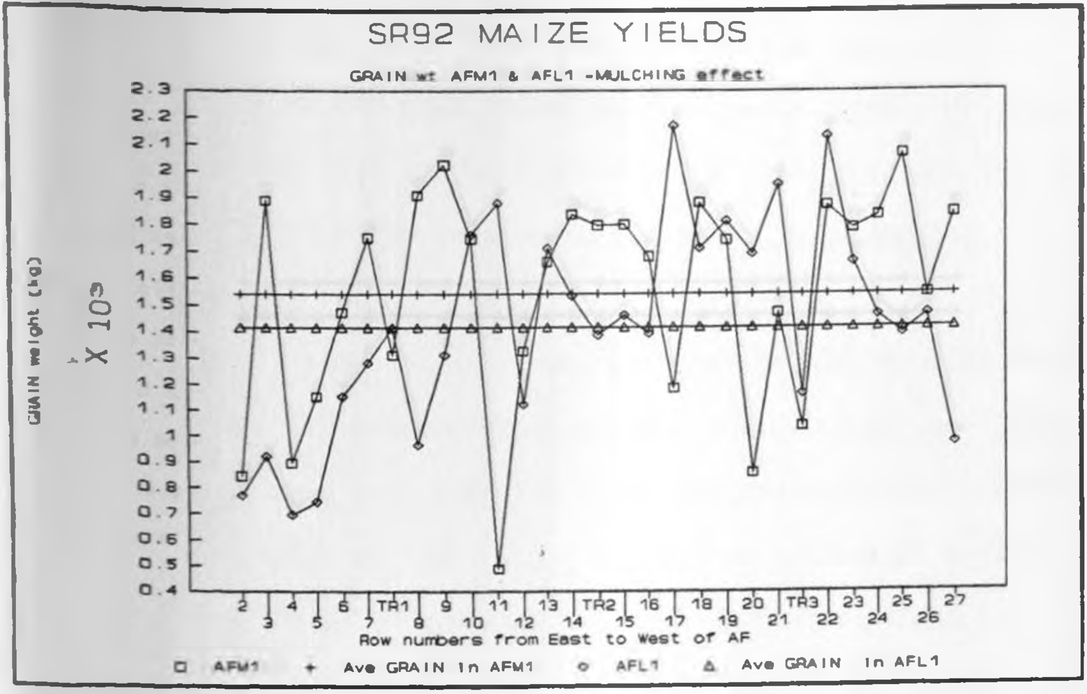


Fig. 52. Average maize grain yields per row in pruned Mulched (AFM1) and pruned Local (AFL1) for SR92.

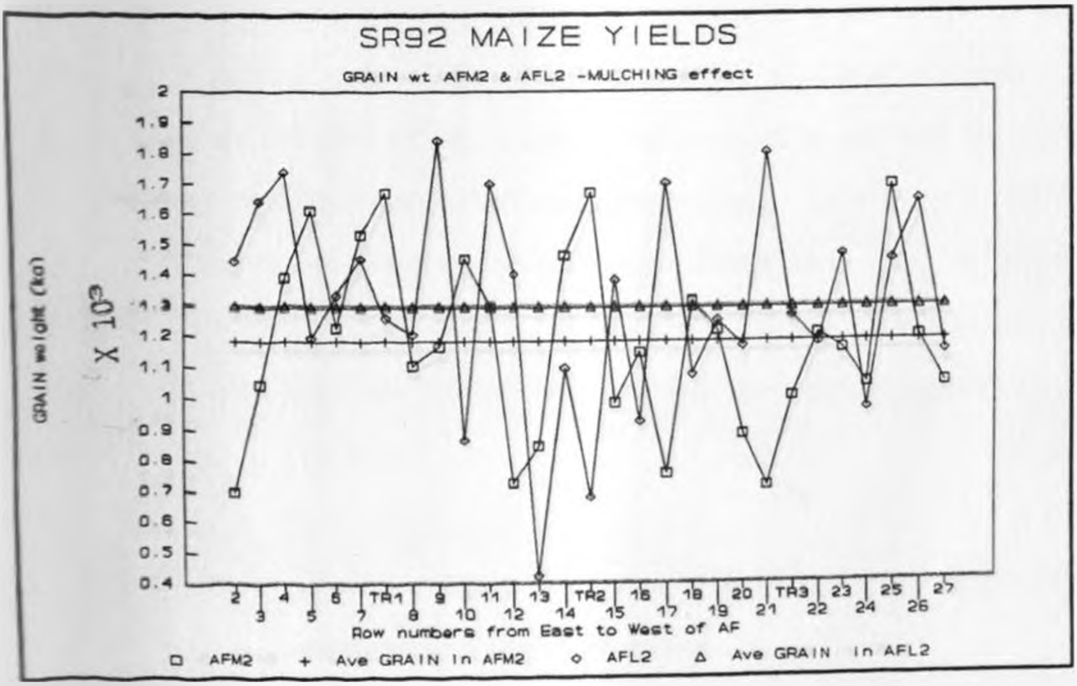


Fig. 53. Average maize grain yields per row in unpruned Mulched (AFM2) and unpruned Local (AFL2) for SR92.

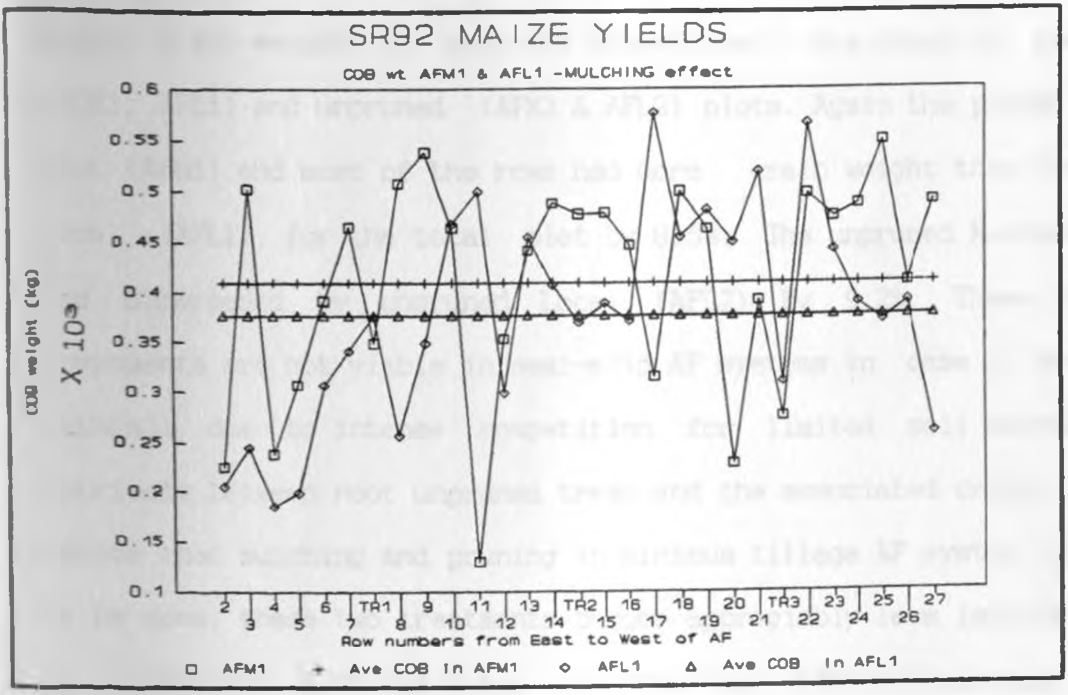


Fig. 54. Average cob splint yields per row in pruned Mulched (AFM1) and pruned Local (AFL1) for SR92.

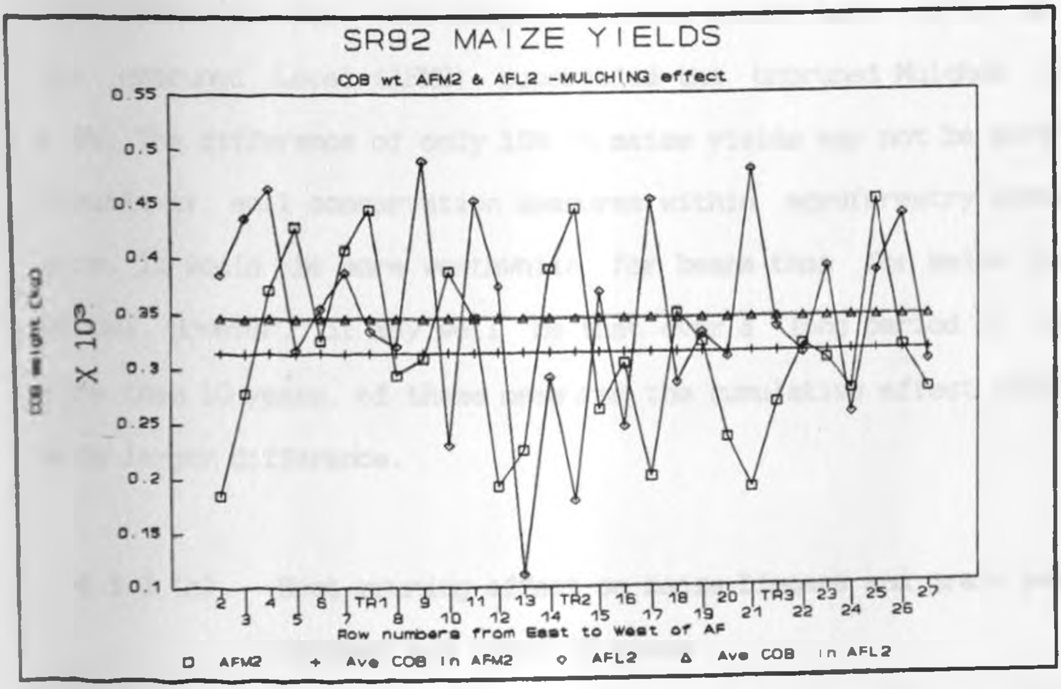


Fig. 55. Average cob splint yields per row in unpruned Mulched (AFM2) and unpruned Local (AFL2) for SR92.

Figs. 52 & 53 and Table 21a compare the mulching effects on the maize grain weights in each row respectively the total of the pruned (AFM1, AFL1) and unpruned (AFM2 & AFL2) plots. Again the pruned Mulched plot (AFM1) and most of the rows had more grain weight than the pruned Local (AFL1), for the total plot by 8.5%. The unpruned Mulched (AFM2) was superseded by unpruned Local (AFL2) by 9.2%. These two last treatments are not viable in semi-arid AF systems in case of inadequate rainfall due to intense competition for limited soil moisture and nutrients between root unpruned trees and the associated crops. Once we decide that mulching and pruning in minimum tillage AF system have both to be done, these two treatments become appreciably less important.

Figs. 54 & 55 and Table 21a show the effect of mulching on the maize cob splint weights in rows respectively the total of the pruned (AFM1, AFL1) and unpruned (AFM2 & AFL2) plots. Again the pruned Mulched plot (AFM1) had more cob weight than the pruned Local (AFL1) by 7.9 %. The unpruned Local (AFM2) superseded the unpruned Mulched (AFL2) by 8.8%. The difference of only 10% in maize yields may not be worth the trouble of soil conservation measures within agroforestry systems like ours. It would be more worthwhile for beans than for maize (see also below). However, it may well be that over a long period of time, say more than 10 years, of these measures the cumulative effect would make a much larger difference.

4.1.3 (h). Root pruning effect on maize biomass and grain weights in Mulched and Local AF plots

Figs. 56 & 57 and Table 21b compare the effect of *Grevillea robusta* root pruning on the maize biomass weights in each row of the

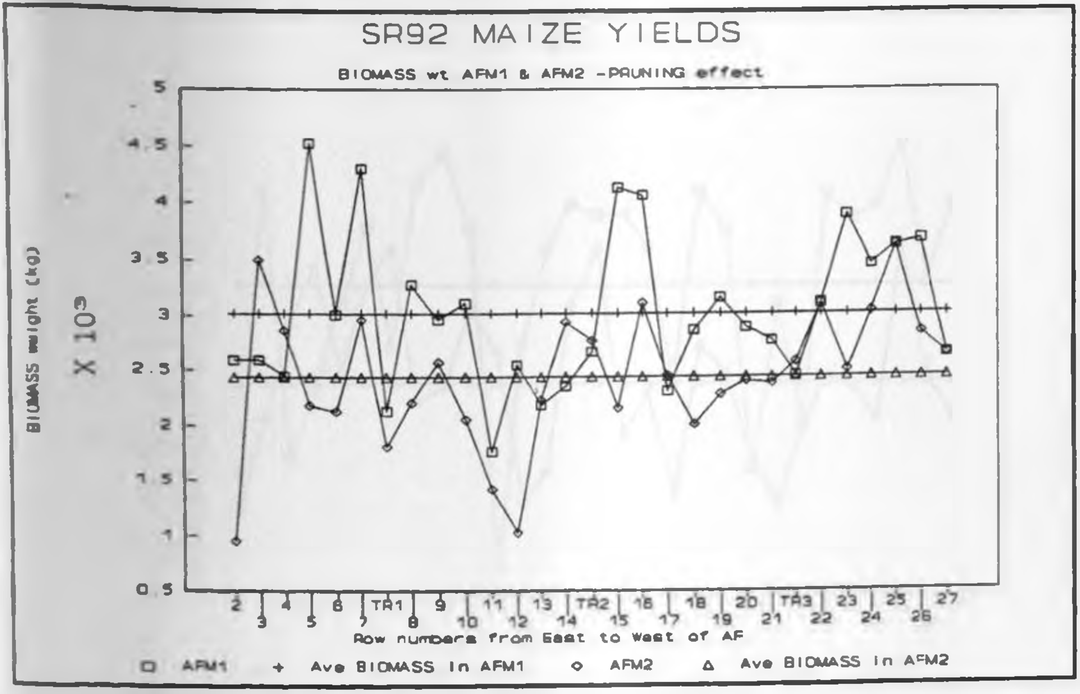


Fig. 56. Average maize biomass yields per row in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for SR92.

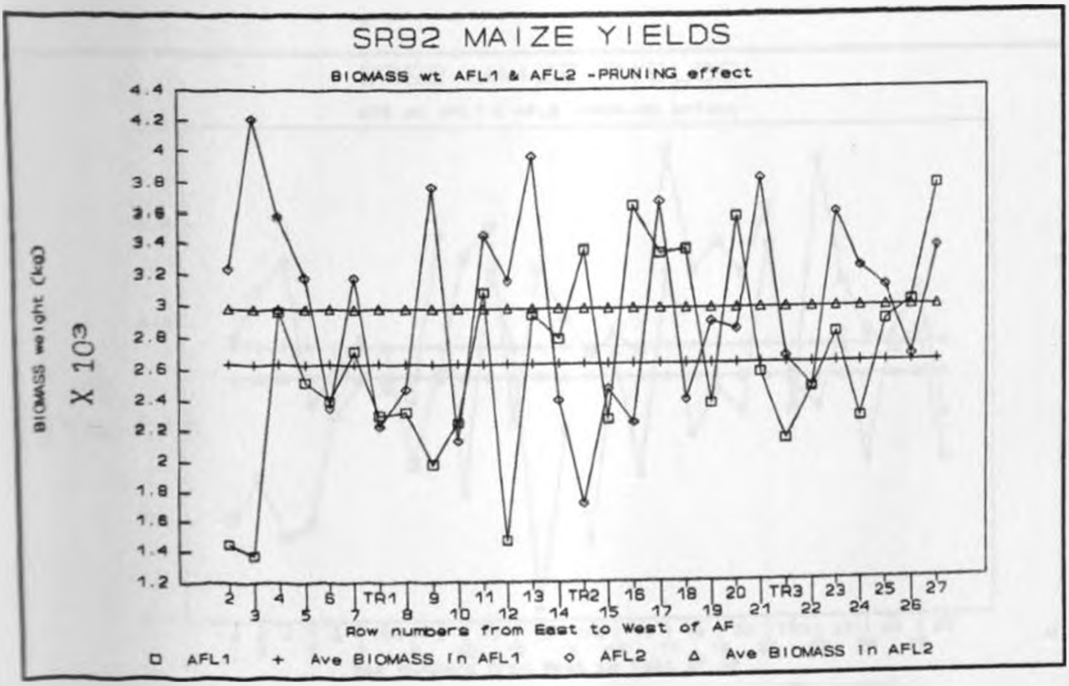


Fig. 57. Average maize biomass yields per row in pruned Local (AFL1) and unpruned Local (AFL2) for SR92.

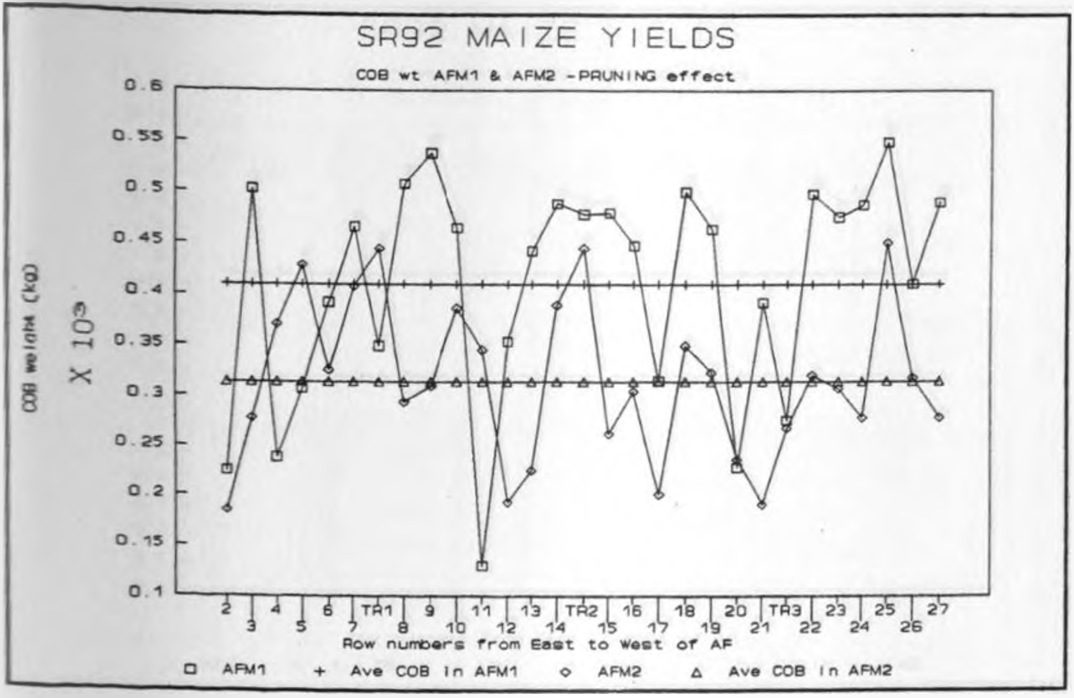


Fig. 58. Average maize cob splint yields per row in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for SR92.

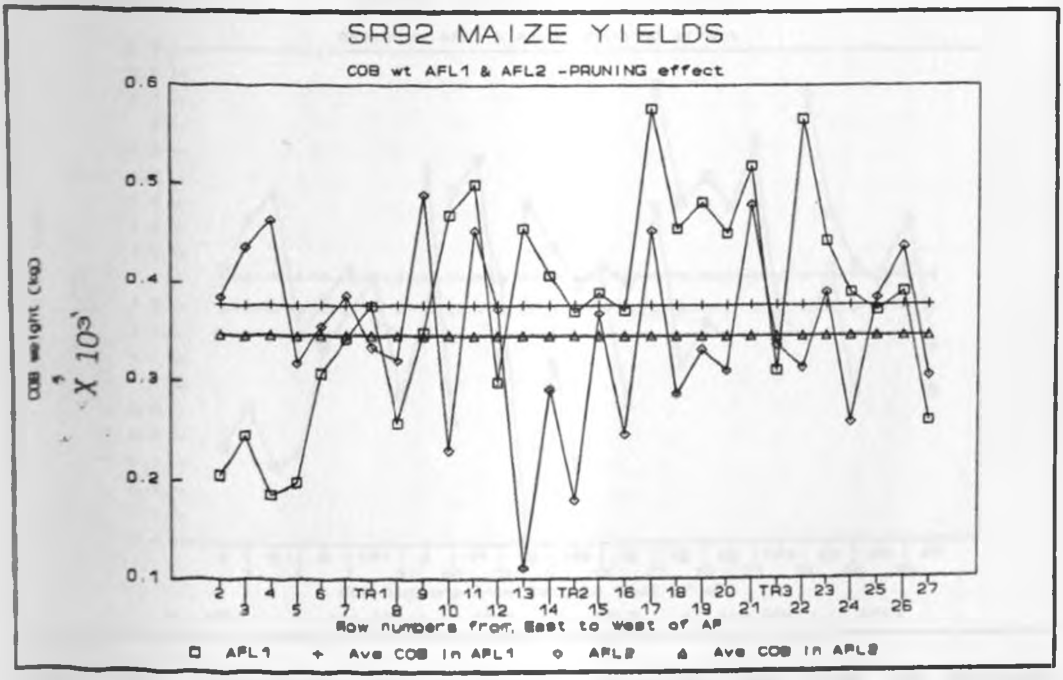


Fig. 59. Average maize cob splint yields per row in pruned Local (AFL1) and unpruned Local (AFL2) for SR92.

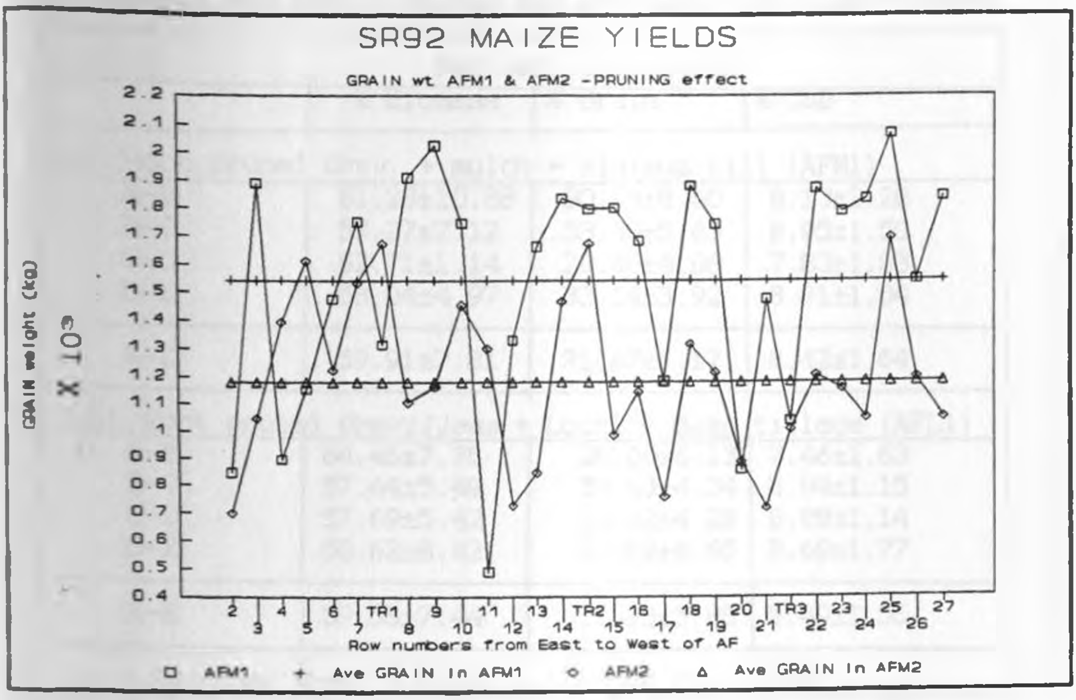


Fig. 60. Average maize grain yields per row in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for SR92.

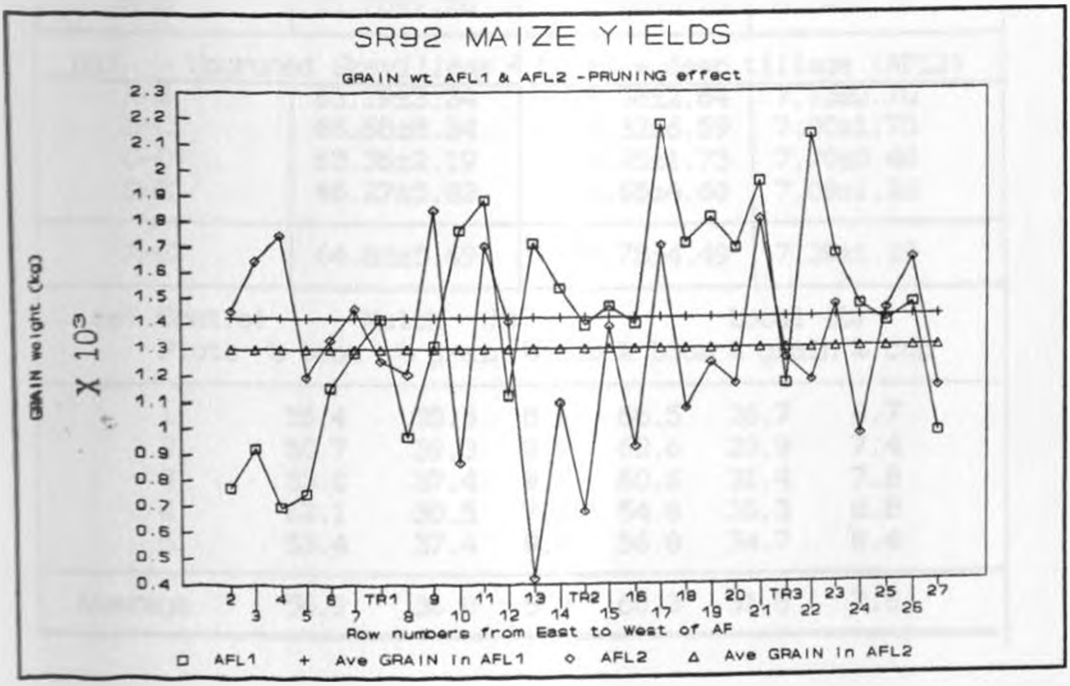


Fig. 61. Average maize grain yields per row in pruned Local (AFL1) and unpruned Local (AFL2) for SR92.

Table 20. SR92 per cent by weight of maize stover biomass. grain and cob in pruned and unpruned *Grevillea robusta*.

	Per cent components		
	% Biomass	% Grain	% Cob
(a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A-B	61.28±10.88	30.59±8.60	8.13±2.28
B-C	57.37±7.12	33.68±5.63	8.95±1.50
C-D	62.71±1.14	29.46±4.06	7.83±1.08
D-E	58.04±4.97	33.14±3.92	8.81±1.04
A-E	59.91±7.81	31.67±6.17	8.42±1.64
(b) Root pruned *Grevilleas* + Local + deep tillage (AFL1)			
A-B	64.46±7.75	28.08±6.13	7.46±1.63
B-C	57.44±5.49	33.63±4.34	8.94±1.15
C-D	57.69±5.42	33.42±4.28	8.88±1.14
D-E	58.62±8.42	32.69±6.65	8.69±1.77
A-E	59.58±7.44	31.93±5.88	8.49±1.56
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	57.59±7.50	33.50±5.93	8.91±1.58
B-C	57.78±6.47	33.37±5.11	8.87±1.36
C-D	65.64±5.69	27.14±4.50	7.21±1.20
D-E	66.39±2.69	26.55±2.12	7.06±0.56
A-E	61.70±7.26	30.26±5.73	8.04±1.52
(d) Unpruned *Grevilleas* + Local + deep tillage (AFL2)			
A-B	63.19±3.34	29.08±2.64	7.73±0.70
B-C	66.68±8.34	26.32±6.59	7.00±1.75
C-D	63.36±2.19	28.95±1.73	7.70±0.46
D-E	66.27±5.82	26.65±4.60	7.08±1.22
A-E	64.83±5.69	27.78±4.49	7.39±1.19

(e) Control	Mulch (M)			Local (L)		
Plots	% biom	% grain	% cob	% biom	% grain	% cob
1	55.4	35.5	8.9	66.5	26.7	6.7
2	50.7	39.3	9.9	62.6	29.9	7.4
3	53.0	37.4	9.4	60.6	31.4	7.8
4	62.1	30.5	7.3	54.8	36.3	8.8
5	53.4	37.4	9.0	56.8	34.7	8.4
Average	54.9	36.0	8.9	60.3	31.8	7.8

Table 21. Effects of Mulched and pruning within AF plots on maize grain, cob and biomass weights (a) Mulched (b) pruning SR92

treatments	average biomass (t/ha)	Average grain (t/ha)	Average cob (t/ha)
a) Mulched			
AFM1	3.01±0.69	1.54±0.40	0.41±0.11
AFL1	2.63±0.62	1.42±0.39	0.38±0.10
% increase for mulched	14.45	8.45	7.89
AFM2	2.44±0.62	1.18±0.29	0.31±0.08
AFL2	2.98±0.62	1.30±0.33	0.34±0.09
% decrease for mulched	-18.12	-9.23	-8.82
(b) Pruning effect			
AFM1	3.01±0.69	1.54±0.40	0.41±0.11
AFM2	2.44±0.62	1.18±0.29	0.31±0.08
% increase for pruned	23.36	30.5	32.26
AFL1	2.63±0.62	1.42±0.39	0.38±0.10
AFL2	2.98±0.62	1.30±0.33	0.34±0.09
% decrease or increase for pruned	-11.74	9.23	11.76

Mulched (AFM1. AFM2) and Local (AFL1. AFL2) plots for SR92. Figs. 58 & 59 compare the effect of *Grevillea robusta* root pruning on the cob weights while Figs. 60 & 61 compare the pruning effect on grain weights. AFM1 had more biomass than AFM2 by 23.4% and for some grain and cobs this was 30.5 and 32.4% respectively. From Table 21b we see that AFL2 this time yielded more biomass than AFL1 by 11.7% whereas AFL1 had now more grain and cob weights than the AFL2 by 9.2±1.2% and 11.8% respectively.

4.1.3 (j) Bean yields for SR92

(i) Mulch effect on bean biomass and grain weights in pruned and unpruned Grevillea plots

Figs. 62-65 and Table 22a compare the effects of mulching on the bean biomass weights in each row of the pruned (AFM1 & AFL1) and unpruned (AFM2 & AFL2) plots.

The pruned Mulched plot (AFM1) had more per cent biomass than the pruned Local (AFL1) by 47.5% even at this low crop residue mulch rate of 3 t/ha (Fig. 62 & Table 22a). In the unpruned plots (AFL2 & AFM2) the Mulched plot again had higher per cent biomass yield than the Local by 31.6% (Fig. 63 & Table 22a).

Figs. 65 & 66 and Table 22b compare the pruning effects on the bean seeds per cent weights in each row of the pruned and unpruned plots (AFM1. AFL1. AFM2 & AFL2). Again AFM1 had more per cent seed weights than AFL1 by 12.1%. AFM2 had higher yields than AFL2 by 10.0%. Also here the fluctuations over rows have to be considered large. certainly for the same reasons as in maize.

Mulched (AFM1. AFM2) and Local (AFL1. AFL2) plots for SR92. Figs. 58 & 59 compare the effect of *Grevillea robusta* root pruning on the cob weights while Figs. 60 & 61 compare the pruning effect on grain weights. AFM1 had more biomass than AFM2 by 23.4% and for some grain and cobs this was 30.5 and 32.4% respectively. From Table 21b we see that AFL2 this time yielded more biomass than AFL1 by 11.7% whereas AFL1 had now more grain and cob weights than the AFL2 by 9.2±1.2% and 11.8% respectively.

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Figs. 65 & 66 and Table 22b compare the pruning effects on the bean seeds per cent weights in each row of the pruned and unpruned plots (AFM1. AFL1. AFM2 & AFL2). Again AFM1 had more per cent seed weights than AFL1 by 12.1%. AFM2 had higher yields than AFL2 by 10.0%. Also here the fluctuations over rows have to be considered large. certainly for the same reasons as in maize.

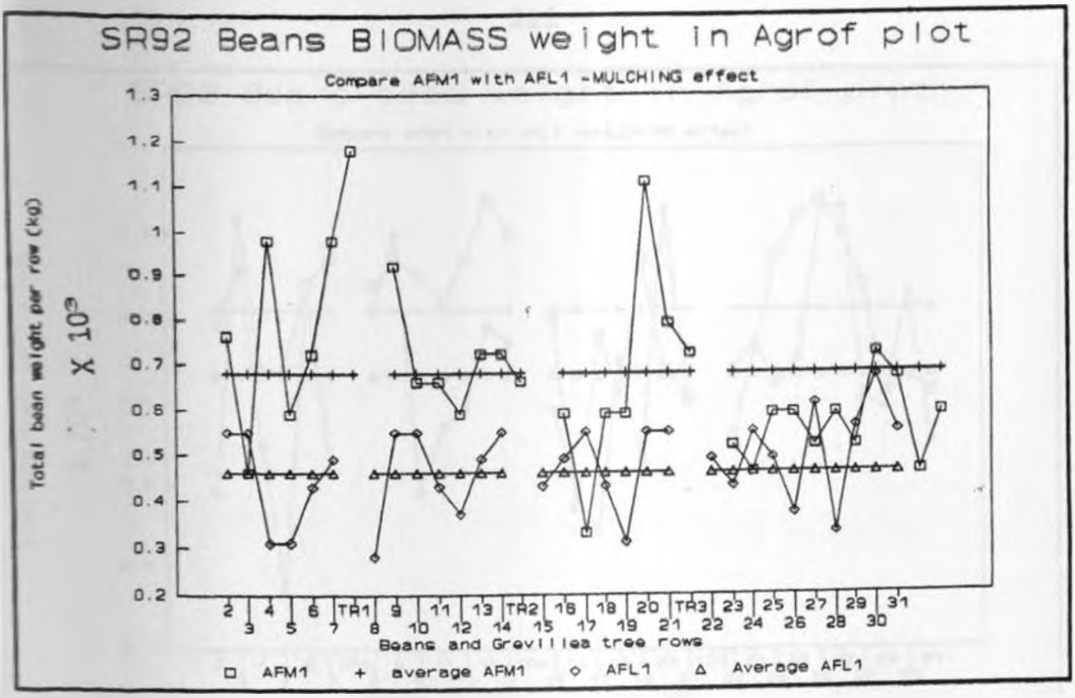

Fig. 62. Average beans biomass yields per row in pruned Mulched (AFM1) and pruned Local (AFL1) for SR92.

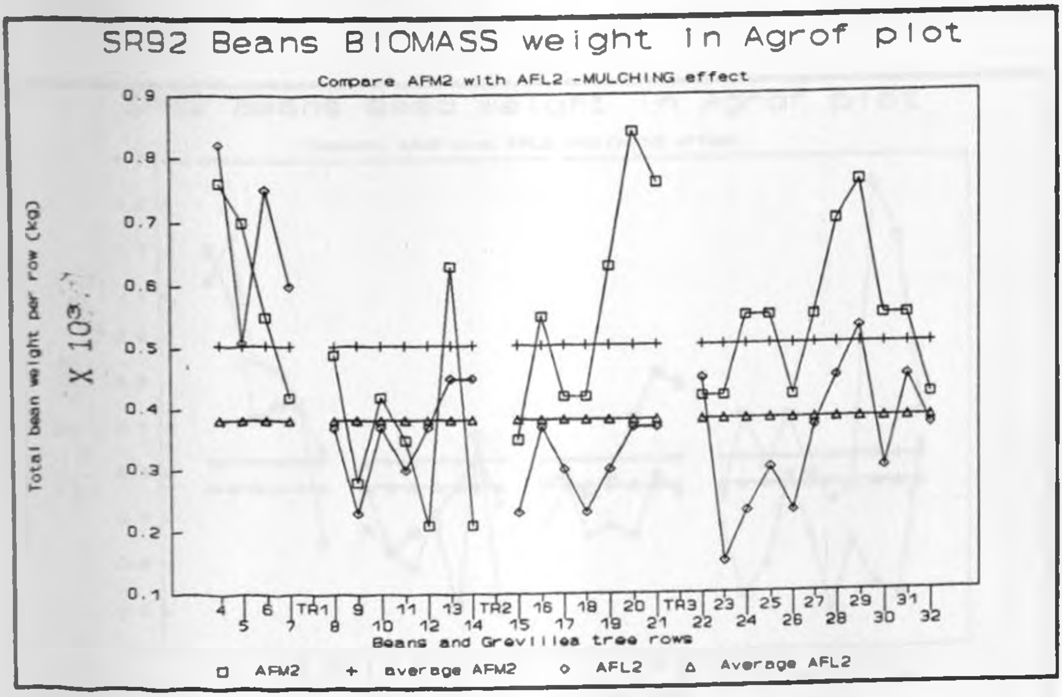

Fig. 63. Average beans biomass yields per row in unpruned Mulched (AFM2) and unpruned Local (AFL2) for SR92.

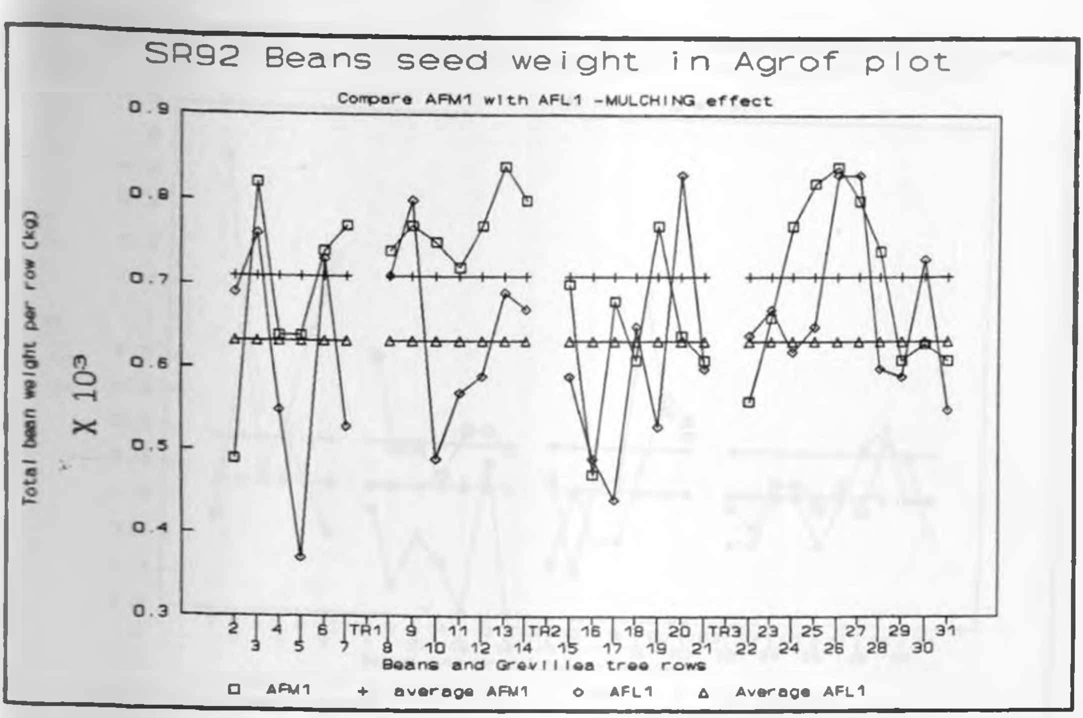

Fig. 64. Average beans seed yields per row in pruned Mulched (AFM1) and pruned Local (AFL1) for SR92.

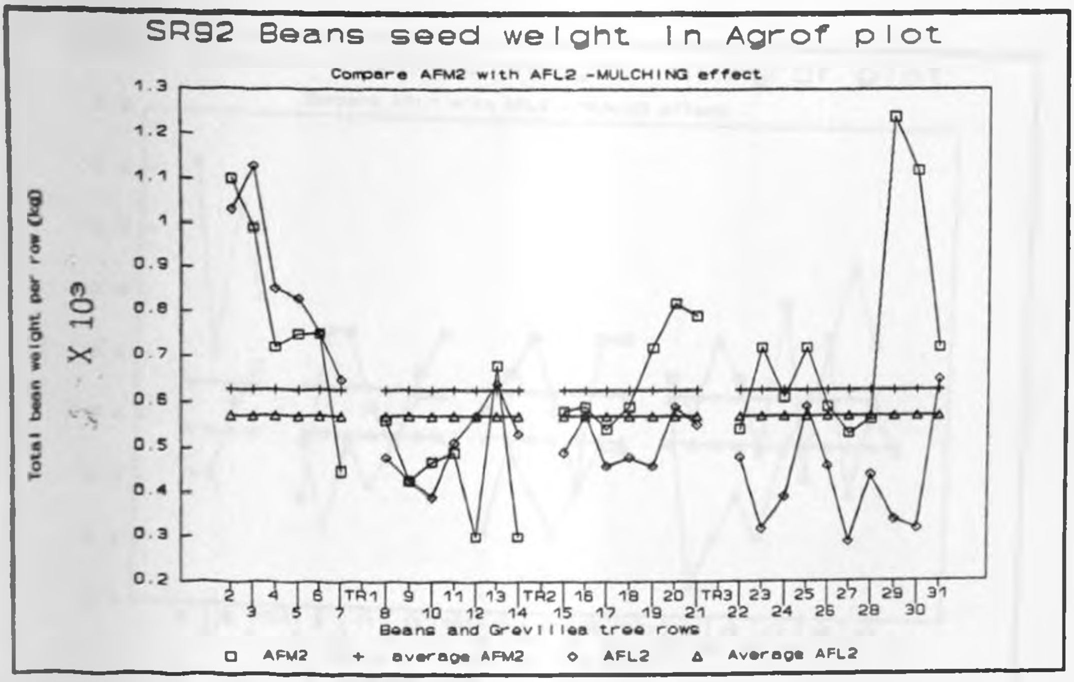

Fig. 65. Average beans seed yields per row in unpruned Mulched (AFM2) and unpruned Local (AFL2) for SR92.

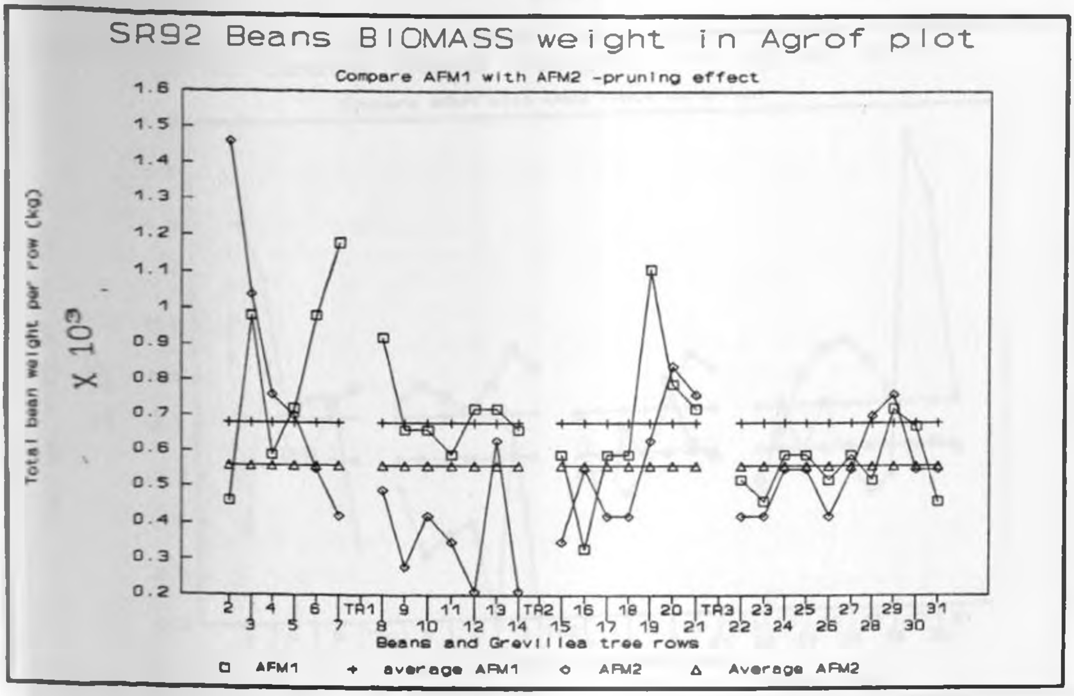

Fig. 66. Average beans biomass yields per row in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for SR92.

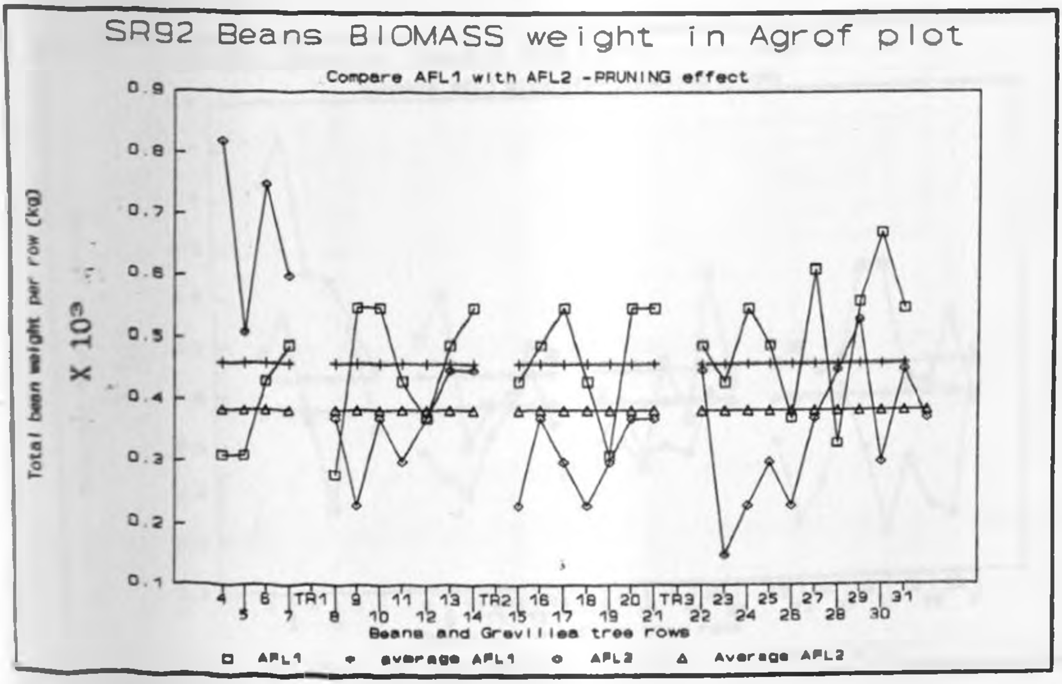

Fig. 67. Average beans biomass yields per row in pruned Local (AFL1) and unpruned Local (AFL2) for SR92.

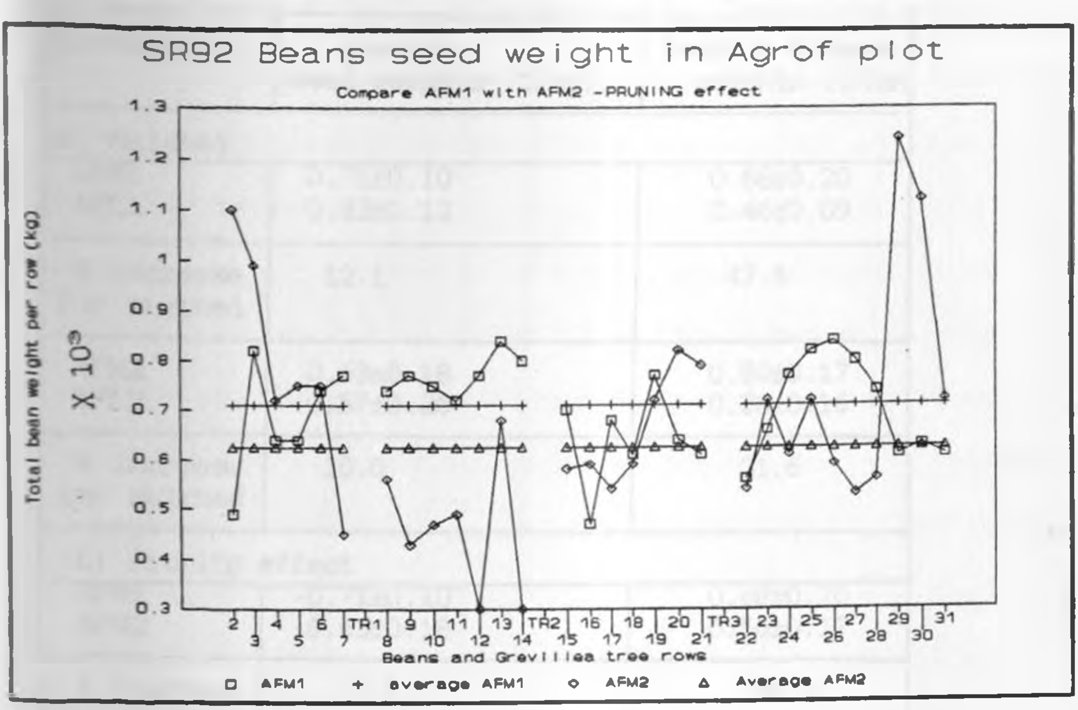

Fig. 68. Average beans seed biomass yields per row in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for SR92.

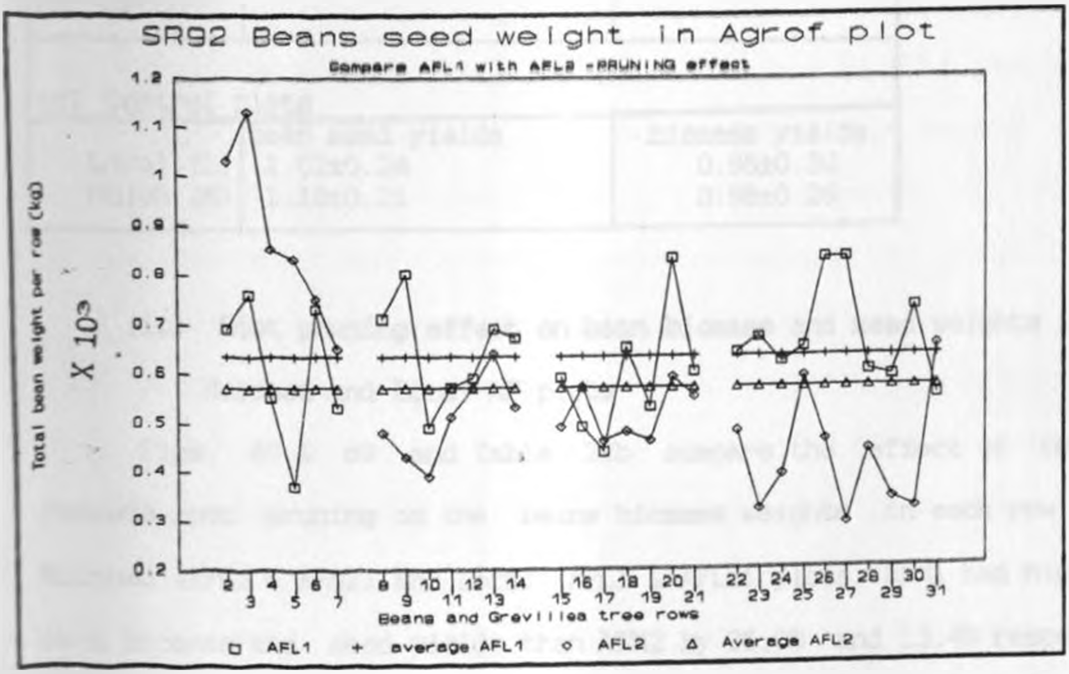

Fig. 69. Average beans seed biomass yields per row in pruned Local (AFL1) and unpruned Local (AFL2) for SR92.

Table 22. Effects of Mulched and pruning on bean seed and biomass weights (a) Mulched (b) pruning SR92

treatments	average seed weights (t/ha)	Average biomass weights (t/ha)
a) Mulched		
AFM1	0.71±0.10	0.68±0.20
AFL1	0.63±0.12	0.46±0.09
% increase for mulched	12.1	47.5
AFM2	0.63±0.18	0.50±0.17
AFL2	0.57±0.26	0.38±0.16
% increase for mulched	10.0	31.6
(b) Pruning effect		
AFM1	0.71±0.10	0.68±0.20
AFM2	0.63±0.18	0.50±0.17
% increase for pruned	13.4	36.0
AFL1	0.63±0.12	0.46±0.18
AFL2	0.57±0.26	0.38±0.16
% increase for pruned	11.3	20.4
(c) Control plots		
	bean seed yields	biomass yields
Local (L)	1.02±0.24	0.96±0.30
Mulch (M)	1.18±0.21	0.98±0.26

(ii) Root pruning effect on bean biomass and seed weights in Mulched and Local AF plots

Figs. 68 & 69 and Table 22b compare the effect of *Grevillea robusta* root pruning on the beans biomass weights in each row of the Mulched (AFM1 & AFM2) and Local (AFL1 & AFL2) plots. AFM1 had higher per cent biomass and seed yields than AFM2 by 36.0% and 13.4% respectively (Figs. 68 & 69 and Table 22b). AFL1 had more biomass and seed than the

AFL2 by 20.4% and 11.3% respectively (Figs. 67 & 69 and Table 22b).

On the average much more beans biomass was received from the pruned than the unpruned plots. The bean plants, like the maize plants, were also responsive in seed yields to mulching and pruning treatments (both in the order of 10%). These water conservation measures might have been useful to the beans at the early stage of their growth in October and November as they flowered before the onset of the heavier rains in December and January, 1993. The heavier rainfall at flowering may even have deflowered (made the plants drop the flowers) the plants resulting in poor pollination. Nevertheless an increase in both bean seed and total biomass is worth the trouble of conservation measures, within agroforestry systems like ours in a season with adequate water.

Results for the bean seed yields given in Table 22c with regard to the Mulched AF plots (AFM1 & AFM2) indicate that on the average, the pruned Mulched AF plot (AFM1) gave 0.31±0.34 t/ha less than the Local control plot (L) and 0.47±0.31 t/ha less than the Mulched control plot (M), while unpruned Mulched AF plot gave 0.39±0.42 t/ha less than the Local control and 0.55±0.39 t/ha less than the Mulched control (M) plots respectively. This confirms that with little exception NAF yields were higher than AF yields, due to more moisture running off in the AF plots.

Table 22c with regard to the Local AF plots (AFL1 & AFL2) indicate that on the average, the pruned Local AF plot (AFL1) gave 0.39±0.36 t/ha less than the Local control plot (L) and 0.55±0.33 t/ha less than the Mulched control plot (M), while unpruned Mulched AF plot gave 0.45±0.50 t/ha less than the Local control and 0.61±0.47 t/ha less than the Mulched control (M) plots respectively. The conclusion therefore is the same as given above for the mulched case. This also applies to the biomass differences between NAF and AF.

4.1.4 Long Rains season 1993

4.1.4 (a) Rainfall and evaporation climate during growing season

The maize/bean intercrop was planted on 14th April, 1993, after cumulative rainfall total of 22.5 mm was received against 66.5 mm of pan evaporation spread over 13 days prior to planting date. The rainfall throughout the four months of the season was below the long term mean except May which received 43.8 mm above its long term mean (see Fig. 15). We see in Table 7 that the rains were concentrated in April and May, which received 84.7 and 90.4 mm respectively. April with rainfall of 37.5 mm below its long term mean had the highest negative value followed by March and June, 1993 with 22.0 and 15.2 mm respectively below their long term means. The pan evaporation rates for April and May were 138.2 and 154.4 mm respectively. May, 1993 had pan evaporation of 3.6 mm below the long term mean. All pan evaporation rates were below their long term means pointing to high cloudiness. March had the highest negative deviation of 15.0 mm below its long term mean value.

The rainfall that was received in April was only adequate for seedling emergence and initial growth. Like earlier seasons (SR91 and LR92) there was a good initial start and a bad ending. Inadequate rainfall and onset of strong winds in June, and after, resulted in plants attaining the permanent wilting point rapidly, by mid July. Beans were harvested on 27/7/93 and maize that remained in the field was drying quite fast.

4.1.4 (b) Maize and beans phenology

Of the maize seedlings 30% in AF plots and 20% in Local and Mulched controls had emerged by 7 DAP (by 21/4/93). By 15 DAP 85% in the Local control plots, 85% in the Mulched control and 90% in the AF plot

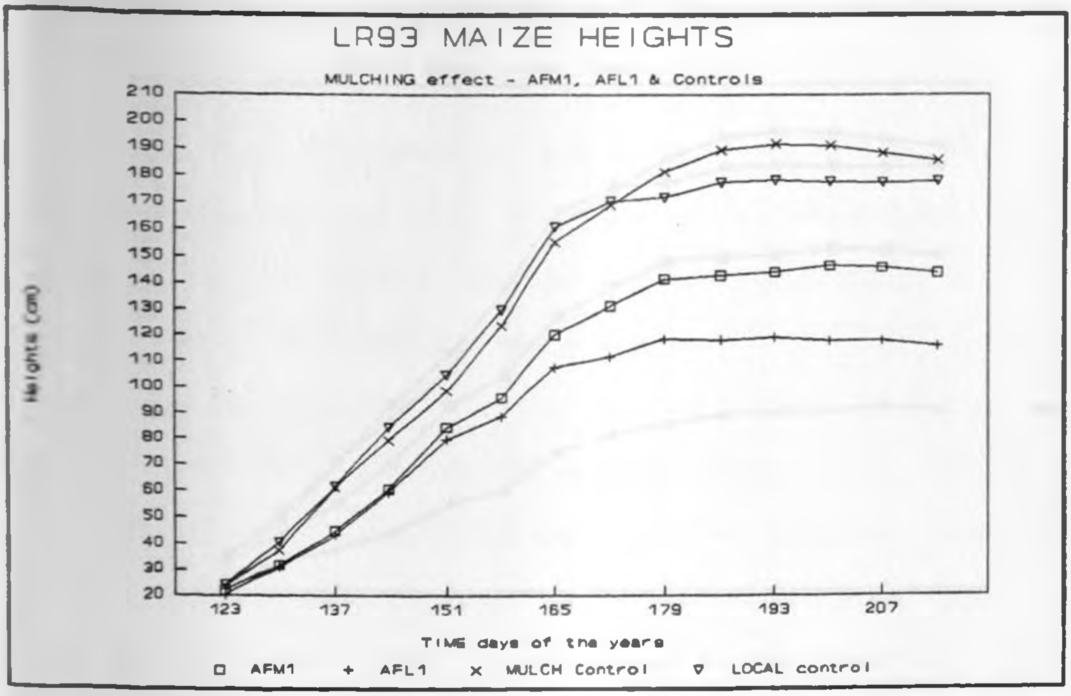

Fig. 70. Average maize heights in pruned Mulched (AFM1) and pruned Local (AFL1) for LR93, compared with the control plots.

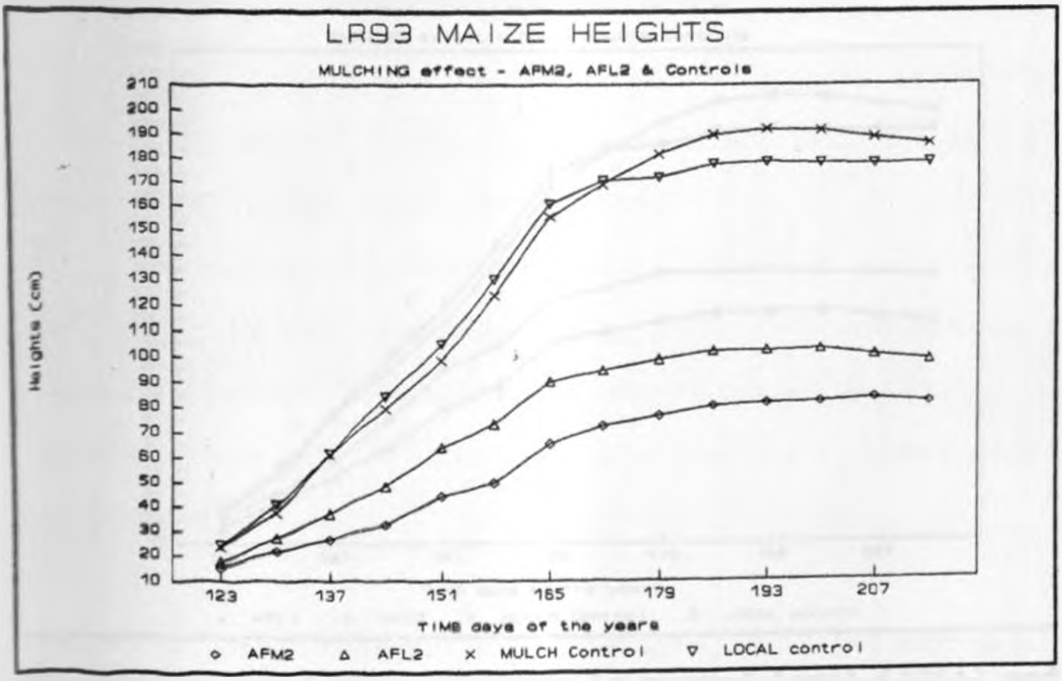

Fig. 71. Average maize heights in unpruned Mulched (AFM2) and unpruned Local (AFL2) for LR93, compared with the control plots.

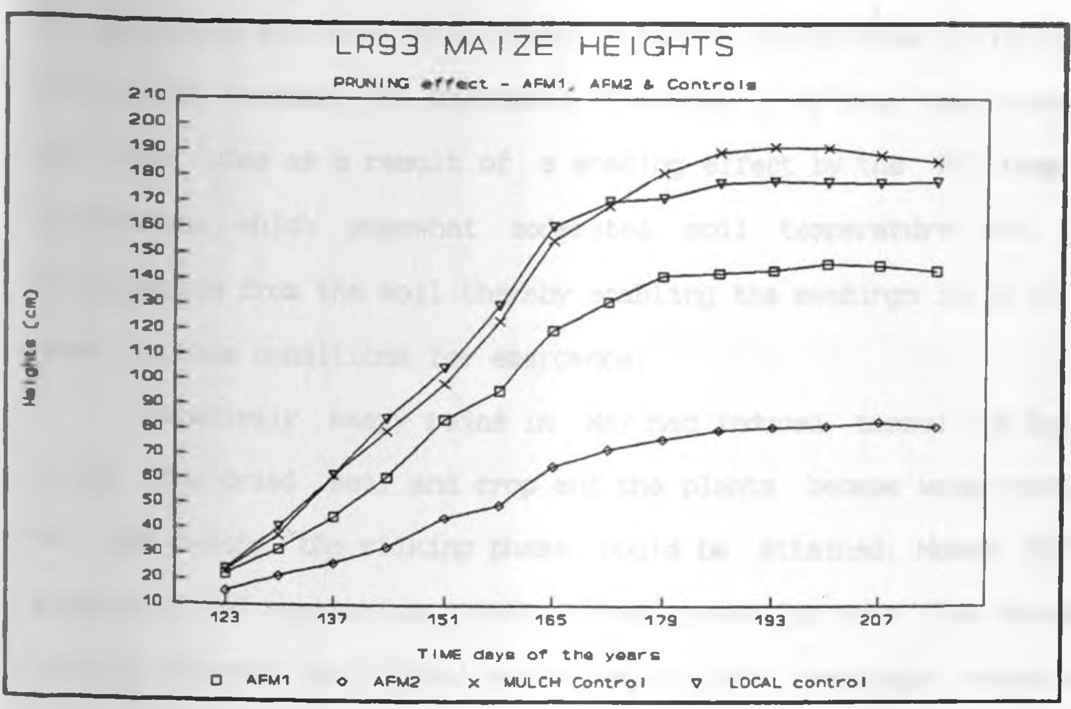

Fig. 72. Average maize heights in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for LR93.

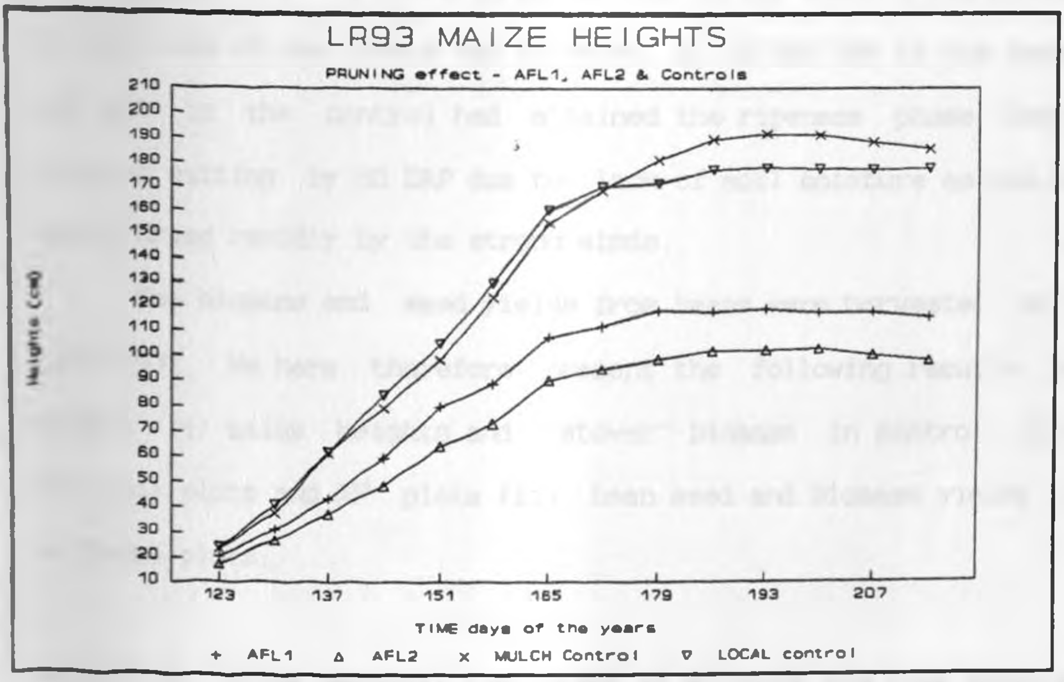

Fig. 73. Average maize heights in pruned local (AFL1) and unpruned Local (AFL2) for LR93.

had emerged. Emergence attained 100% level by 22 DAP. These differences in emergence may have contributed to marked differences in yields of LR93 maize biomass. The emergence advantage in AF over the control plots may have come as a result of a shading effect by the AF trees and the live-fence which somewhat moderated soil temperature and reduced evaporation from the soil thereby enabling the seedings in AF to receive near optimum conditions for emergence.

Relatively heavy rains in May had induced tasselling but strong winds soon dried soil and crop and the plants became water stressed by 68 DAP before the silking phase could be attained. Hence the plants generally had vegetative growth without producing cobs. The strong winds mostly affected the control plots due to their immediate exposure since they were in open area. The plants dried up by 103 DAP (i.e. 26/7/93).

By 7 DAP 85% of all the beans in plots (M. L & AF) had emerged. By 45 DAP 15% of the beans in AF and 10% in the control had flowered. By 50 DAP 100% of the plants had flowered. By 68 DAP 30% of the beans in AF and 15% in the control had attained the ripeness phase. The plants started wilting by 80 DAP due to lack of soil moisture as the soil was being dried rapidly by the strong winds.

The biomass and seed yields from beans were harvested on 104 DAP (27/7/93). We here therefore present the following results for this season (i) maize heights and "stover" biomass in control (Local and Mulched) plots and AF plots (ii) bean seed and biomass yields in each of these plots.

4.1.4 (c) Maize heights: The effect of mulching and root pruning on maize heights

Intercomparisons were made of the effect of mulching (Figs. 70 &

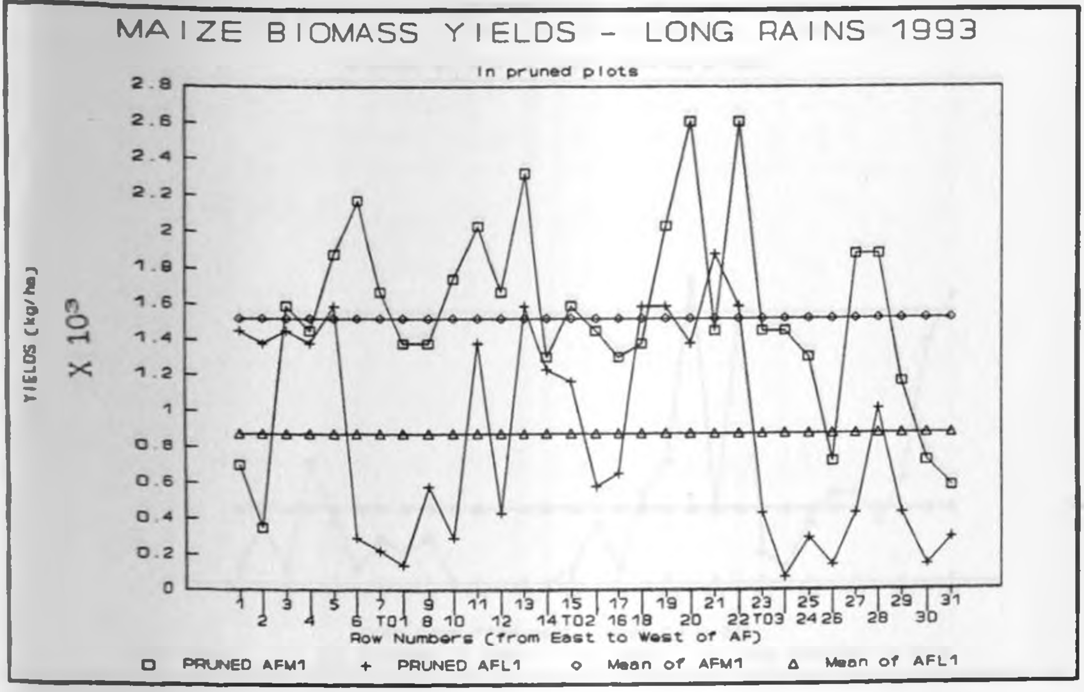

Fig. 74. Average maize biomass yields per row in pruned Mulched (AFM1) and pruned Local (AFL1) for LR93.

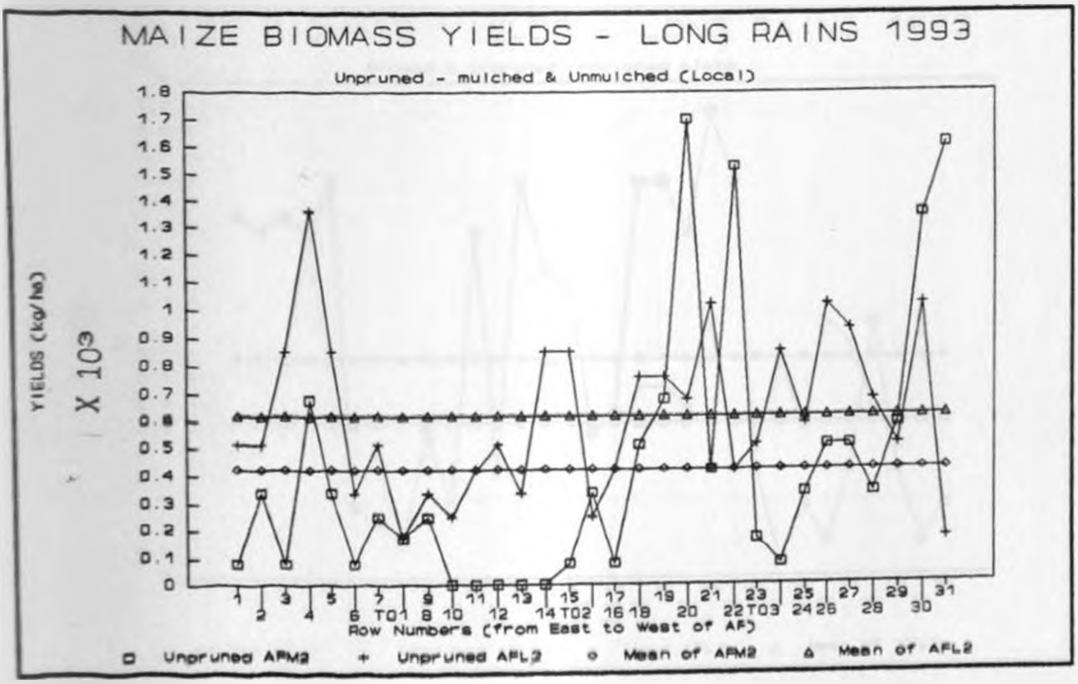

Fig. 75. Average maize biomass yields per row in unpruned Mulched (AFM2) and unpruned Local (AFL2) for LR93.

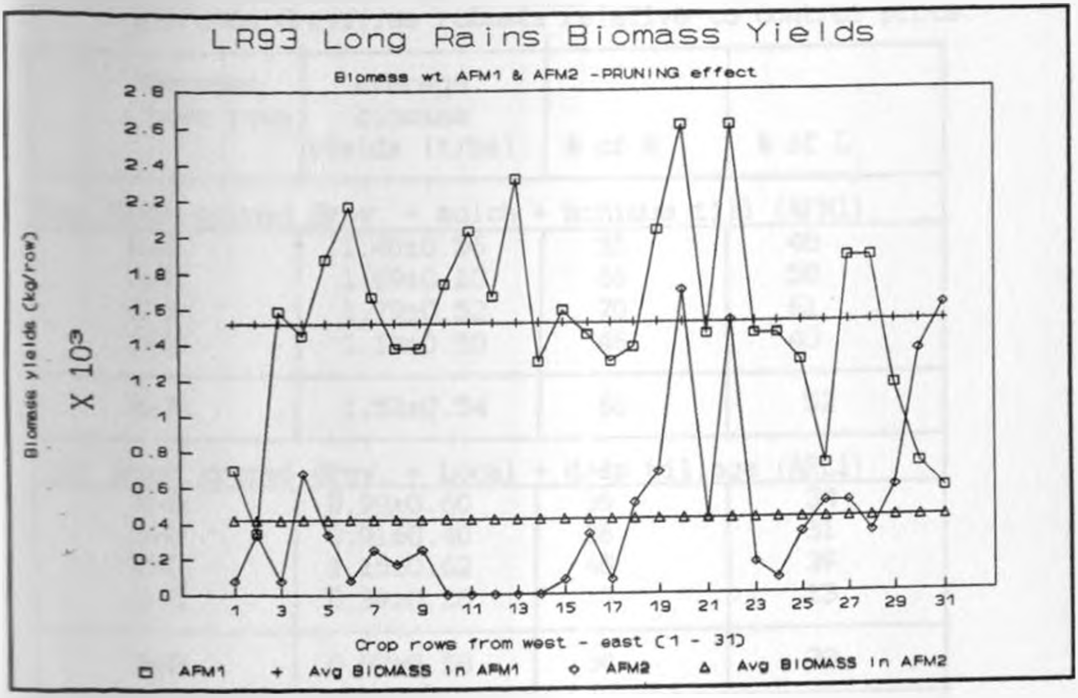

Fig. 76. Average maize biomass yields per row in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for LR93.

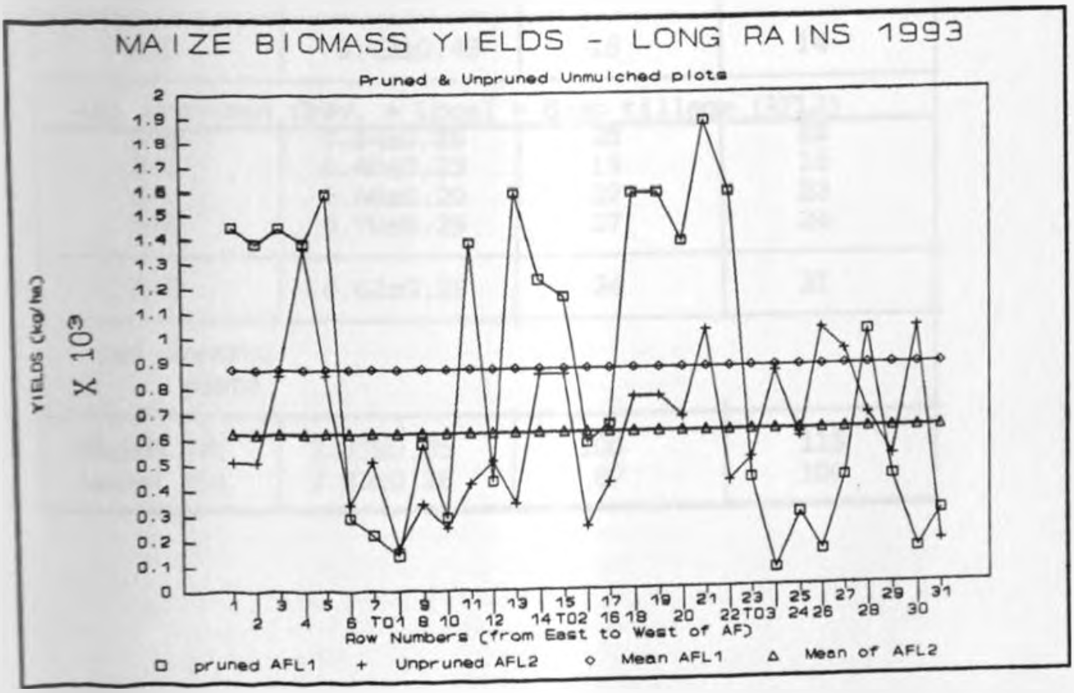

Fig. 77. Average maize biomass yields per row in pruned Local (AFL1) and unpruned Local (AFL2) for LR93.

Table 23. LR93 maize biomass yields in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average biomass yields (t/ha)	% of M	% of L
(a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A-B	1.40±0.56	55	48
B-C	1.69±0.10	66	58
C-D	1.79±0.52	70	61
D-E	1.18±0.50	46	40
A-E	1.52±0.54	60	52
(b) Root pruned *Grev.* + Local + deep tillage (AFL1)			
A-B	0.99±0.60	39	34
B-C	0.91±0.40	36	31
C-D	1.15±0.62	45	39
D-E	0.39±0.28	15	13
A-E	0.87±0.58	34	30
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	0.25±0.19	10	9
B-C	0.08±0.13	3	3
C-D	0.65±0.59	25	22
D-E	0.75±0.47	29	26
A-E	0.42±0.48	16	14
(d) Unpruned *Grev.* + Local + deep tillage (AFL2)			
A-B	0.64±0.35	25	22
B-C	0.48±0.23	19	16
C-D	0.68±0.20	27	23
D-E	0.70±0.29	27	24
A-E	0.62±0.29	24	21
(e) Control plots			
Mulch (M)	2.55±0.85	100	115
Local (L)	2.93±0.28	87	100

Table 24. Effects of Mulching and pruning on maize biomass weights for LR93 (a) Mulched (b) pruning.

treatments	average biomass weights (t/ha)
a) Mulched	
AFM1 AFL1	1.52±0.54 0.87±0.58
% increase for mulched	74.7
AFM2 AFL2	0.42±0.48 0.62±0.29
decrease for mulch of	32.3
(b) Pruning effect	
AFM1 AFM2	1.52±0.54 0.42±0.48
% increase for pruned	261.9
AFL1 AFL2	0.87±0.58 0.62±0.29
% increase for pruned	40.3

Table 25. Effects of Mulching and pruning on beans seed & biomass weights (a) Mulched (b) pruning LR93

treatments	average biomass (t/ha)	Average seed (t/ha)
(a) Mulched		
AFM1 AFL1	0.41±0.12 0.33±0.16	0.53±0.16 0.39±0.15
% increase	24.2	35.9
AFM2 AFL2	0.19±0.14 0.31±0.11	0.20±0.14 0.37±0.12
% increase	-38.7	-46.0

(b) Pruning effect		
AFM1 AFM2	0.41±0.12 0.19±0.14	0.53±0.16 0.20±0.14
% increase for pruned	115.79	165
AFL1 AFL2	0.33±0.16 0.31±0.11	0.39±0.15 0.37±0.12
% increase for pruned	6.5	5.4

71) and of *Grevillea* root pruning (Figs. 72 & 73) on the progress of maize heights in AF and control plots. From the date of emergence, the plants in the control plots were growing faster than those in AF (shown in Figs. 70 & 71).

We can observe the effect of mulching in Figs. 70 & 71. The plants in the pruned Mulched plot (AFM1, Fig. 70) in AF had grown taller than those in the pruned Local plot (AFL1). The plants in the unpruned Mulched plot (AFM2, Fig. 71) in AF were, however, shorter than those in the unpruned Local plot (AFL2). Also those in the Mulched NAF grew taller than those in the Local NAF. This confirmed the superiority under LR93 conditions of mulching with minimum tillage to other treatments that small-scale farmers may use on their farms.

We observe the effect of pruning in Figs. 72 & 73. Inter-comparisons of the Mulched plots show that the pruned Mulched (AFM1) maize had grown especially taller than the unpruned Mulched (AFM2) maize. This was also the case with the Local plots, where the pruned Local (AFL1) had grown taller than the unpruned Local (AFL2) (Fig. 73). This again confirmed the superiority of pruning to the unpruned treatment, for the LR93 conditions.

4.1.4 (d) Maize biomass yields: Effects of Mulched and pruning on maize biomass weights

We hereby present comparisons of the effects of mulching on stover biomass weights in pruned and unpruned plots in the AF plots for the LR93 (Figs. 74 & 75, Tables 23 & 24).

We observed in several cases very strong effects of both mulching and pruning during this season. The effect of mulching was positive and much higher in the pruned (AFM1, AFL1) than the negative effect in the unpruned (AFM2, AFL2) plots. There was more biomass harvested from the pruned Mulched with minimum tillage (AFM1) than from the pruned Local with deep tillage (AFL1) by 74.7%. The situation reversed in favour of the Local deep tilled treatment in the unpruned plots in which the Local unpruned plot (AFL2) had more biomass than the Mulched one by 12.5%, but at appreciably lower yield levels. As we have already mentioned earlier, this last case is not so interesting for us once we decide to advise pruned Mulched with minimum tillage for adoption by farmers, which would be logical given the yield levels of LR93.

The effect of pruning was most evident in Mulched plots when the pruned had more stover biomass than the unpruned by more than 261.9% (Figs. 76 & 77), Table 24). This trend was maintained for the Local plots as the pruned plots recorded more biomass weight than the pruned by 40.3%. This was of course also reflected in the actual yields, although particularly the unpruned Mulched yields were rather low. A large maize biomass yield with no grain as in LR93 confirms, in the ultimate limit, our observation that cob and grain weights are inversely related to stover biomass. Hence a large biomass may result in little or no cob and grain yields if rainfall distribution is not favourable.

Because we have illustrated sufficiently the large fluctuations of yields per row with the data of previous seasons but ultimately deal with totals yields have longer given such data here and in the remaining seasons.

4.1.4 (e) Beans biomass and seed yields

Tables 25 and Table 26 present the effects of mulching and pruning on the bean biomass and seed yields for the LR93. We can see in Table 25a that bean biomass and seed yields from Mulched plots were more than from the Local plots by 24.2 and 35.9% respectively, in pruned plots.

In unpruned plots mulch application had a negative effect on the beans biomass and seed yields, just as in the case of maize, as the unpruned Local plot (AFL2) had 38.7 and 46.0% more biomass and seed yields than the Mulched plot (AFM2) (Table 25). This was particularly the case through depressed yields in the unpruned Mulched plots.

In unpruned plots mulching (with minimum tillage) must have improved soil conditions favourably for increased root ramification in which tree roots competed vigorously with the maize/beans intercrop for soil resources (i.e. for water and nutrients) thus affecting both biomass and grain yields.

The effect of root-pruning was assessed by comparing plots under the same surface cover treatments (Mulched or Local) in the AF. From Table 25b we learn that root-pruning was more effective as a control measure in the pruned Mulched plot (AFM1) than in the unpruned Mulched plot (AFM2. Table 25b) for both biomass and seed yields.

Of the Mulched (plus minimum tillage) plots, the pruned plot (AFM1) produced more bean biomass and bean seed yields than the unpruned one (AFM2) by 115.8 and 165% respectively (Table 25b). In the Local (deep tillage) plots the pruned plot produced more biomass and grain yields than unpruned Local, but only by a negligible 6.5 and 5.4% respectively.

Comparing the biomass and seed yields from AF plots with the controls (Tables 26 and 27) we find that more and seed yields were obtained from AFM1, particularly from the lower part of the AF plot between TR3 and tree row E (see Fig. 9), which is the only plot with yields comparable to the controls. AFM1 biomass yields, although

Table 26. LR93 beans biomass yields in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average biomass yields (t/ha)	% of L	% of M
(a) Root pruned *Grev.* + mulch + minimum tillage (AFM1)			
A-B	0.39±0.11	64	58
B-C	0.39±0.10	64	58
C-D	0.37±0.08	61	55
D-E	0.49±0.12	80	73
A-E	0.41±0.12	67	61
(b) Root pruned *Grev.* + Local + deep tillage (AFL1)			
A-B	0.22±0.03	36	33
B-C	0.20±0.05	33	30
C-D	0.32±0.10	52	48
D-E	0.51±0.21	84	76
A-E	0.33±0.16	54	49
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	0.13±0.06	21	19
B-C	0.07±0.04	11	10
C-D	0.21±0.08	34	31
D-E	0.35±0.15	57	52
A-E	0.19±0.14	31	28

(d) Unpruned *Grev.* + Local + deep tillage (AFL2)			
A-B	0.30±0.04	49	45
B-C	0.31±0.05	51	46
C-D	0.25±0.05	41	37
D-E	0.38±0.18	62	57
A-E	0.31±0.11	51	46
(e) Control plots			
Local (L)	0.67±0.25	110	100
Mulch (M)	0.61±0.27	100	91

Table 27. LR93 beans seed yields in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average seed yields (t/ha)	% of L	% of M
(a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A-B	0.43±0.15	67	72
B-C	0.57±0.17	89	95
C-D	0.53±0.11	83	88
D-E	0.61±0.17	95	102
A-E	0.53±0.16	83	88
(b) Root pruned *Grev.* + Local + deep tillage (AFL1)			
A-B	0.31±0.05	48	52
B-C	0.38±0.08	59	63
C-D	0.48±0.12	75	80
D-E	0.39±0.23	61	65
A-E	0.39±0.15	61	65
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	0.14±0.07	22	23
B-C	0.09±0.04	14	15
C-D	0.32±0.13	50	53
D-E	0.27±0.13	42	45
A-E	0.20±0.14	31	33
(d) Unpruned *Grev.* + Local + deep tillage (AFL2)			
A-B	0.43±0.07	67	72
B-C	0.40±0.07	63	67
C-D	0.38±0.07	59	63
D-E	0.27±0.16	42	45
A-E	0.37±0.12	58	62

(e) Control plots			
Local (L)	0.60±0.21	94	100
Mulch (M)	0.64±0.20	100	106

superior to the other treatments, did not come even close to the values of the controls and the lower half was only marginally better. Pruned Local and unpruned Mulched had both much more seed and biomass yields in the lower half of the plots with the exception of AFL1 where this effect was smaller. There was marginally more beans biomass yield and marginally less bean seed yield from the Local control than from the Mulched control plots. On the average, the control plots produced both more seed and biomass yields than the averaged AF plots.

4.1.5 Short Rains season 1993

4.1.5 (a) Rainfall and evaporation climate during growing season

The maize/bean intercrop was planted on 16th October, 1993, after a rainfall total of 14.4 mm was received against 8.9 mm of pan evaporation in the period preceding the planting date. The rainfall throughout the four months of the season was below the long term mean while pan evaporation rates were above their long term means (Fig. 14). The rains were concentrated mainly in November which received 117.2 mm. January 1994, with rainfall of 49.2 mm below its long term mean, had the highest negative value followed by December and November, 1993, which had 32.1 and 18.1 mm too low respectively. The pan evaporation rates for November, December and January were 115.8, 174.7 and 172.5 mm respectively. All pan evaporation rates were above their long means, with December having the highest positive deviation of 41.0 mm above its long term mean.

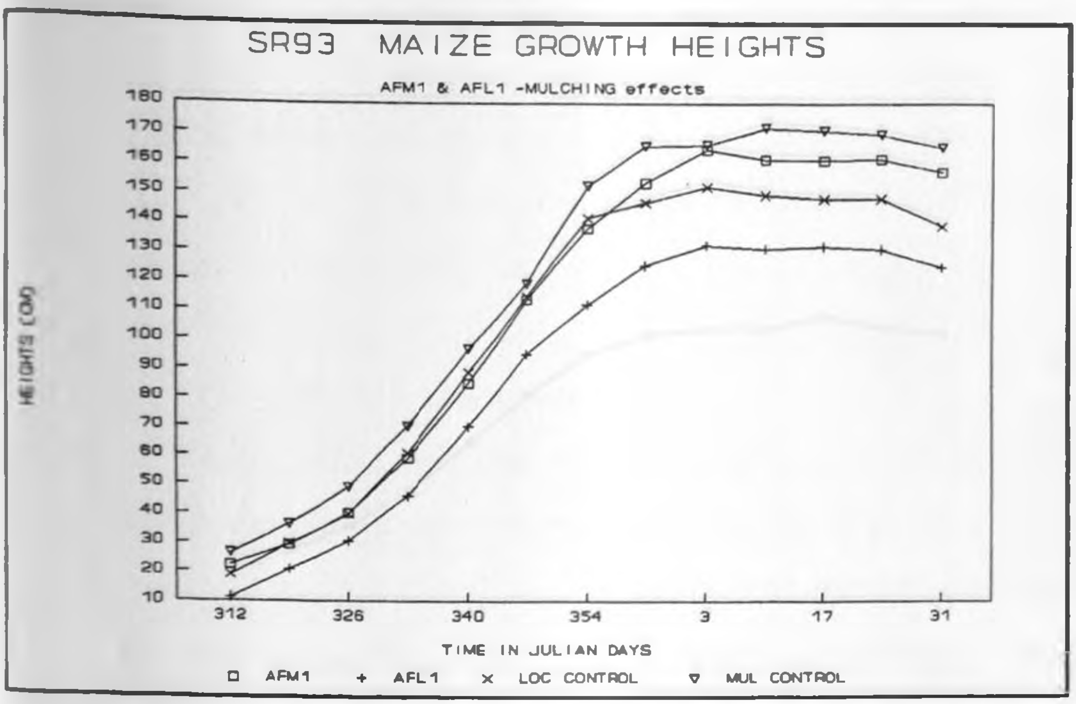

Fig. 78. Average maize heights per row in pruned Mulched (AFM1) and pruned Local (AFL1) for SR93, compared with the control plots.

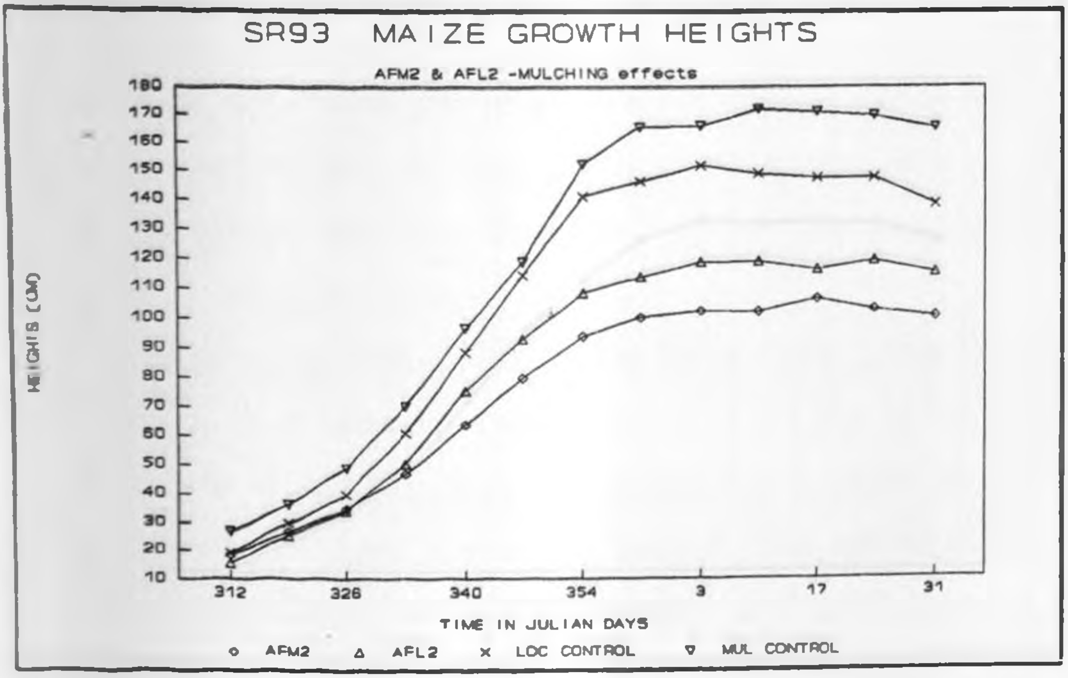

Fig. 79. Average maize heights per row in unpruned Mulched (AFM2) and unpruned Local (AFL2) for SR93, compared with the control plots.

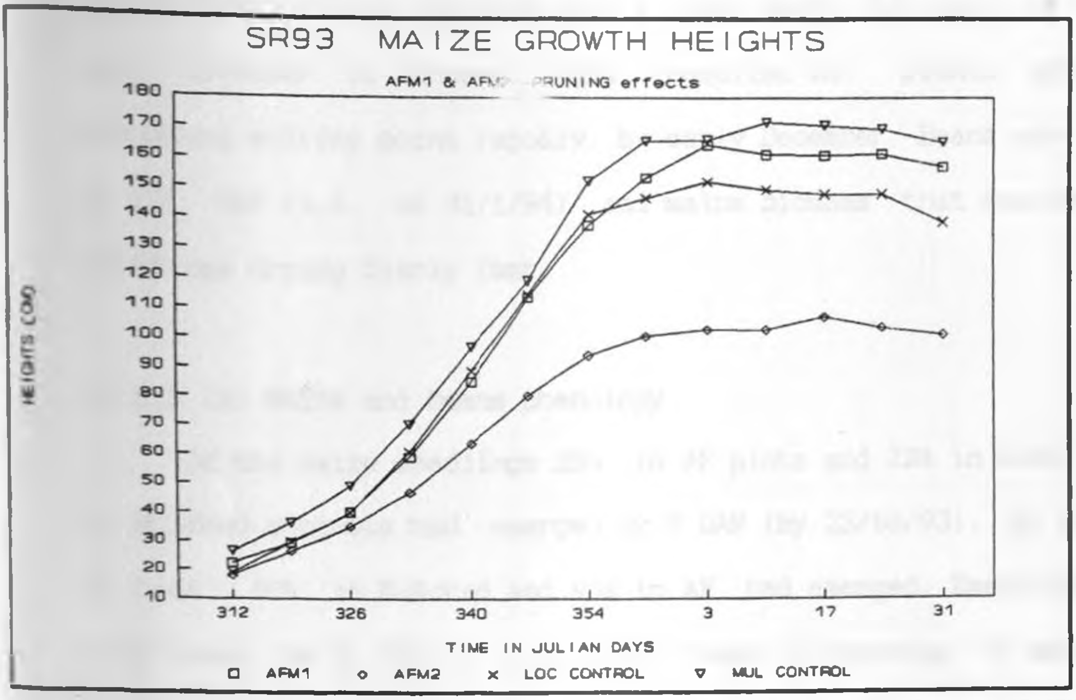

Fig. 80. Average maize heights per row in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for SR93, compared with the control plots .

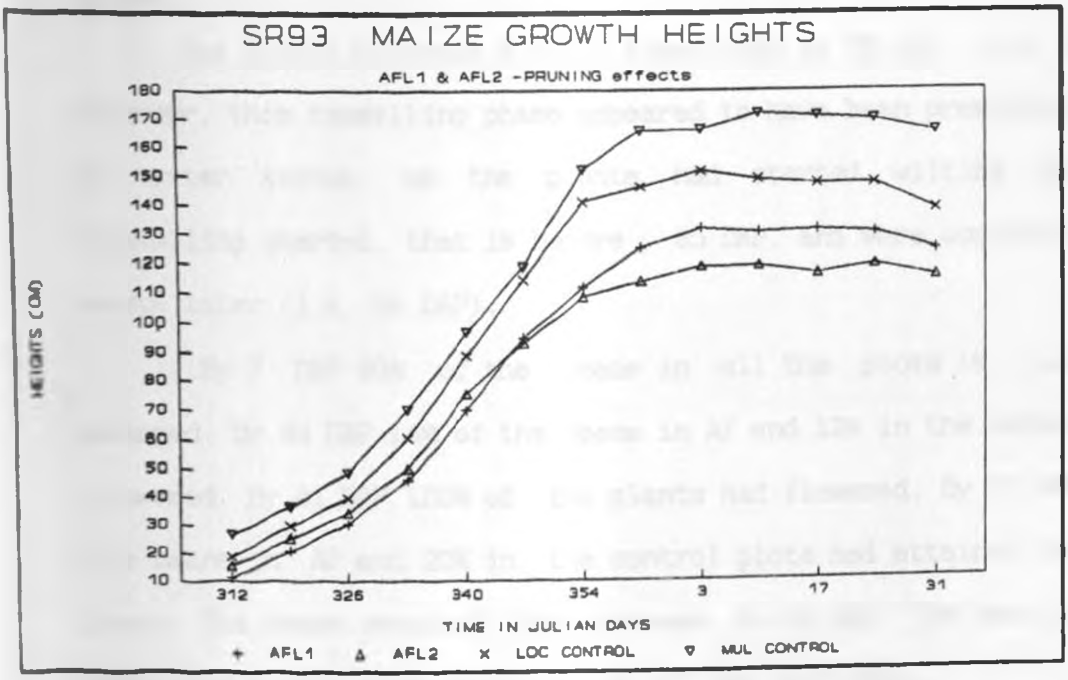

Fig. 81. Average maize heights per row in pruned Local (AFL1) and unpruned Local (AFL2) for SR93, compared with the control plots.

The rainfall received in October and November was only adequate for seedling emergence and early growth. Like earlier seasons (SR91, LR92, LR93) initial growing made a good start, but lack of rain, from late November to January, 1994, resulted in plants attaining the permanent wilting point rapidly, by early December. Beans were harvested on 107 DAP (i.e. on 31/1/94) and maize biomass that remained in the field was drying fairly fast.

4.1.5 (b) Maize and beans phenology

Of the maize seedlings 35% in AF plots and 22% in Local and 25% in Mulched controls had emerged by 7 DAP (by 23/10/93). By 14 DAP, 90% in Local, 93% in Mulched and 95% in AF had emerged. Emergence attained 100% level by 21 DAP in all plots. These differences in emergence may again have contributed to in marked differences in maize biomass yields in SR93. Again the shading effect by the AF trees and the live-fence may have been of influence, as we have mentioned in section 4.1.4 (b) above.

The plants attained 10-20 % tasselling by 72 DAP (i.e. 27/12/93). However, this tasselling phase appeared to have been prematurely induced by water stress, as the plants had started wilting just before tasselling started, that is before 65 DAP, and were completely dry two weeks later (i.e. 86 DAP).

By 7 DAP 90% of the beans in all the plots (M, L & AF) had emerged. By 44 DAP 16% of the beans in AF and 12% in the control had flowered. By 51 DAP 100% of the plants had flowered. By 75 DAP, 35% of the beans in AF and 20% in the control plots had attained the ripeness phase. The beans attained 100% ripeness by 86 DAP. The bean biomass and bean seed yields were harvested on 107 DAP (27/7/93).

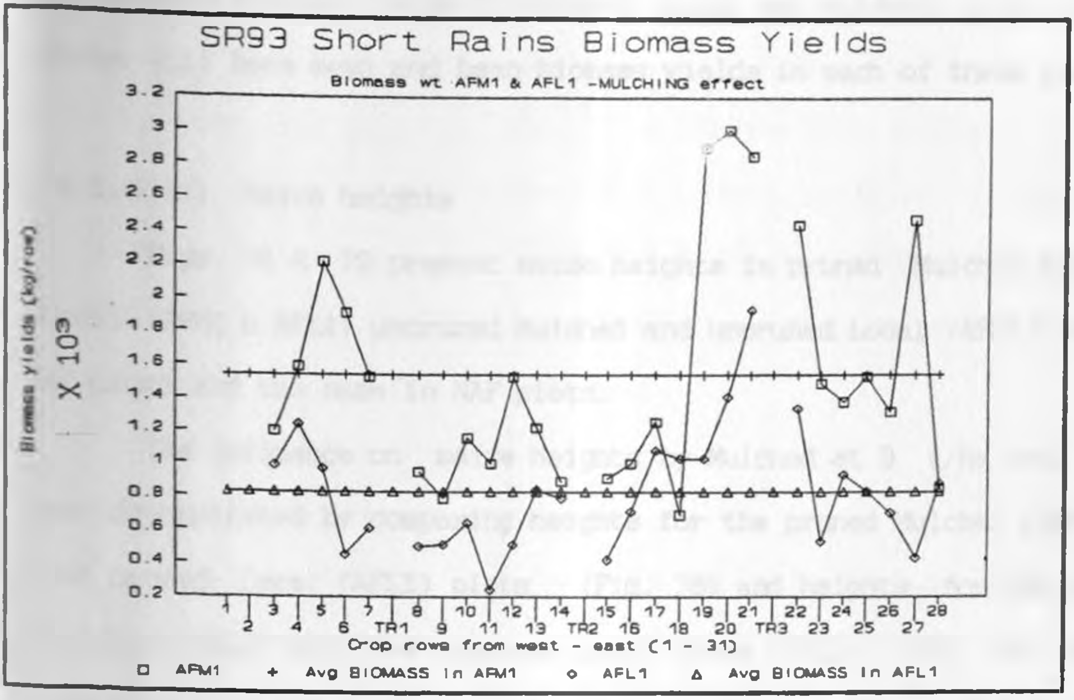

Fig. 82. Average maize biomass yields per row in pruned Mulched (AFM1) and pruned Local (AFL1) for SR93.

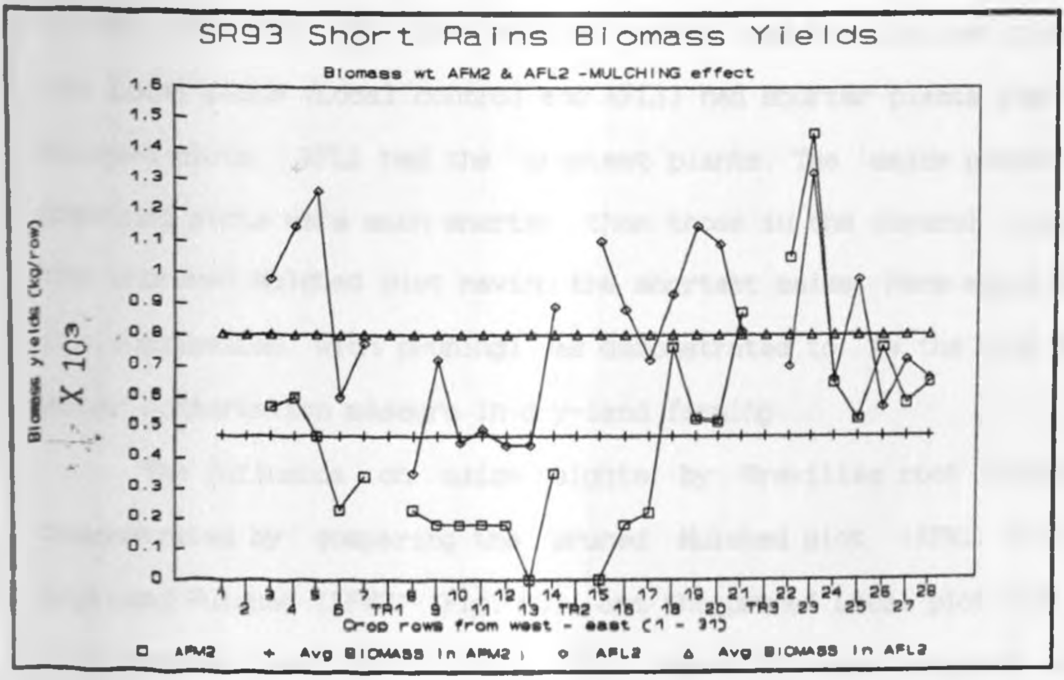

Fig. 83. Average maize biomass yields per row in unpruned Mulched (AFM2) and unpruned Local (AFL2) for SR93.

We present the following results for this season (i) maize heights and stover biomass yields in control (Local and Mulched) plots and in AF plots (ii) bean seed and bean biomass yields in each of these plots.

4.1.5 (c) Maize heights

Figs. 78 & 79 present maize heights in pruned Mulched and pruned Local (AFM1 & AFL1) unpruned Mulched and unpruned Local (AFM2 & AFL2) in AF plots and the same in NAF plots.

The influence on maize heights by Mulched at 3 t/ha crop residue was demonstrated by comparing heights for the pruned Mulched (AFM1) with the pruned Local (AFL1) plots (Fig. 78) and heights for the unpruned Mulched (AFL2) with the unpruned Local plots (AFL2) (Fig. 79). All were compared with the Mulched and Local control plots (Figs. 78 & 79).

The maize plants in both, Mulched plots in pruned AF (AFM1) and the Mulched control (Mulched control), had grown taller by 65 DAP (i.e. by DOY 354, Fig. 78). The Mulched control had the tallest plants. The two Local plots (Local control and AFL1) had shorter plants than the two Mulched plots. AFL1 had the shortest plants. The maize plants in the unpruned plots were much shorter than those in the control plots. with the unpruned Mulched plot having the shortest maize. Here again Mulching (in combination with pruning) was demonstrated to be the best feasible water conservation measure in dry-land farming.

The influence on maize heights by Grevillea root pruning was demonstrated by comparing the pruned Mulched plot (AFM1) with the unpruned Mulched (AFM2) (Fig. 80), and the pruned Local plot (AFL1) with the unpruned Local (AFL2) (Fig. 81). Again all were compared with the Mulched and Local control plots (Figs. 80 & 81).

In the Mulched plots, plants were appreciably higher in the pruned Mulched (AFM1) than in the unpruned Mulched (AFM2) plots (Fig. 80). Also plants in the pruned plots were generally higher than those in Local control plot (Fig. 80). In Fig. 81 we observe shorter plants in the AF plots than in NAF Local control plots. AFL1 had grown somewhat taller than AFL2, indicating higher competition for soil moisture between trees and the intercrop in AF during SR93, even in the pruned area, than within intercrops in the control plots.

4.1.5 (d) Maize biomass yields

Figs. 82 & 83 (for row details) and Table 28a present results of the intercomparison of maize biomass yields for SR93 as influenced by crop residue mulch application. The maize biomass yields were generally higher in the Mulched pruned (AFM1) than in the Local pruned (AFL1). The highest yields were obtained in the intercrop rows 19-27. The average maize biomass yields in the pruned plots (AFM1 & AFL1) were higher in the Mulched (AFM1) than in the Local (AFL1) plot by 85.5% (Table 27a, details per row in Fig. 82). In the unpruned plots (AFM2 & AFL2) application of mulch appeared to have depressed the biomass yields since the unpruned Local had 41.3 % more yields than unpruned Mulched (see Table 28a & Fig. 91). We observed such trends already earlier in this thesis and it could even be observed visually easily. The only reason we can forward is the damage done by larger scale turbulent eddies shown by smoke trails to particularly affect this area. About such thigmomorphogenetic responses in plant growth to mechanical stimuli little is known (see Chapter 5).

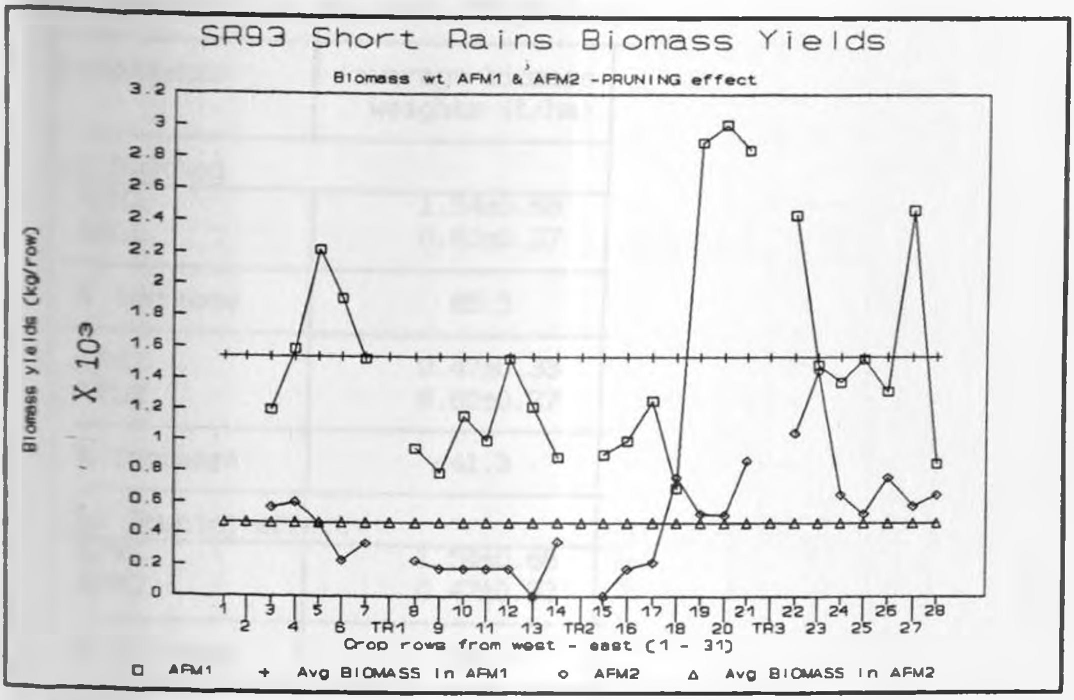

Fig. 84. Average maize biomass yields per row in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for SR93.

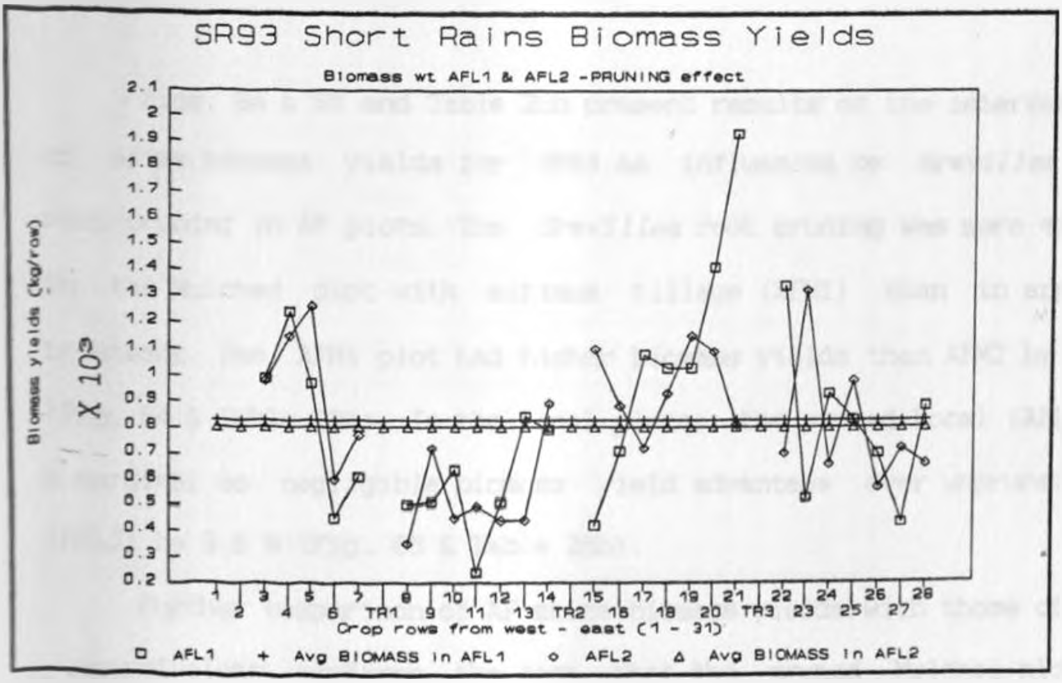

Fig. 85. Average maize biomass yields per row in pruned Local (AFL1) and unpruned Local (AFL2) for SR93.

Table 28. Effects of Mulched and pruning on maize biomass weights for SR93 (a) Mulched (b) pruning.

treatments	average biomass weights (t/ha)
a) Mulched	
AFM1 AFL1	1.54±0.68 0.83±0.37
% increase	85.5
AFM2 AFL2	0.47±0.33 0.80±0.27
% increase	-41.3
(b) Pruning effect	
AFM1 AFM2	1.54±0.68 0.47±0.33
% increase	227.7
AFL1 AFL2	0.83±0.37 0.80±0.27
% increase	3.8

Figs. 84 & 85 and Table 28b present results of the intercomparison of maize biomass yields for SR93 as influenced by *Grevillea robusta* root-pruning in AF plots. The *Grevillea* root pruning was more effective in the Mulched plot with minimum tillage (AFM1) than in any other treatment. The AFM1 plot had higher biomass yields than AFM2 by 227.7 % (Fig. 84 & Table 28b). In the Local plots, the pruned Local (AFL1) had a marginal so negligible biomass yield advantage over unpruned Local (AFL2) by 3.8 % (Fig. 85 & Table 28b).

Further comparison of AF maize biomass yields with those of the control plots confirms the fact that the pruned Mulched plot with minimum tillage (AFM1) gave the highest yields of 78 and 77% relative

Table 29. SR93 maize biomass yields (t/ha) in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average biomass yields (t/ha)	% of M	% of L
a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A-B	1.69±0.35	86	85
B-C	1.08±0.23	55	54
C-D	1.80±0.98	91	90
D-E	1.64±0.56	83	82
A-E	1.54±0.68	78	77
(b) Root pruned *Grev.* + Local + deep till (AFL1)			
A-B	0.85±0.28	43	43
B-C	0.58±0.19	29	29
C-D	1.09±0.45	55	55
D-E	0.81±0.28	41	41
A-E	0.83±0.37	42	42
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	0.44±0.14	22	22
B-C	0.19±0.10	10	10
C-D	0.44±0.30	22	22
D-E	0.81±0.31	41	41
A-E	0.47±0.33	24	24
(d) Unpruned *Grev.* + Local + deep tillage (AFL2)			
A-B	0.95±0.24	48	48
B-C	0.54±0.18	27	27
C-D	0.95±0.15	48	48
D-E	0.80±0.24	41	40
A-E	0.80±0.27	41	40
(e) Control plots			
Local (L) Mulch (M)	2.00±0.74 1.97±0.76	96 100	100 102

to Mulched (M) and Local (L) control plots respectively (Table 29). AFL1 with 42% relative to both M and L, was second to AFM1. Where there was no tree competition, in the control plots, mulch application gave only a very marginal increase compared to the Local by 2%. From Table 29 we see that the lowest yields in all the AF plots (AFM1, AFL1, AFM2 & AFL2) were obtained between tree rows TR1 and TR2 (i.e. interspace B-C). The highest yields were received in all AF plots, except AFM2, between tree rows TR2 and TR3 (i.e. interspace C-D see Table 29). This is for the unpruned plots in line with LR93.

Table 30. Effects of Mulched and pruning on beans seed & biomass weights (a) Mulched (b) pruning SR93

treatments	average biomass (t/ha)	Average grain (t/ha)
(a) Mulched		
AFM1	0.29±0.09	0.15±0.07
AFL1	0.34±0.11	0.12±0.05
% decrease for mulched	-14.7	25.0
AFM2	0.22±0.12	0.08±0.06
AFL2	0.24±0.08	0.10±0.05
% decrease for mulched	-8.3	-20.0
(b) Pruning effect		
AFM1	0.29±0.09	0.15±0.09
AFM2	0.22±0.12	0.08±0.06
% increase for pruned	31.8	87.5
AFL1	0.34±0.11	0.12±0.05
AFL2	0.24±0.08	0.10±0.05
% increase for pruned	41.7	20.0

Table 31. SR93 Beans biomass yields (t/ha) in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average biomass yields (t/ha)	% of M	% of L
a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A-B	0.38±0.05	56	41
B-C	0.26±0.08	38	28
C-D	0.26±0.08	38	28
D-E	0.28±0.07	41	30
A-E	0.29±0.09	43	31
(b) Root pruned *Grev.* + Local + deep till (AFL1)			
A-B	0.42±0.13	62	45
B-C	0.33±0.13	49	35
C-D	0.30±0.06	44	32
D-E	0.30±0.05	44	32
A-E	0.34±0.11	50	37
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	0.19±0.12	28	20
B-C	0.11±0.07	16	12
C-D	0.28±0.08	41	30
D-E	0.30±0.10	44	32
A-E	0.22±0.12	32	24
(d) Unpruned *Grev.* + Local + deep till (AFL2)			
A-B	0.32±0.11	47	34
B-C	0.21±0.03	31	23
C-D	0.19±0.02	28	20
D-E	0.23±0.07	34	25
A-E	0.24±0.08	35	26
(e) Control plots			
Local (L)	0.93±0.33	137	100
Mulch (M)	0.68±0.46	100	73

Table 32. SR93 Beans seed yields (t/ha) in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average beans seed yields (t/ha)	% of M	% of L
(a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A-B	0.15±0.08	48	58
B-C	0.14±0.05	45	54
C-D	0.18±0.05	58	69
D-E	0.10±0.06	32	38
A-E	0.15±0.07	48	58
(b) Root pruned *Grev.* + Local + deep till (AFL1)			
A-B	0.12±0.03	39	46
B-C	0.15±0.06	48	58
C-D	0.14±0.03	45	54
D-E	0.08±0.03	26	30
A-E	0.12±0.05	39	36
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	0.03±0.04	10	12
B-C	0.04±0.05	13	15
C-D	0.14±0.03	45	54
D-E	0.09±0.05	29	35
A-E	0.08±0.06	26	31
(d) Unpruned *Grevilleas* + Local + deep tillage (AFL2			
A-B	0.11±0.05	35	42
B-C	0.11±0.05	35	42
C-D	0.11±0.03	35	42
D-E	0.06±0.05	19	23
A-E	0.10±0.05	32	38
(e) Control plots			
Local (L)	0.26±0.13	84	100
Mulch (M)	0.31±0.06	100	119

4.1.5 (e) Beans, biomass and seed yields

Tables 30a, b present the effects of mulching and pruning on the beans biomass and seed yields for the SR93. We can see in Table 30a that

AFM1 had less beans biomass yields than AFL1 by 14.7% but more bean seed yields by 25%.

In unpruned plots mulch application had negative effect on both beans biomass and seed yields, as the unpruned Local plot (AFL2) had 20 and 8.3% respectively more seed and biomass yields than the Mulched unpruned plot (AFM2) (Table 30a). The pruned plot (AFM1) produced more biomass and seed yields than pruned Local (AFL1) by 41.7 and 20.0 % respectively.

Table 30b shows that a combination of root-pruning with mulching (AFM1) was a more effective water conservation measure than a combination of not pruning with mulching (AFM2, Table 30b). In AF, in the Mulched (plus minimum tillage) plots the pruned Mulched plot (AFM1) produced more beans biomass and seed yields than the unpruned Mulched (AFM2) by 31.8 and 87.5% respectively (Table 30b). In the Local (plus deep tillage) plots the pruned Locald plot (AFL1) produced more beans biomass and seed yields than the unpruned Local (AFL2) by 41.7 and 20.0% respectively.

We notice from Tables 31 and 32 that in the upper part of AF there were higher biomass yields between tree rows A-B(TR1) than between B(TR1)-C(TR2) in all upper halves of the plots (see Fig. 9), but this did not apply to seed yields. Comparing the bean biomass and bean seed yields from AF plots with the controls (Tables 31 and 32), while there were more bean biomass and seed yields from the Local control than from the Mulched controls, on the average the control plots produced appreciably more both seed and biomass yields than the AF plots, again due to severe competition for soil moisture between the trees and the intercrop as compared to absence of the same in NAF.

4.1.6 Long Rains season 1994

4.1.6 (a) Rainfall and evaporation climate during growing season

The intercrop of maize/beans for LR94 was planted on the 13th April, 1994, after a cumulative rainfall total of 33.4 mm spread over 12 days before the planting, day against total pan evaporation of 70.9 mm. The rainfall totals in two months out of four, that is April and May, 1994, in this season were above their long term means (see Fig. 15). Pan evaporation for April was 15.7 mm above the long term mean. April, with rainfall of 68.3 mm above its long term mean, had the highest positive value followed by May with 27.1 mm. March had the highest negative value of 31.1 mm below the long term mean. March had the highest positive evaporation deviation of 16.4 mm from its long term mean for that month, while June had the highest negative deviation of 23.3 mm (see Fig. 15).

On the planting day, there was no rain but a total of 60.2 mm against evaporation of 73.7 mm was recorded in the three days following the planting day. This season was relatively wet but too short for a complete maize growth cycle. The strong winds started too early, in late May 1994, and dried the soil and lodged most plants, observed visually, resulting in no grain harvest from maize.

We present the following results: maize heights and maize biomass yields, and bean seed and remaining biomass yields. There were no grain yields from maize.

4.1.6 (b) Maize and beans phenology

In the control plots, 16% of the maize plants in Local plots and 20% in Mulched plots, as well as 25% in AF plots had emerged by 8 DAP. By 10 DAP 80% in Local, 85% in Mulched and 90% in AF had emerged. Emergence attained 100% level by 22 DAP. Differences in maize biomass

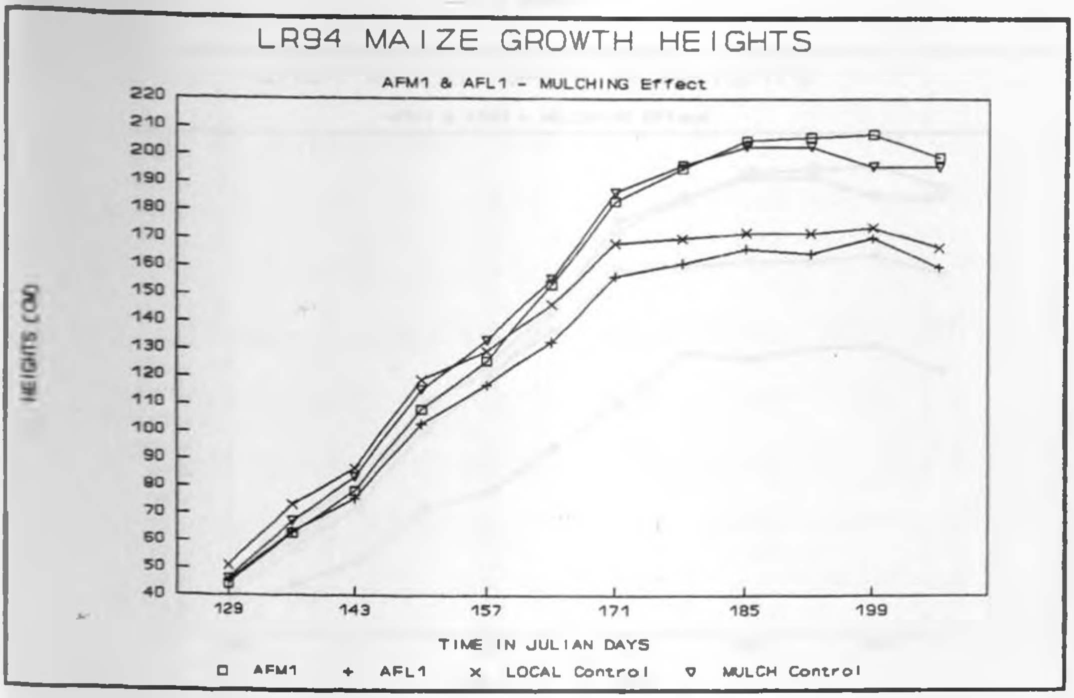

Fig. 86. Average maize heights in pruned Mulched (AFM1) and pruned Local (AFL1) for LR94, compared with the control plots.

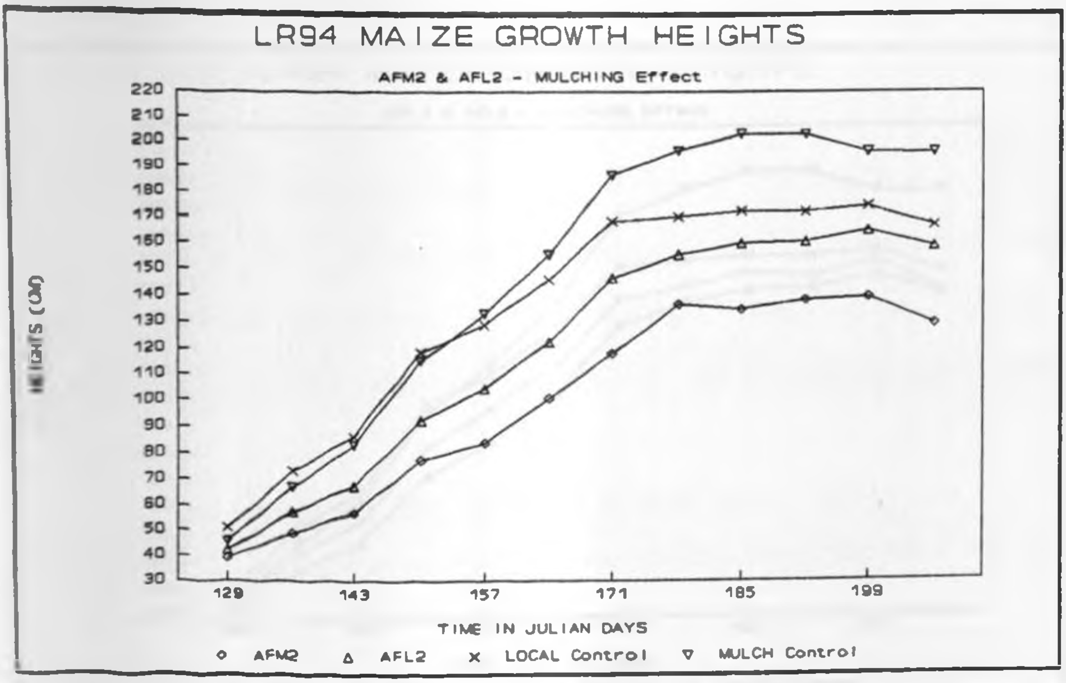

Fig. 87. Average maize heights in unpruned Mulched (AFM2) and unpruned Local (AFL2) for LR94, compared with the control plots.

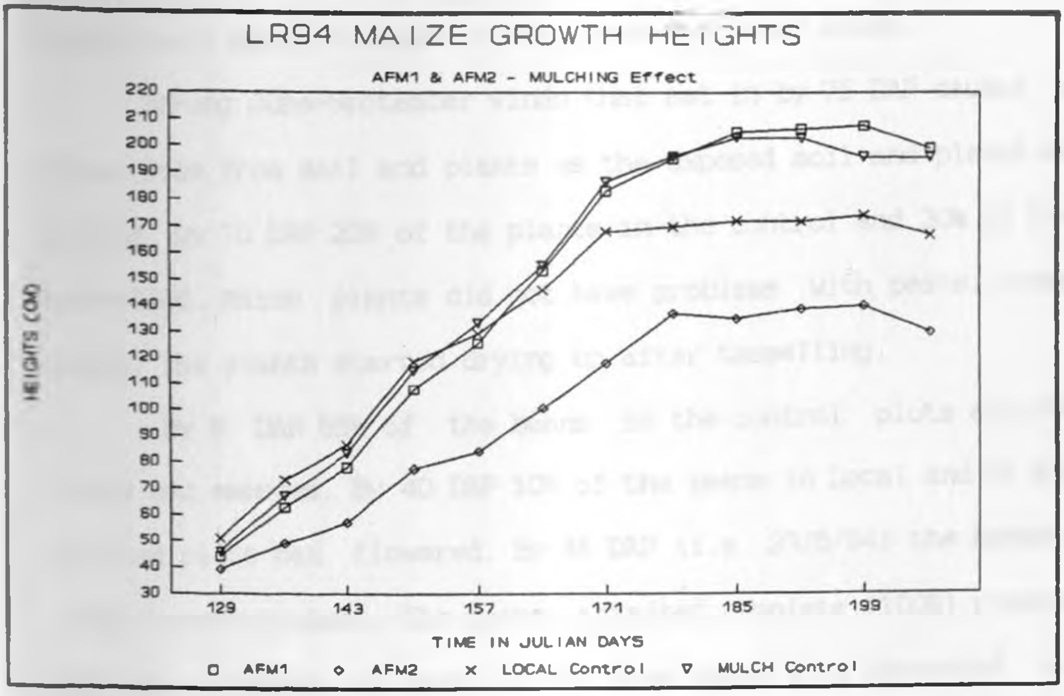

Fig. 88. Average maize heights in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for LR94, compared with the control plots.

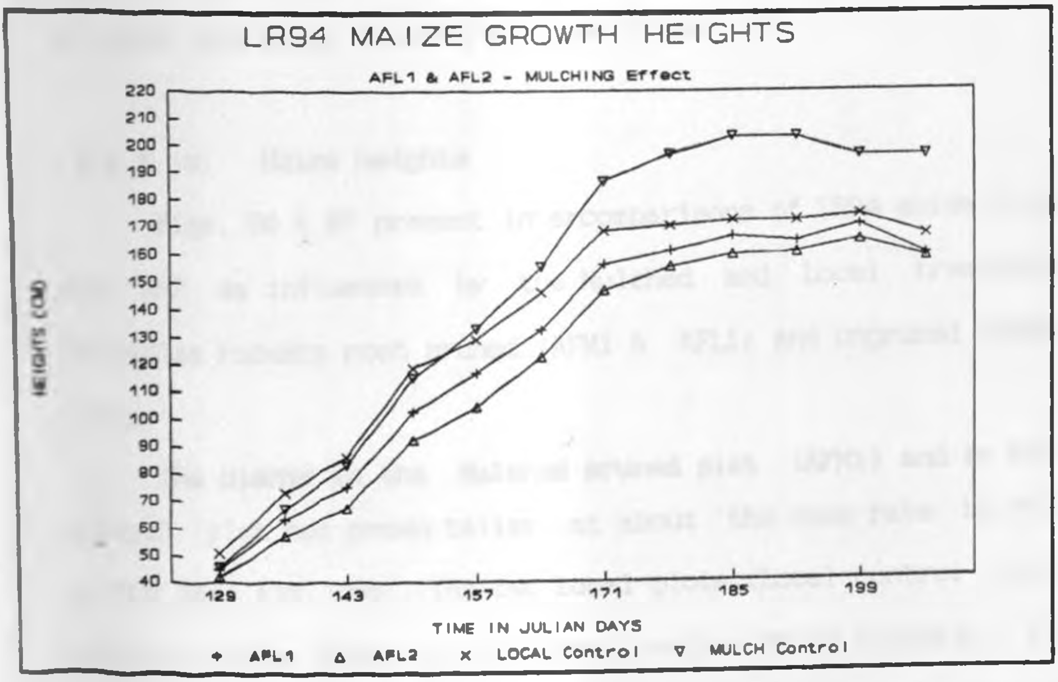

Fig.89. Average maize heights in pruned Local (AFL1) and unpruned Local (AFL2) for LR94, compared with the control plots.

yields may have resulted partly from differences in emergence and partly from post-emergence response of plants to environmental physical quantities, which included strong June–September winds.

Strong June-September winds that set in by 75 DAP caused a lot of water loss from soil and plants as the exposed soil and plants were drying. By 70 DAP 20% of the plants in the control and 30% in the AF had tasselled. Maize plants did not have problems with pests, diseases and weeds. The plants started drying up after tasselling.

By 8 DAP 85% of the beans in the control plots and 90% in AF plots had emerged. By 40 DAP 10% of the beans in Local and AF and 15% in Mulched plots had flowered. By 46 DAP (i.e. 23/5/94) the beans attained 100% flowering phase. The beans attained complete (100%) ripeness by 81 DAP. The biomass and seed yields from beans were harvested on 104 DAP (i.e. 26/7/94). We here therefore present the following results for this season (i) maize heights in AF and in control (Local and Mulched) plots and (ii) maize and remaining beans biomass as well as bean seed yields of maize and beans in each of these plots.

4.1.6 (c) Maize heights

Figs. 86 & 87 present intercomparisons of LR94 maize heights in AF and NAF as influenced by the Mulched and Local treatments in the Grevillea robusta root pruned (AFM1 & AFL1) and unpruned (AFM2 & AFL2) plots.

The plants in the Mulched pruned plot (AFM1) and in the Mulched control plot had grown taller, at about the same rate, by 54 DAP (i.e. by DOY 164, Fig. 86). The two Local plots (Local control and AFL1) had shorter plants, those in the Local control being slightly taller than those in the AFL1. The plants in the unpruned plots were shorter than

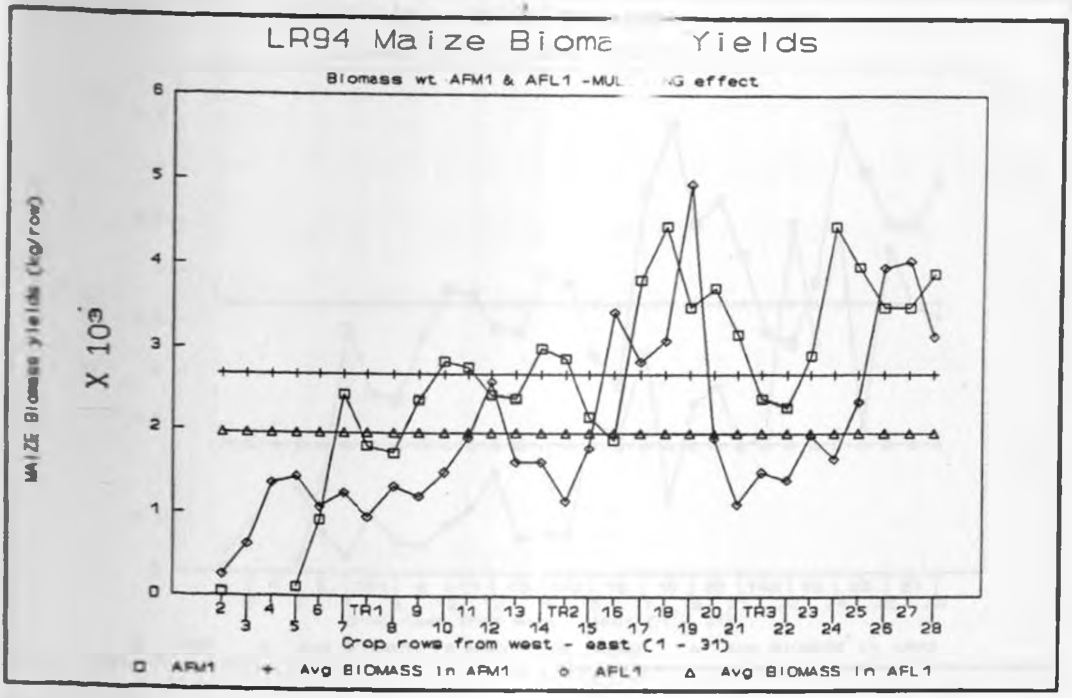

Fig. 90. Average maize biomass yields per row in pruned Mulched (AFM1) and pruned Local (AFL1) for LR94.

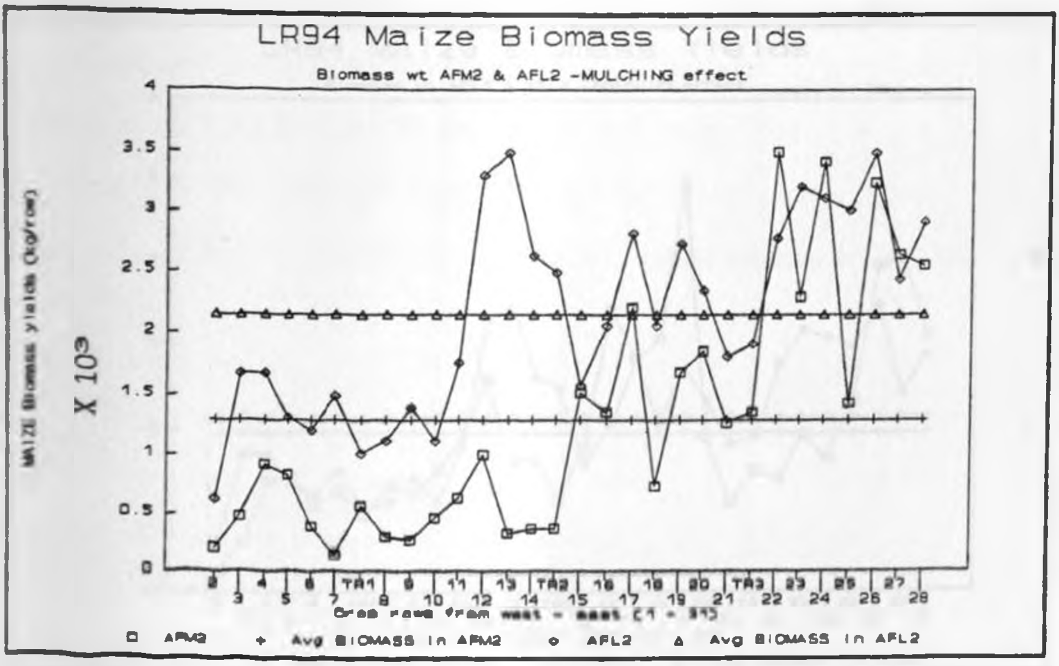

Fig. 91. Average maize biomass yields per row in unpruned Mulched (AFM2) and unpruned Local (AFL2) for LR94.

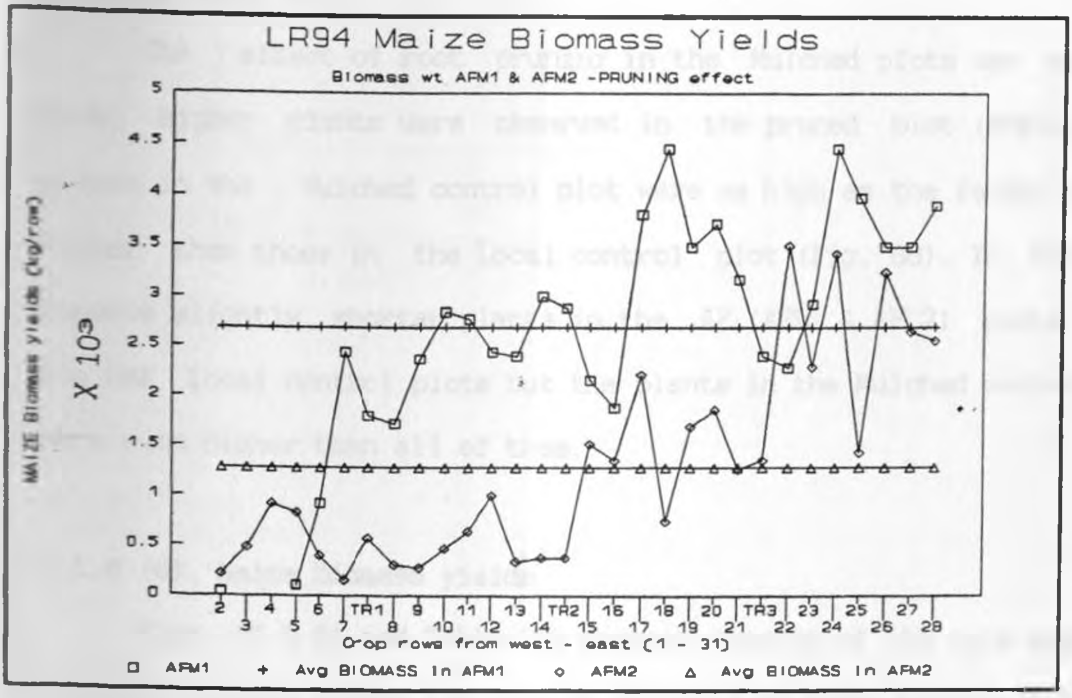

Fig. 92. Average maize biomass yields per row in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for LR94.

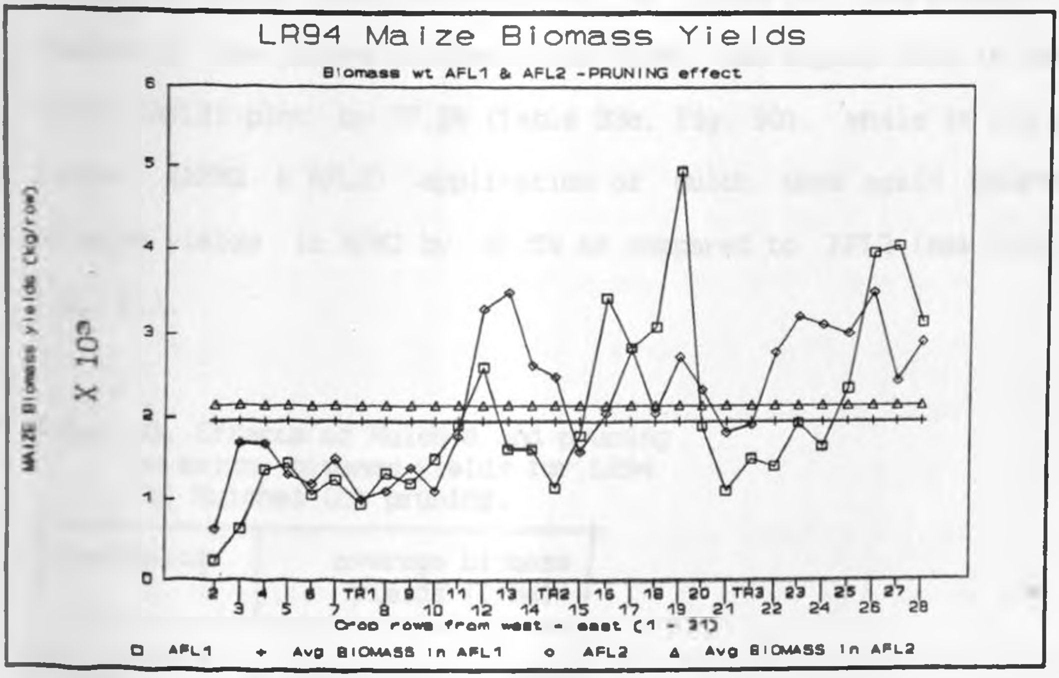

Fig. 93. Average maize biomass yields per row in pruned Local (AFL1) and unpruned Local (AFL2) for LR94.

those in the controls, with the unpruned Mulched plot having the shortest (Fig. 87).

The effect of root pruning in the Mulched plots was such that much higher plants were observed in the pruned plot (AFM1), while plants in the Mulched control plot were as high as the former and much higher than those in the Local control plot (Fig. 88). In Fig. 89 we observe slightly shorter plants in the AF (AFL1 & AFL2) plots than in the NAF Local control plots but the plants in the Mulched control plots were much higher than all of them.

4.1.6 (d) **Maize biomass yields**

Figs. 90 & 91 and Table 33a present results of the intercomparison of maize biomass yields for LR94 as affected by crop residue mulch from the previous season's intercrop. Generally there were higher yields in the lower parts of plots with the exception of rows 20-25 in AFL1 and 11-TR2 in AFL2. This is confirmed by Table 34. The average biomass yields in the pruned Mulched plots (AFM1) was higher than in the pruned Local (AFL1) plot by 37.2% (Table 33a. Fig. 90), while in the unpruned plots (AFM2 & AFL2) application of mulch once again depressed the biomass yields in AFM2 by 40.5% as compared to AFL2 (see Table 33a & Fig. 91).

Table 33. Effects of Mulched and pruning on maize biomass yields for LR94 (a) Mulched (b) pruning.

treatments	average biomass yields (t/ha)
(a) Mulched	
AFM1	2.69±1.10
AFL1	1.96±1.07

% increase	37.2
AFM2 AFL2	1.28±1.00 2.15±0.80
% decrease	-40.5

(b) Pruning effect

AFM1 AFM2	2.69±1.10 1.28±1.00
% increase	110.2
AFL1 AFL2	1.96±1.07 2.15±0.80
% decrease	-8.8

Figs. 92 & 93 and Table 33b present results of the intercomparison of maize biomass yields for LR94 as influenced by *Grevillea robusta* root-pruning in AF plots. Again pruning was most effective in the mulch with minimum tillage plot (AFM1). AFM1 had higher biomass yields than the unpruned mulch (AFM2) of 110.2% (Fig. 92 & Table 33b). However, between Local plots (AFL1 & AFL2), AFL2 had slightly higher biomass yields than AFL1, by 8.8% (Fig. 93 & Table 33b).

Further comparison of AF maize biomass yields with those of the control plots confirms the fact that AFM1 gave the highest yields with average of 2.69±1.10 t/ha and AFM2 was the next highest with 2.15±0.80 t/ha (Table 34). In the control plots the mulch gave higher yields relative to the Local by more than two and a quarter times. From Table 34 we see that the lowest yields in the four AF plots (AFM1, AFL1, AFM2 & AFL2) were received in the first maize rows (i.e. interspace A-C) which may have been due to the channelling effect by the deliberate gap and other protection differences (see section 4.3) from the strong southerly winds into the AF plot. Maize rows 15-28 lie in the lower half of the AF where strong protective effects of the southern hedge and western hedge overlap to give maximum shelter to crops in AF.

4.1.6 (e) Beans biomass and seed yields

Table 35a & 35b present the effects of Mulching and pruning on the beans biomass and seed yields for the LR94. We can see in Table 35a that mulching had a slightly suppressive effect on bean biomass yields, as Mulched plots (AFM1, AFM2) had less biomass yields than Local plots (AFL1, AFL2) by 5.6 and 42.4% respectively. The mulch application had a slightly positive influence on seed yields in pruned plots by 10.0% and a somewhat lower negative effect in unpruned plots of 30%. This again illustrates our earlier assertion that seed yields are inversely related to biomass yields. An increase in biomass tends to result in a decrease in seed yields. This was also true for maize biomass and maize grain yields as our result herein have shown.

Table 35b shows that a combination of root-pruning and mulch application on minimum tilled land in an agroforestry system as in AFM1 was more effective as a control measure than other combinations considered here (particularly in AFM2 and appreciably less in AFL1 & AFL2).

In the mulch (plus minimum tillage) plot, AFM1 produced more biomass and seed yields than AFM2 by 41.7 and 57.1% respectively (Table 35b). AFL1 produced less beans biomass than AFL2 by 14.3 but as much seed yields as AFL2.

Comparing the biomass and seed yields from AF plots (Tables 36/37) we observe that the unpruned Local (AFL2) plot had the highest yields. We notice from Tables 36 and 37 that the lower halves (between C-D and D-E) of all AF plots (see Fig. 9), except AFM1, obtained higher beans seed and biomass yields than the upper halves (between A-B and B-C). The interspace B-C in the upper half of all the plots obtained the lowest bean seed and biomass yields.

Table 34. LR94 maize biomass in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average biomass yields (t/ha)	% of M	% of L
(a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A-B	0.88±0.97	14.0	31.3
B-C	2.51±0.39	40.0	89.3
C-D	3.24±0.85	51.7	115.3
D-E	3.50±0.67	55.8	124.6
A-E	2.69±1.10	42.9	95.7
(b) Root pruned *Grev.* + Local + deep tillage (AFL1)			
A-B	1.00±0.43	16.0	35.6
B-C	1.68±0.43	26.8	59.8
C-D	2.73±1.18	43.5	97.2
D-E	2.64±1.00	42.1	94.0
A-E	1.96±1.07	31.3	69.8
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	0.50±0.29	8.0	17.8
B-C	0.49±0.24	7.8	17.4
C-D	1.52±0.44	24.2	54.1
D-E	2.72±0.68	43.4	96.8
A-E	1.28±1.00	24	24
(d) Unpruned *Grev.* + Local + deep tillage (AFL2)			
A-B	1.33±0.36	21.2	47.3
B-C	2.11±0.94	33.7	75.1
C-D	2.20±0.42	35.1	78.3
D-E	2.99±0.31	47.7	106.4
A-E	2.15±0.80	34.3	76.5
(e) Control plots			
Local (L)	2.81±1.10	44.8	100
Mulch (M)	6.27±1.77	100	223.1

Table 35. Effects of Mulched and pruning on beans seed & biomass yields (a) Mulched (b) pruning for LR94

treatments	average seed (t/ha)	Average biomass (t/ha
a) Mulched		
AFM1 AFL1	0.22±0.11 0.20±0.09	0.17±0.07 0.19±0.10
% increase /decrease for mulched	10.0	-5.6
AFM2 AFL2	0.14±0.08 0.20±0.09	0.12±0.08 0.21±0.08
% decrease for mulched	-30.0	-42.9
(b) Pruning effect		
AFM1 AFM2	0.22±0.11 0.14±0.08	0.17±0.07 0.12±0.08
% increase for pruned	57.1	41.7
AFL1 AFL2	0.20±0.09 0.20±0.09	0.18±0.10 0.21±0.08
% increase /decrease for mulched	0.0	-14.3

There were more beans biomass and seed yields from the Mulched control than from the Local control. The control plots produced (in most cases appreciably) more both seed and biomass yields than the AF plots.

4.1.7 Short Rains season 1994

4.1.7 (a) Rainfall and evaporation climate during growing season

The intercrop of maize/beans for SR94 was planted on the 10th October 1994. after a cumulative rainfall total of 19.8 mm against total pan evaporation of 16.3 mm was received in 3 days before the planting day.

Table 36. LR94 Beans biomass yields in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average biomass yields (t/ha)	% of M	% of L
(a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A-B	0.22±0.08	57.9	66.7
B-C	0.12±0.03	31.6	36.4
C-D	0.17±0.06	44.7	51.5
D-E	0.17±0.05	44.7	51.5
A-E	0.17±0.07	44.7	51.5
(b) Root pruned *Grev.* + Local + deep tillage (AFL1)			
A-B	0.15±0.07	39.5	45.5
B-C	0.08±0.03	21.1	24.2
C-D	0.19±0.10	50.0	57.6
D-E	0.30±0.05	78.9	90.9
A-E	0.18±0.10	47.4	54.5
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	0.08±0.06	21.1	24.2
B-C	0.07±0.03	18.4	21.2
C-D	0.11±0.08	28.9	33.3
D-E	0.22±0.05	57.9	66.7
A-E	0.12±0.08	31.6	36.4
(d) Unpruned *Gre.* + Local + deep tillage (AFL2)			
A-B	0.24±0.07	63.7	72.7
B-C	0.12±0.06	31.6	36.4
C-D	0.19±0.07	50.0	57.6
D-E	0.28±0.04	73.7	84.8
A-E	0.21±0.08	55.3	63.6
(e) Control plots			
Local (L)	0.33±0.12	86.8	100
Mulch (M)	0.38±0.13	100	115.2

Table 37. LR94 Beans seed yields in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average beans seed yields (t/ha)	% M	% L
(a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A-B	0.29±0.15	67.4	87.9
B-C	0.15±0.03	34.9	45.5
C-D	0.20±0.08	46.5	60.6
D-E	0.24±0.09	55.8	72.7
A-E	0.22±0.11	51.2	66.7
(b) Root pruned *Grev.* + Local + deep tillage (AFL1)			
A-B	0.21±0.10	48.8	63.6
B-C	0.13±0.05	30.2	39.4
C-D	0.20±0.08	46.5	60.6
D-E	0.28±0.06	65.1	84.8
A-E	0.20±0.09	46.5	60.6
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	0.09±0.05	20.9	27.3
B-C	0.05±0.02	11.6	15.2
C-D	0.16±0.06	37.2	48.5
D-E	0.21±0.03	48.8	63.6
A-E	0.14±0.08	32.6	42.4
(d) Unpruned *Grev.* + Local + deep tillage (AFL2)			
A-B	0.22±0.04	51.2	66.7
B-C	0.11±0.04	24.6	33.3
C-D	0.15±0.06	34.9	45.5
D-E	0.30±0.04	69.8	90.9
A-E	0.20±0.09	46.5	60.6
(e) Control plots			
Local (L)	0.33±0.11	76.7	100
Mulch (M)	0.43±0.18	100	130.3

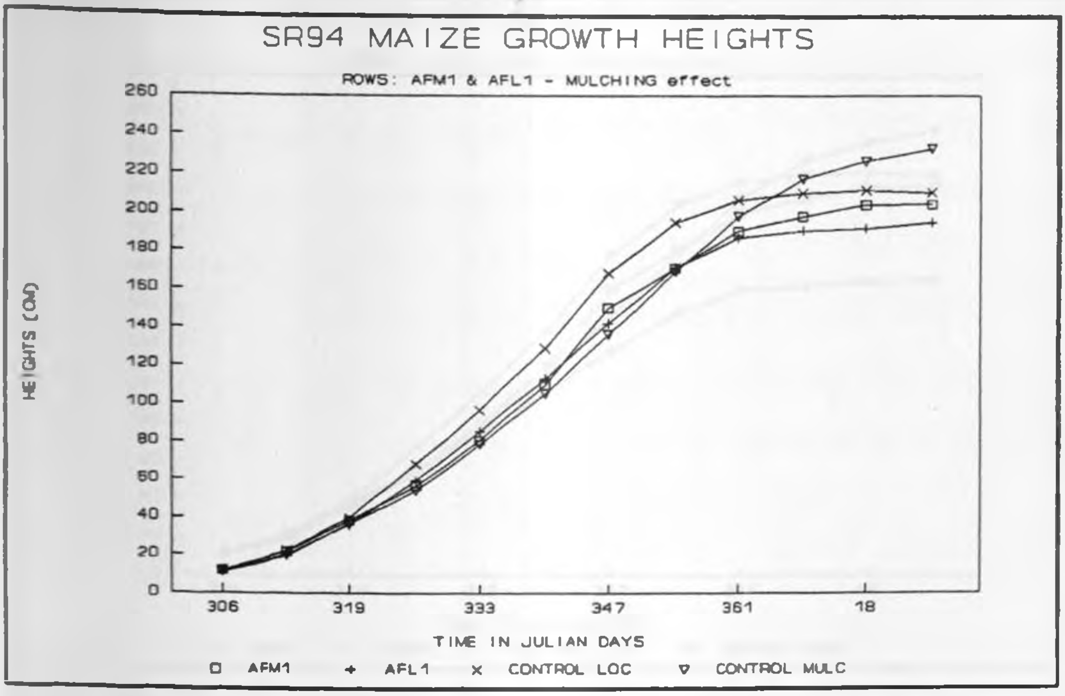

Fig. 94. Average maize heights in pruned Mulched (AFM1) and pruned Local (AFL1) for SR94, compared with the control plots.

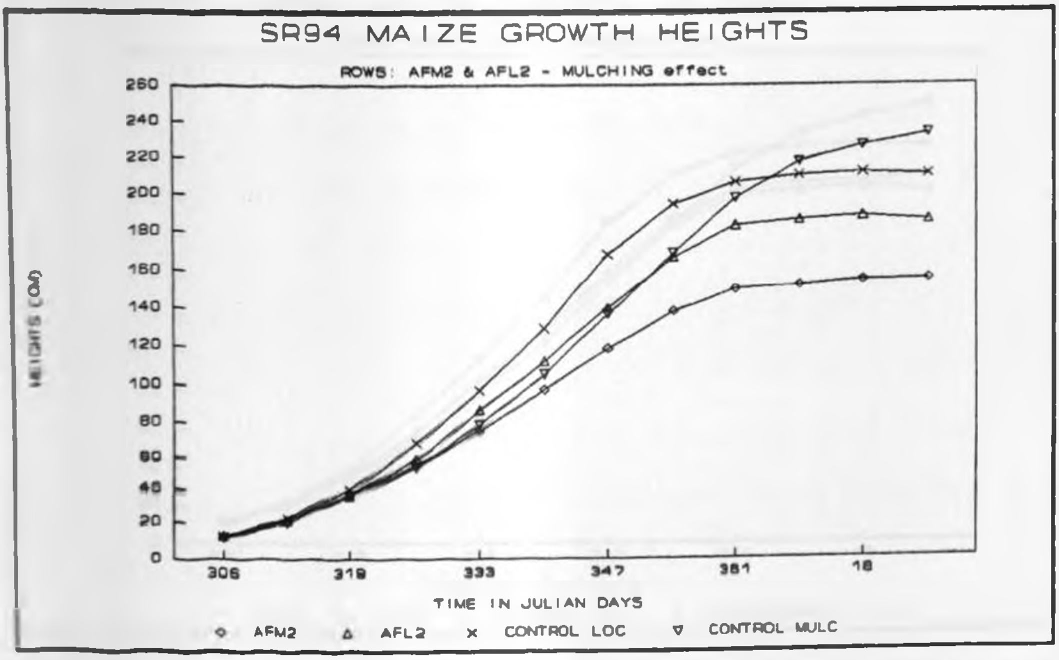

Fig. 95. Average maize heights in unpruned Mulched (AFM2) and unpruned Local (AFL2) for SR94, compared with the control plots.

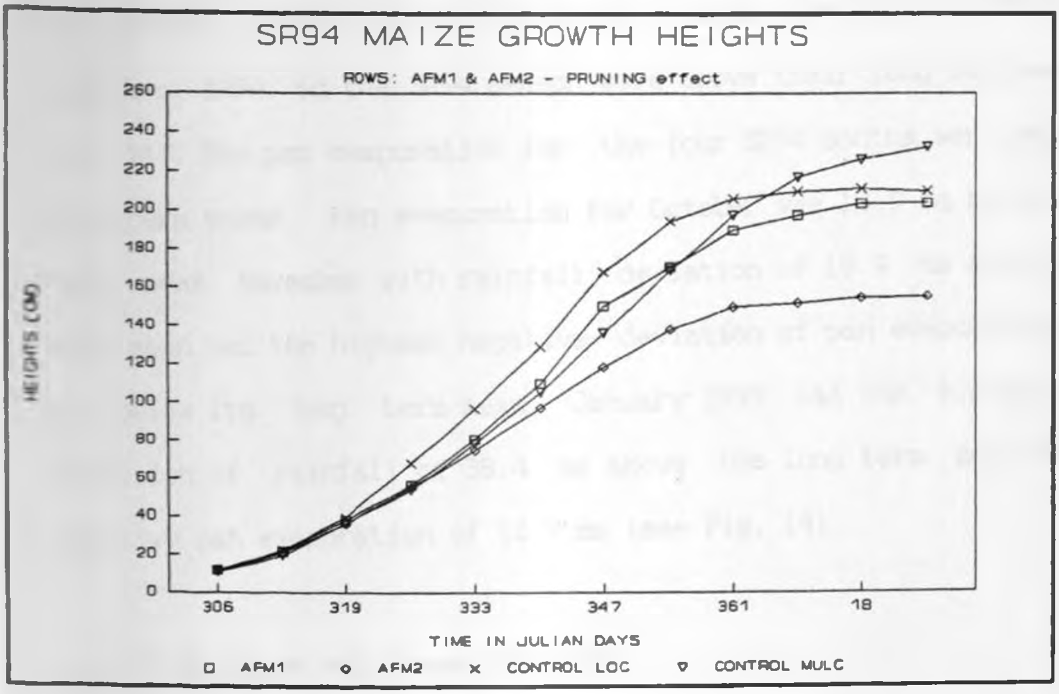

Fig. 96. Average maize heights in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for SR94, compared with the control plots.

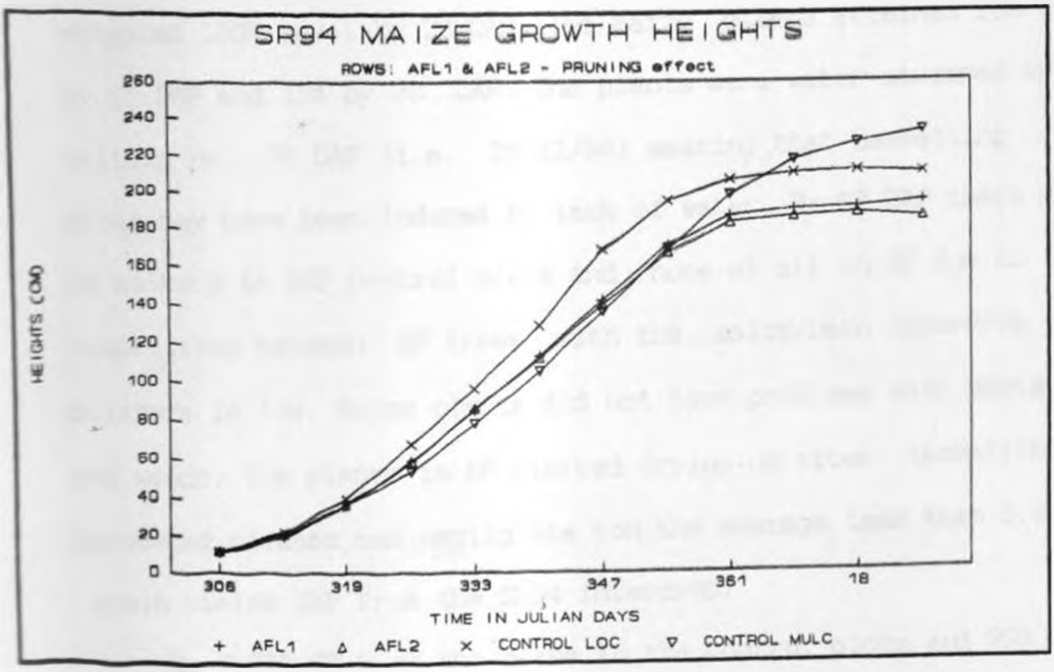

Fig. 97. Average maize heights in pruned Local (AFL1) and unpruned Local (AFL2) for SR94, compared with the control plots.

The rainfall totals in two months out of four, that is October and November, 1994, in the SR94 season were above their long term means (see Fig. 14). The pan evaporation for the four SR94 months were below their long term means. Pan evaporation for October was 18.9 mm below its long term mean. November with rainfall deviation of 19.9 mm above its long term mean had the highest negative deviation of pan evaporation of 20.1 mm below its long term mean. January 1995 had the highest negative deviation of rainfall of 38.4 mm above the long term mean against a positive pan evaporation of 16.7 mm (see Fig. 14).

4.1.7 (b) Maize and beans phenology

In the control plots, 20% of the maize plants in Local and 25% in Mulched, as well as 25 % in agroforestry had emerged by 7 DAP. By 10 DAP 85% in Local, 90% in Mulched and 95% in AF had emerged. Emergence attained 100% level by 22 DAP. The maize plants attained 10% tasselling by 65 DAP and 15% by 70 DAP. The plants were water stressed and started wilting by 76 DAP (i.e. 25/12/94) meaning that tasselling in the NAF plots may have been induced by lack of water. By 97 DAP there was a mere 2% silking in NAF control plots and none at all in AF due to increased competition between AF trees with the maize/bean intercrop when soil moisture is low. Maize plants did not have problems with pests, diseases and weeds. The plants in AF started drying up after tasselling. We only harvested biomass and negligible (on the average less than 0.01 t/ha) grain yields NAF from the SR94 intercrop.

By 9 DAP 95 % of the beans in the control plots and 90% in AF had emerged. By 11 DAP 100% in all plots had emerged. By 48 DAP 20 % of the beans in control and 30% in AF plots had flowered. The flowering phase ended by 76 DAP (i.e. 25/12/94) as the plants started wilting.

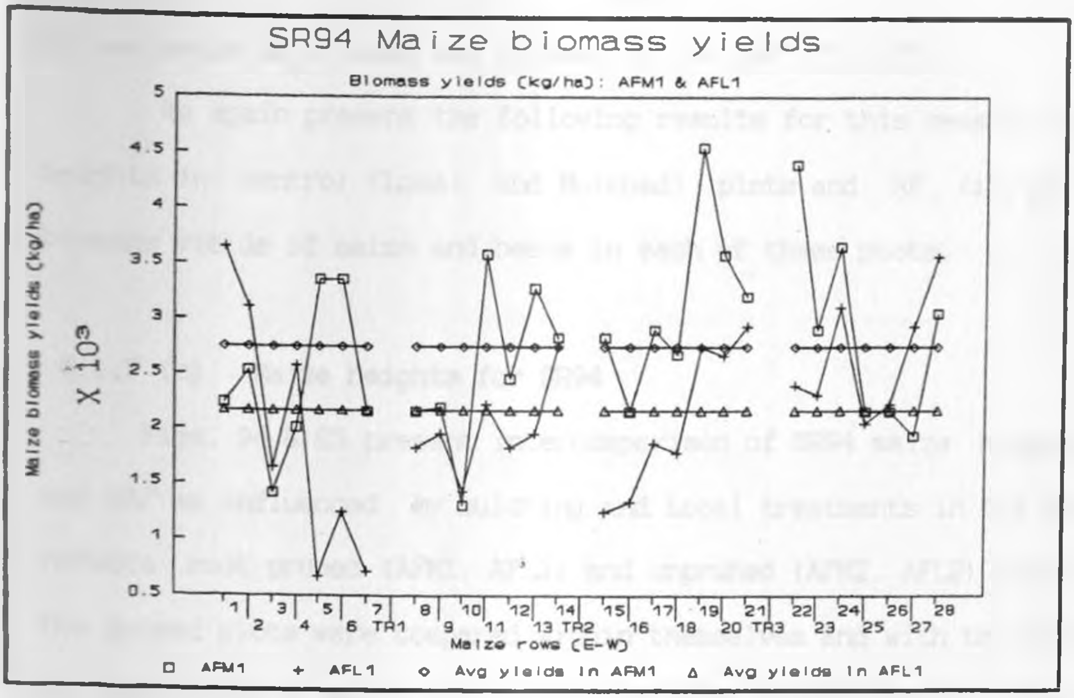

Fig. 98. Average maize biomass yields per row in pruned Mulched (AFM1) and pruned Local (AFL1) for SR94.

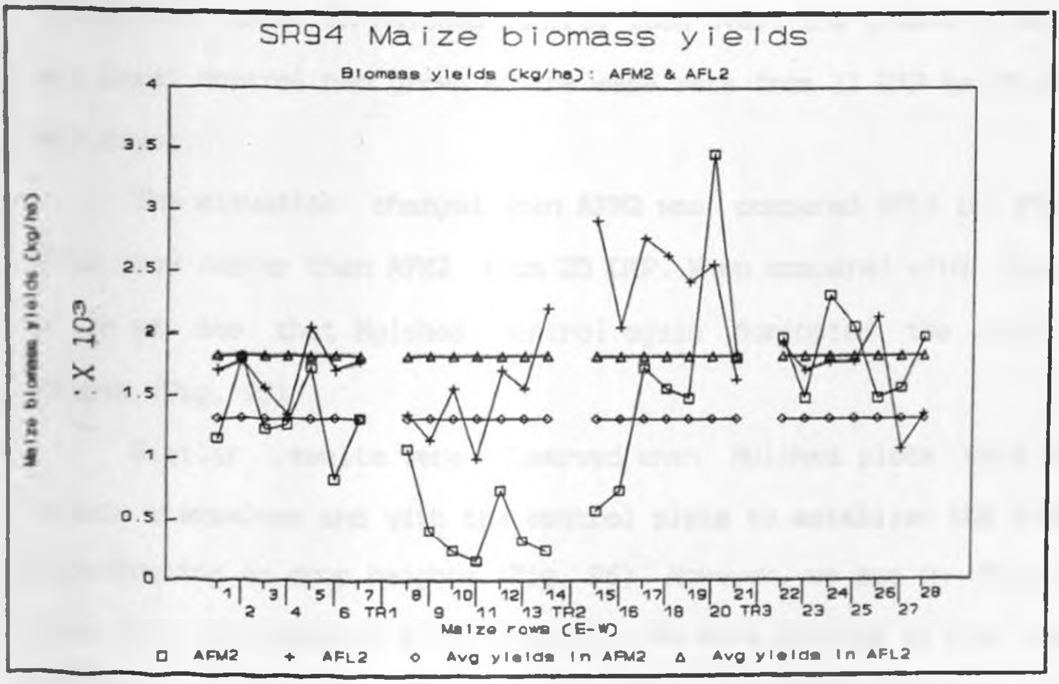

Fig. 99. Average maize biomass yields per row in unpruned Mulched (AFM2) and unpruned Local (AFL2) for SR94.

We harvested both seeds and biomass on 109 DAP (27/1/95).

We again present the following results for this season: (i) maize heights in control (Local and Mulched) plots and AF. (ii) grain and biomass yields of maize and beans in each of these plots.

4.1.7 (c) Maize heights for SR94

Figs. 94 & 95 present intercomparison of SR94 maize heights in AF and NAF as influenced by mulching and Local treatments in the *Grevillea robusta* root pruned (AFM1. AFL1) and unpruned (AFM2. AFL2) plots. The pruned plots were compared within themselves and with the control to see the effect of mulch application on maize heights growth rates (Fig. 94). We can see in Fig. 94 that plants in Local control dominated the growth right from 25 DAP (i.e. 319 days) to 97 DAP (i.e. 351 days). thereafter those in Mulched control took over. The plants in AFM1. AFL1 and Local control had grown at the same rate from 11 DAP to 55 DAP (i.e. 349 days).

The situation changed when AFM2 was compared AFL2 in Fig. 95 as AFL2 grew faster than AFM2 from 25 DAP. When compared with the control plots we see that Mulched control again dominated the later growth stages (Fig. 95).

Similar results were observed when Mulched plots were compared within themselves and with the control plots to establish the effect of root-pruning on crop heights (Fig. 96). However, we see in Fig. 97 that when AFL1 was compared with AFL2 the two were growing at the same rate all the way from day 351 (i.e. 97 DAP), thereafter because of having been root-pruned AFL1 overtook AFL2 (Fig. 97).

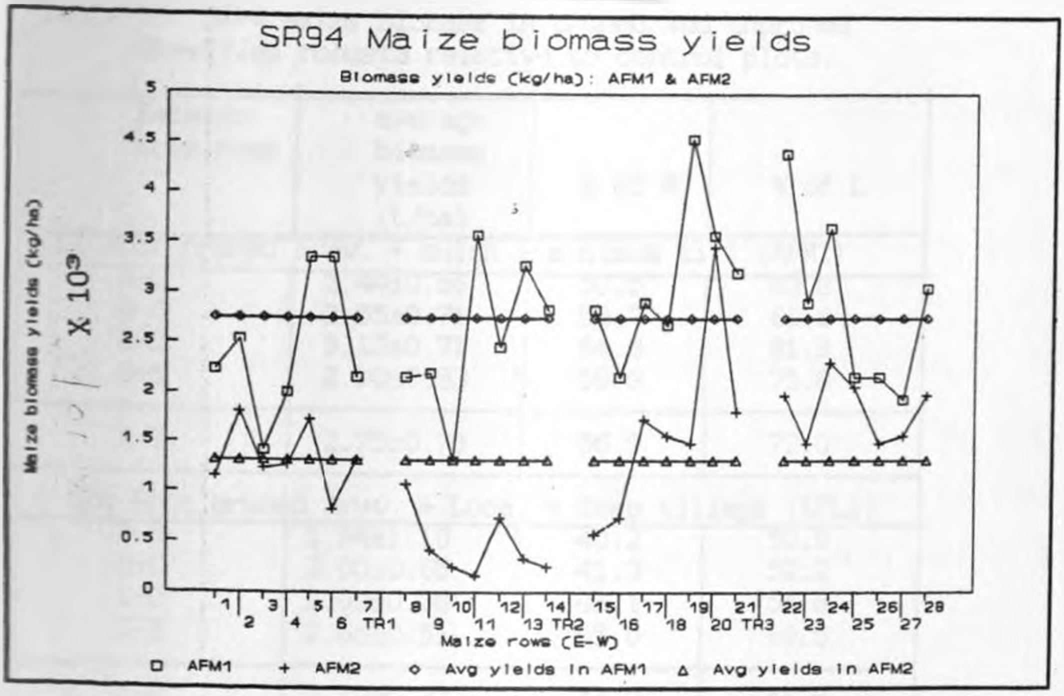

Fig. 100. Average maize biomass yields per row in pruned Mulched (AFM1) and unpruned Mulched (AFM2) for SR94.

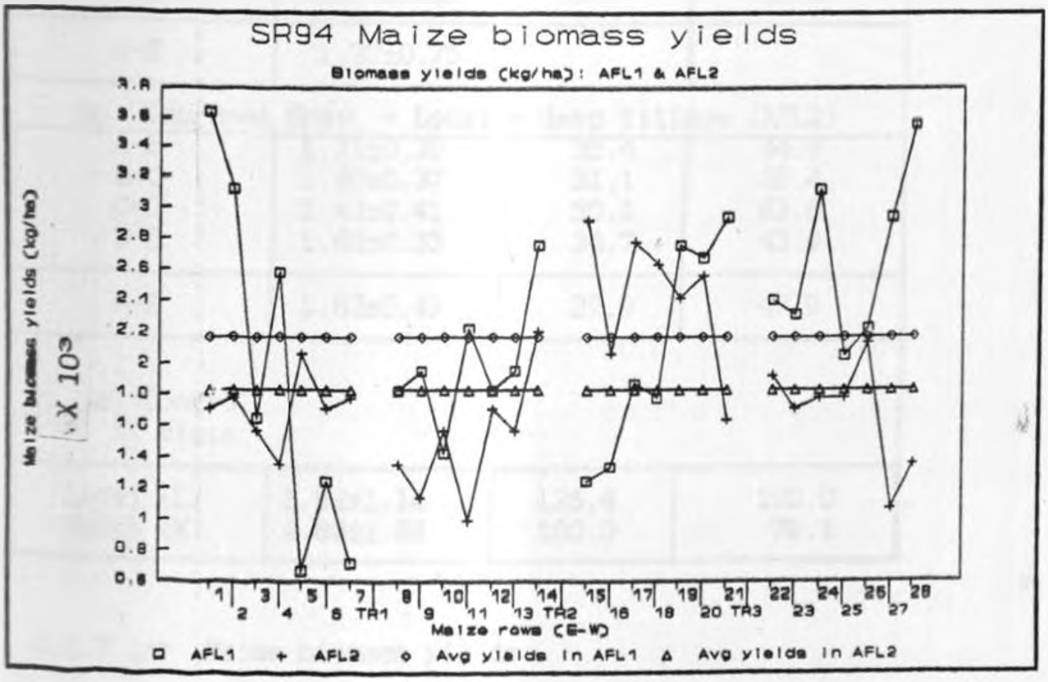

Fig. 101. Average maize biomass yields per row in pruned Local (AFL1) and unpruned Local (AFL2) for SR94.

Table 38. SR94 maize biomass in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average biomass yields (t/ha)	% of M	% of L
(a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A-B	2.44±0.66	50.5	63.8
B-C	2.55±0.71	52.7	66.6
C-D	3.13±0.71	64.8	81.9
D-E	2.90±0.83	59.9	75.8
A-E	2.75±0.78	56.9	72.0
(b) Root pruned *Grev.* + Local + deep tillage (AFL1)			
A-B	1.94±1.10	40.2	50.9
B-C	2.00±0.65	41.3	52.2
C-D	2.09±0.38	43.1	54.6
D-E	2.66±0.51	55.0	69.5
A-E	2.17±0.77	44.9	56.8
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	1.34±0.32	27.6	35.0
B-C	0.46±0.30	9.5	12.0
C-D	1.63±0.87	33.7	42.7
D-E	1.84±0.30	38.1	48.2
A-E	1.32±0.75		
(d) Unpruned *Grev.* + Local + deep tillage (AFL2)			
A-B	1.71±0.20	35.4	44.8
B-C	1.50±0.37	31.1	39.4
C-D	2.43±0.41	50.2	63.6
D-E	1.68±0.33	34.7	43.9
A-E	1.83±0.49	37.9	47.9
(e) Control plots			
Local (L) Mulch (M)	3.82±1.14 4.83±1.83	126.4 100.0	100.0 79.1

4.1.7 (d) Maize biomass yields

Figs. 98 & 99 (for row details) and Tables 38 & 39 present results of comparing maize biomass yields for SR94 as affected by crop residue mulch from the previous seasons. Table 38 and Figs. 98 & 99 show that the upper half of AF obtained less maize stover biomass yields in all the four treatments. In the unpruned plots that gave lowest yields overall the area BC gave again lowest yields and CD highest. The control plots gave higher stover biomass yields than the AF plots. Of the AF plots the highest stover biomass yield of 2.75±0.78 t/ha was obtained from AFM1. which was 43.1% less than Mulched control (i.e. 56.9% of M) but 28.0% less than Local control (i.e. 72.0% of L) (Table 39). The next highest average yield of 2.17±0.77 t/ha came from AFL1 (Table 38 & 39. We see from Table 39 that the intercrop residue mulch contributed to increased biomass yields in Mulched pruned plot in AF since AFM1 gave more yields than AFL1 by 26.7%. However in unpruned plots application of residue mulch made no difference between AFM2 and AFL2 as biomass yields were only 0.5% apart in favour of AFM2 (Table 39a).

Figs. 100 & 101 and Table 38 & 39 present results of the comparisons of maize biomass yields for SR94 as influenced by *Grevillea robusta* root-pruning in AF plots. Again pruning was most effective in combination with the mulch with minimum tillage treatment (AFM1). AFM1 had higher biomass yields than the unpruned mulch (AFM2) by 49.5% (Table 39). The same direction of the pruning effect was true for the Local plots as AFL1 had more biomass yields than AFL2 by 18.6%. Thus in both cases in SR94 pruning had advantage over not pruning.

However, when compared to the control plots, Mulched control gave the highest yield of 4.83±1.83 t/ha followed by Local control with 3.82±1.47 t/ha and then only third was AFM1. In the control plots the mulch had higher yields relative to the Local by 126.5%. From Table 39 we see that although clearly the lowest biomass yields in the four AF plots (AFM1, AFL1, AFM2 & AFL2) were received in the upper half (i.e. interspace A-C), this was not as extreme as in LR94 when the channelling effect of the strong southerly winds into the AF plot, as a result of the deliberate gap, most likely caused crop damage through shaking, lodging and higher evaporation rates from the soil and plants (see section 4.3). Higher biomass yields in all AF plots were obtained in the lower half of AF (i.g. D-C & D-E) than in the upper half (Table 38). The highest yields in the lower half, interspace 'C-D', may be due to gravitational run on water, due to the sloping land (at a slope of 4-5%) where this area is down slope, and to protection from strong winds in

Table 39. Effects of Mulched and pruning on maize biomass yields (a) Mulched (b) pruning for SR94

treatments	Average biomass (t/ha)
(a) Mulched	
AFM1 AFL1	2.75±0.78 2.17±0.77
% increase for mulched	26.7
AFM2 AFL2	1.32±0.75 1.83±0.49
% decrease for Mulched	-28
(b) Pruning effect	
AFM1 AFM2	2.75±0.78 1.84±0.30
% increase for pruned	49.5
AFL1 AFL2	2.17±0.77 1.83±0.49
% increase for pruned	18.6

the region between 7.5 and 15 m from the western hedge, where no interference of roots from the nearest hedge plants will cause differences.

4.1.7 (e) Beans biomass and seed yields

Table 40a & 40b present the effects of Mulched and pruning on the beans seed and biomass yields for the SR94. The Mulched treatment did not do well in this season. In the pruned plots AFL1 had more biomass and seed yields than AFM1 by 19.1 and 54.5% respectively (Table 40a). In the unpruned plots AFL2 produced more seed yields than AFM2 by 54.5% but less biomass albeit by a mere 3.8%.

Even pruning was not any better with regard to grain yields as the treatments had equal yields (Table 40a). Differences were observed with respect to biomass production as pruned plots produced more than unpruned plots. AFM1 produced more biomass than AFM2 by 40.7% while AFL1 had more biomass than AFL2 by 80.8 %. Comparing the bean biomass and seed yields from AF plots with the controls (Tables 41 and 42) we observe equal differences relative to the controls as both Mulched and Local controls received equal grain and biomass yields.

Table 40. Effects of Mulched and pruning on beans seed & biomass yields (a) Mulched (b) pruning for SR94

treatments	average seed (t/ha)	Average biomass (t/ha)
(a) Mulched		
AFM1	0.05±0.03	0.38±0.12
AFL1	0.11±0.06	0.47±0.12
% decrease	-54.5	-19.1
AFM2	0.05±0.06	0.27±0.11
AFL2	0.11±0.05	0.26±0.07

% decrease	-54.5	3.8
(b) Pruning effect		
AFM1	0.05±0.03	0.38±0.12
AFM2	0.05±0.03	0.27±0.11
% increase	0.0	40.7
AFL1	0.11±0.06	0.47±0.12
AFL2	0.11±0.05	0.26±0.07
% increase	0.0	80.8

Comparison of the upper and lower half of each plot in AF indicates that in AFM1 they had almost the same biomass but its lower half had more seed yields. AFL1 and AFM2 obtained more bean biomass and bean seed yields in the lower than in the upper half of AF plot, while in AFL2 plots such a phenomenon did not occur.

4.1.8 Results of on-farm live-fence experiment at Kiahuko-A

4.1.8 (a) Rainfall and evaporation climate during growing season

The maize/beans intercrop for SR93 on-farm was planted on 17/10/93 after a total rainfall amount of 19.5 mm was received in four consecutive days preceding the planting day that marked the onset of the short rains for 1993. The rainfall continued for one and a half months and then soil moisture level had dropped and the intercrop could not survive. The rainfall amounts for November and December as read from the on-farm rain gauge installed on 2/10/93 were 104.1 and 78.3 mm. The intercrop emergence was observed on 24/10/93 (i.e. 7 DAP). The crop grew well for some time whereafter soil moisture level had dropped and the episode of crop failure followed.

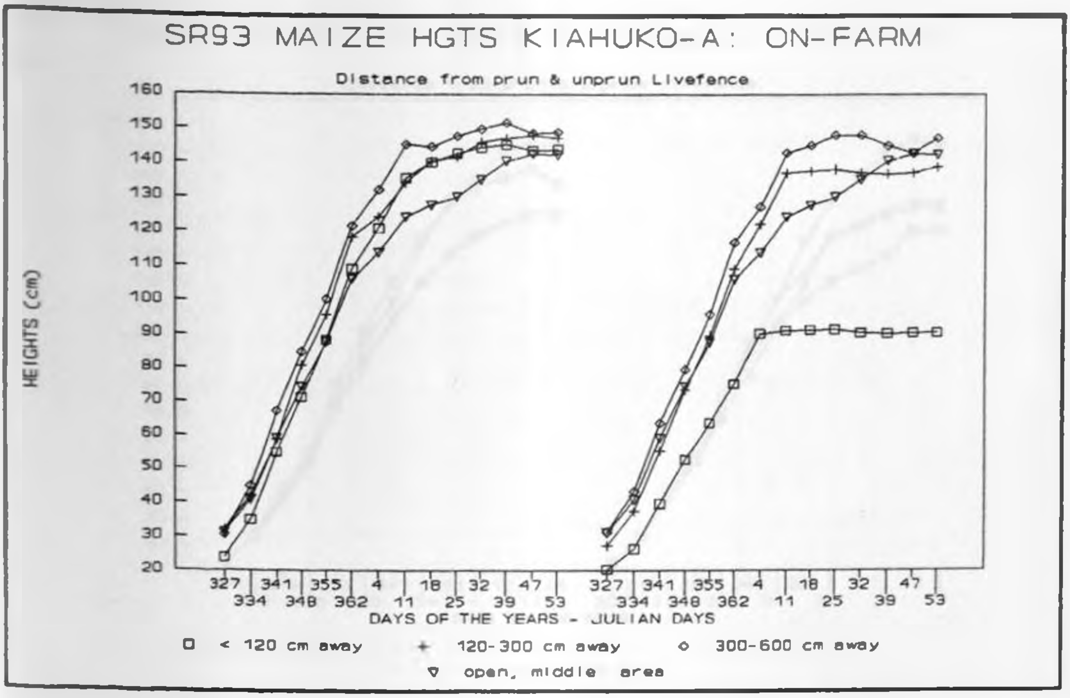

Fig. 102. Average maize heights as a function of distance from pruned (left) and unpruned (right) portions of *Coleus barbatus* live-fence at Kiahuko-A on-farm plot for SR93.

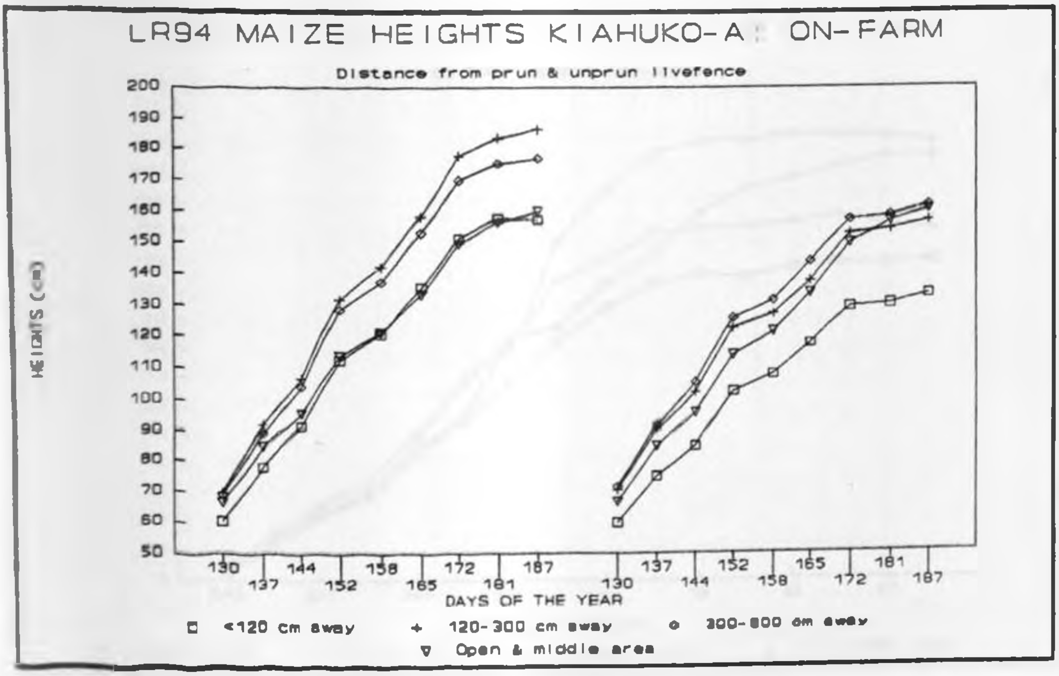

Fig. 103. Average maize heights as a function of distance from pruned (left) and unpruned (right) portions of *Coleus barbatus* live-fence at Kiahuko-A on-farm plot for LR94.

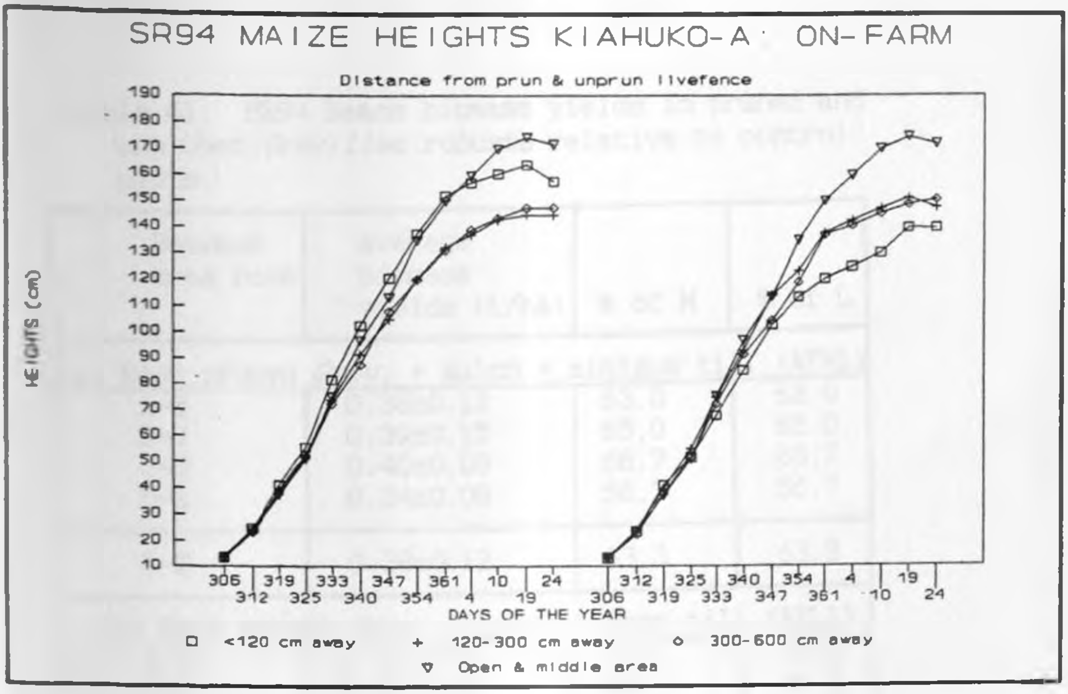

Fig. 104. Average maize heights as a function of distance from pruned (left) and unpruned (right) portions of *Coleus barbatus* live-fence at Kiahuko-A on-farm plot for SR94.

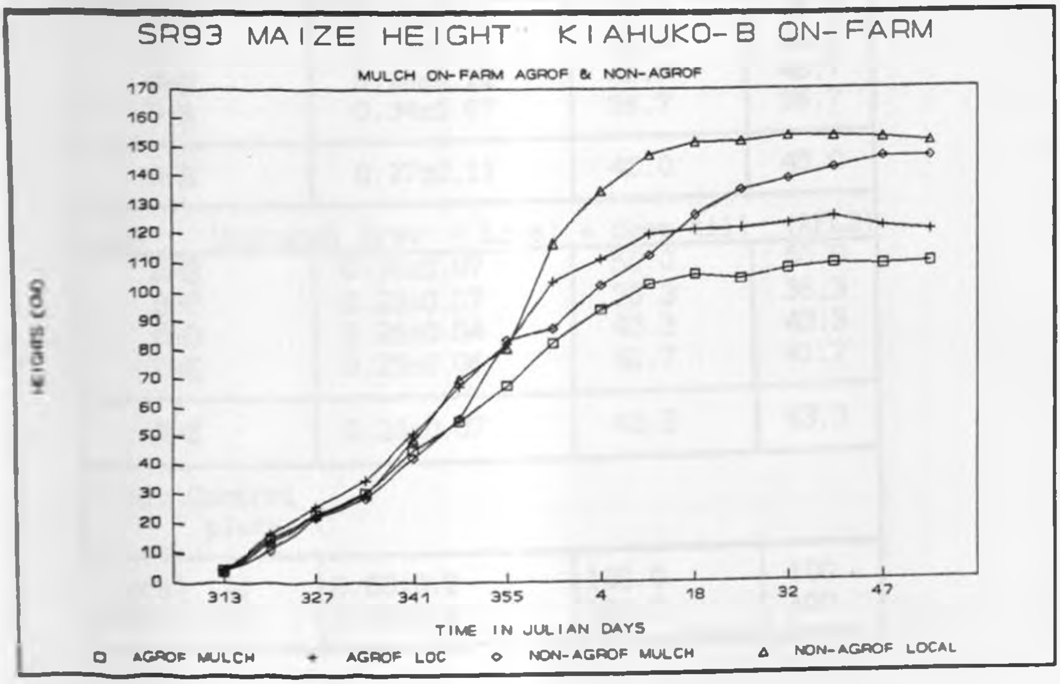

Fig. 105. Average maize heights in Mulched and Local treaments in AF and NAF plots at Kiahuko-B on-farm for SR93.

Table 41. SR94 Beans biomass yields in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average biomass yields (t/ha)	% of M	% of L
(a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A–B	0.38±0.12	63.0	63.0
B–C	0.39±0.15	65.0	65.0
C–D	0.40±0.09	66.7	66.7
D–E	0.34±0.08	56.7	56.7
A–E	0.38±0.12	63.3	63.3
(b) Root pruned *Grev.* + Local + deep till (AFL1)			
A–B	0.42±0.12	70.0	70.0
B–C	0.40±0.09	66.7	66.7
C–D	0.55±0.10	91.7	91.7
D–E	0.53±0.11	88.3	88.3
A–E	0.47±0.12	78.3	78.3
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A–B	0.22±0.11	67.7	36.7
B–C	0.23±0.11	38.3	38.3
C–D	0.28±0.12	46.7	46.7
D–E	0.34±0.07	56.7	56.7
A–E	0.27±0.11	45.0	45.0
(d) Unpruned *Grev.* + Local + deep till (AFL2)			
A–B	0.30±0.07	50.0	50.0
B–C	0.23±0.07	38.3	38.3
C–D	0.26±0.04	43.3	43.3
D–E	0.25±0.06	41.7	41.7
A–E	0.26±0.07	43.3	43.3
(e) Control plots			
Local (L)	0.60±0.2	100.0	100
Mulch (M)	0.60±0.2	100.0	100

Table 42. SR94 beans seed yields in pruned and unpruned *Grevillea robusta* relative to control plots.

Between tree rows	average bean seed yields (t/ha)	% of M	% of L
a) Root pruned *Grev.* + mulch + minimum till (AFM1)			
A-B	0.03±0.00	15	15
B-C	0.04±0.02	20	20
C-D	0.08±0.02	40	40
D-E	0.04±0.04	20	20
A-E	0.05±0.03	25	25
(b) Root pruned *Grev.* + Local + deep till (AFL1)			
A-B	0.07±0.05	35	35
B-C	0.07±0.05	35	35
C-D	0.14±0.03	70	70
D-E	0.16±0.03	80	80
A-E	0.11±0.06	55	55
(c) Unpruned *Grev.* + mulch + minimum till (AFM2)			
A-B	0.03±0.04	15	15
B-C	0.01±0.02	5	5
C-D	0.07±0.04	35	35
D-E	0.10±0.06	50	50
A-E	0.05±0.06	25	25
(d) Unpruned *Grev.* + Local + deep till (AFL2)			
A-B	0.10±0.04	50	50
B-C	0.10±0.04	50	50
C-D	0.14±0.03	70	70
D-E	0.10±0.06	50	50
A-E	0.11±0.05	55	55
(e) Control plots			
Local (L)	0.20±0.10	100	100
Mulch (M)	0.20±0.10	100	100

The on-farm intercrop for LR94 was planted on 25/4/94 and for SR94 it was planted on 22/10/94 and again these seasons' low soil moisture level did not allow the maize to reach maturity. The rainfall totals and distributions did not favour the intercrop (see Appendix Table A3).

4.1.8 (b) Maize heights

Figs. 102-104 give maize heights as measured from the farmers plot at Kiahuko-A in the live-fence experiment. The heights in the open part of the plot (GC-Garden Centre) are repeated in both parts of each graph for every season as a control. Other heights measurements are then gauged against it. The distances 0-120, 120-300 and 300-600 cm were determined with soil moisture gradients in mind, as monitored weekly by the neutron probe in the access tubes installed at 90, 180 and 360 cm from the live-fence.

We notice for SR93 (Fig. 102) that the plants close to the unpruned *Coleus barbatus* live-fence and at 120 cm away were seriously depressed by competition for water with the live-fence. The plants in the same area near the pruned live-fence were growing normally. In fact the plants near the unpruned live-fence had outgrown those in the open by day 4 of January, 1994, but they all ended up equally. The plants in the unpruned area beyond 120 cm were also growing at rates like the others.

Similar competition was observed for the LR94 crop (Fig. 103). We further notice plants in the pruned plots at the distances of 120-300 and 300-600 cm growing even taller than those in the middle (GC) part. This was attributed to strong winds that affect the exposed centre of the on-farm plots during this time of the year and to competition for water between the crop and a mature *Eucalyptus* tree growing near the centre of the farm. During SR94 the winds were light and plants in the

GC (middle) area grew taller than the rest. Meanwhile competition between the crop near to the fence and the unpruned live-fence was evident for the SR94 crop (Fig. 104).

4.1.8 (c) Maize biomass (stover) yields

As we have already pointed out in section 3.1.1 (f). the stover biomass for LR94 was taken by the farmer. before could taken measurements. We were therefore unable for LR94 to determine whether the picture of the values of relative height performance was returning in biomass yields.

Table 43(i) presents results of maize biomass yields for SR93 as a function of the distance from the *Coleus barbatus* live-fence. In the pruned area maize biomass yields slightly decreased (although error limits overlap) away from the live-fence. that is in the range 0-120 cm to 120-300 cm. and then increased for 300-600 cm away. The yields in unpruned were the same every where. The height picture was not repeated in the biomass yields as all were higher. in biomass. than GC and only 300-600 cm from the fence in the pruned area were the yields different. Given the error margins. the differences are almost negligible but for the total areas there is about 0.5 t/ha more yields in the area in front of the pruned fence. Comparing the biomass yields closest to the *Coleus barbatus* live-fence in the pruned area with the unpruned areas we found that pruning accounted for 0.4 t/ha or almost 10% increase in biomass yields. which must be considered a small increase. comparing it to the error margins concerned when real. this increase. though small as far as relief measures are concerned. may provide to the farmer in such a dry environment as Matanya a bonus to his livestock or provide mulching materials. There was also an increase in biomass yields of 1.0 t/ha or 23.3% in the area near the pruned fence over the area near the unpruned fence in the range 300-600 cm away, which might have been caused by the crop residues the farmer had heaped in the pruned area as his mulching materials. The biomass yields in open General Control (GC) were lower than closer to the live-fence due to exposure to the aerodynamic and evaporative effects. There was no windbreak effect in this part of the farm and it was therefore exposed to wind and other microclimatic stresses. Also competition for water between the crop and a mature *Eucalyptus* tree growing near the centre of the farm, as mentioned earlier, affected the biomass yields.

The biomass yields for SR94 (Table 44(i)) were much lower than for SR93. This was due to less rainfall received during early crop establishment and growth in SR94 than in SR93. However, we observe the same trend in SR94 as in SR93. In the pruned area the maize biomass yields slightly decreased from the live-fence (in the range 0-120 cm) to 120-300 cm although error limits strongly overlap and then slightly increased in the range 300-600 cm away, but these differences are marginal. In the unpruned area there was again lower yields on average, by a bit less than 0.2 t/ha or almost 25%.

Comparing the SR94 biomass yields closest to the *Coleus barbatus* live-fence in areas near the pruned and the unpruned fence, we see that pruning accounted for 0.27 t/ha or 34.2% increase in biomass yields, which is a substantial increase, although strongly overlapping error margins remain. The farmer would be very comfortable with such an increase.

General Control (GC) part obtained this year the average highest yield of 1.82±0.27 t/ha. Relative to GC the pruned area obtained 58.2% at 0–120 cm. 52.8% at 120–300 cm and 57.6% at 300–600 cm from the live-fence while unpruned area had 43.4% at 0–120 cm. 51.1% at 120–300 cm and 44.0% at 300–600 cm. These now relatively lower yields compared with GC. in the worst rainfall season are in line with the review of Norman et al. (1984) that under rainfed conditions long-term growth. water use and particularly (grain) yields may depend on soil water availability. The openness and the shade of the *Eucalyptus* tree nearby must have influenced plant growth differently from the other plants. as Fig. 190 confirms for soil moisture. Norman et al. (1984) contend that low maize (grain) yield in the tropics is attributed to dry matter distribution within the crop and to the sensitivity of both net photosynthesis and partitioning to environmental stress. particularly water deficit. Thus it is not unlikely that therefore GC plants were shorter but had relatively higher biomass yield.

The beans in Kiahuko-A were broadcast. as they normally did before we started on-farm experimentation. and were not planted in rows nence we were unable to quantify the yields.

4.1.9 Results of Mulching and pruning experiments at Kiahuko-B

4.1.9 (a) Maize and beans performance

The maize/beans intercrop for SR93 on-farm was planted on 17/10 /93. The intercrop for LR94 was planted on 25/4/94 and for SR94 it was planted on 22/10/94. Like for Kiahuko-A. the rainfall totals and distributions were expected not to favour the intercrop (see appendix Table A3). but surprisingly the maize crop did much better in LR94 at

Kiahuko-B compared to Kiahuko-A.

4.1.9 (b) Maize heights

Fig. 105 gives maize SR93 heights independently from any distance to trees. in Mulched and Local on-farm AF plots. as compared with the NAF control Local and control Mulched plots on-farm. We see in Fig. 105 that Mulched had retarded growth of plants. towards the end especially in the AF plots. The AF tree canopies were really heavy and mulching could not improve that situation, although the final height difference was only 10 cm. The plants in the Local control grew the fastest

Table 43. On-farm yields (t/ha) (grain and biomass) at Kiahuko-A and Kiahuko-B: (i) SR93 maize biomass from live-fence experiment at Kiahuko-A. (ii) yields at Kiahuko-B: (a) SR93 maize biomass at Kiahuko-B. (b) LR94 maize biomass at Kiahuko-B. and (c) LR94 beans yields at Kiahuko-B.

(i) SR93 maize biomass from live-fence experiment at Kiahuko-A

Distance from live-fence (cm)	avg yields		avg yields	
	pruned	% of GC	unpruned	% of GC
0-120	4.5±0.5	121.6	4.1±0.4	110.8
120-300	4.2±0.2	113.5	4.2±0.4	113.5
300-600	5.3±0.8	143.2	4.3±0.4	116.2
GC	3.7±0.9			

(ii) Maize yields at Kiahuko-B

(a) SR93 maize biomass at Kiahuko-B

	pruned	% of M	% of L	unpruned	% of M	% of L
Mulch (AF)	1.4±0.4	50.0	36.8	1.0±0.2	35.7	26.3
Local (AF)	0.7±0.3	25.0	18.4	1.4±1.2	50.0	36.8
Local contr (L)	3.8±0.6	73.7	100			
Mulch contr (M)	2.8±0.3	100	135.7			

(b) LR94 maize biomass at Kiahuko-B

	pruned	% of M	% of L	unpruned	% of M	% of L
Mulch (AF)	0.11±0.08	5.4	9.2	0.03±0.02	1.5	2.5
Local (AF)	0.13±0.09	6.4	10.9	0.09±0.03	4.5	7.6
mulch contr (M)	2.02±0.44	100	169.7			
Local contr (L)	1.19±0.35	58.9	100.0			

(c) LR94 beans yields at Kiahuko-B.

	Seed	Biomass	% of L	% of M
Loc cont (L)	0.11±0.02	0.09±0.02	100	81.8
Mul cont (M)	0.09±0.02	0.14±0.18	122.2	100

followed by those in the Mulched control plots, that, however, ended up very closely to the Local one.

The effect of mulching (Figs. 106 (pruned) & 107, (unpruned)) indicates Mulched plots in AF and NAF were the slowest in growing as compared to their Local neighbours. It is clear from Fig. 106 that, for LR94, in pruned area maize heights in mulched plots decreased while those in Local area increased with the distance from the trees. Maize plants for LR94 (Fig. 107) in Local unpruned plot are somewhat higher than those in Mulched unpruned plot. In Mulched plot (see Fig. 108) only at 200 cm from trees do pruned and unpruned differ but in opposite direction to what we would expect. Only for pruned do heights differ with the distance. For unmulched AF plot (see Fig. 109) maize heights in unpruned are less than the pruned with respect to distances, the heights at 200 cm are slightly higher.

We can see in Fig. 110 for SR94 that in the area with pruned *Grevilleas*, at 90 cm (left) maize in the Local pruned grew taller than in the mulched pruned, while they attained same final heights at 90 cm (left) and 180-270 cm (right). In the unpruned area (Fig. 111 for SR94)

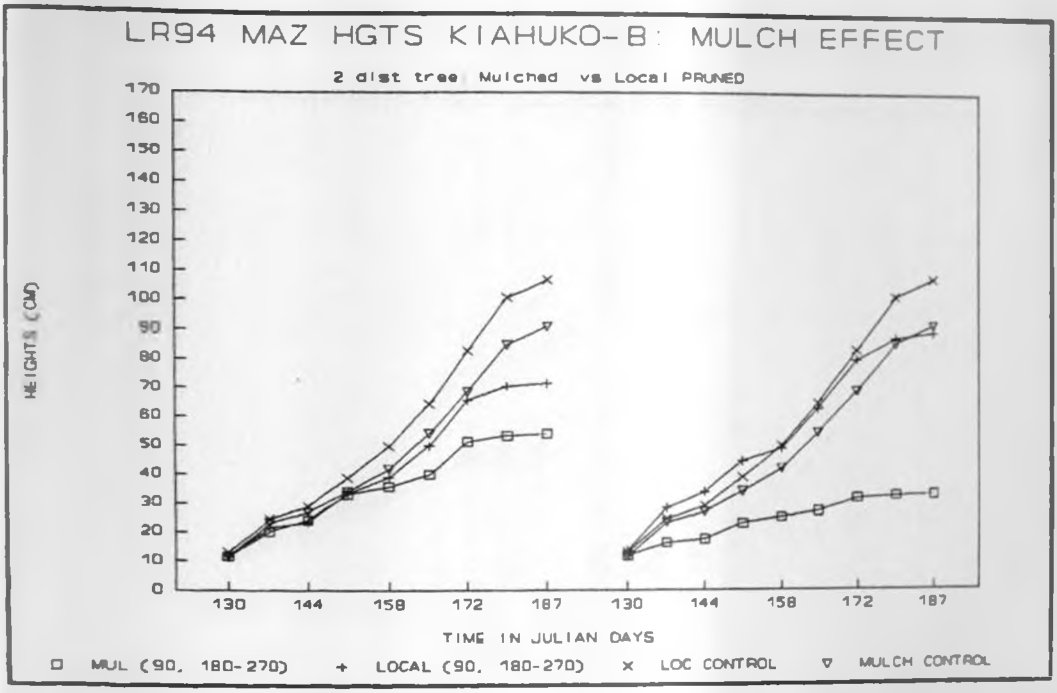

Fig. 106. Average maize heights at distances of 90 cm and 180-270 cm from root pruned *Grevillea robusta trees* in Mulched and Local treaments in AF and in NAF plots at Kiahuko-B on-farm for LR94.

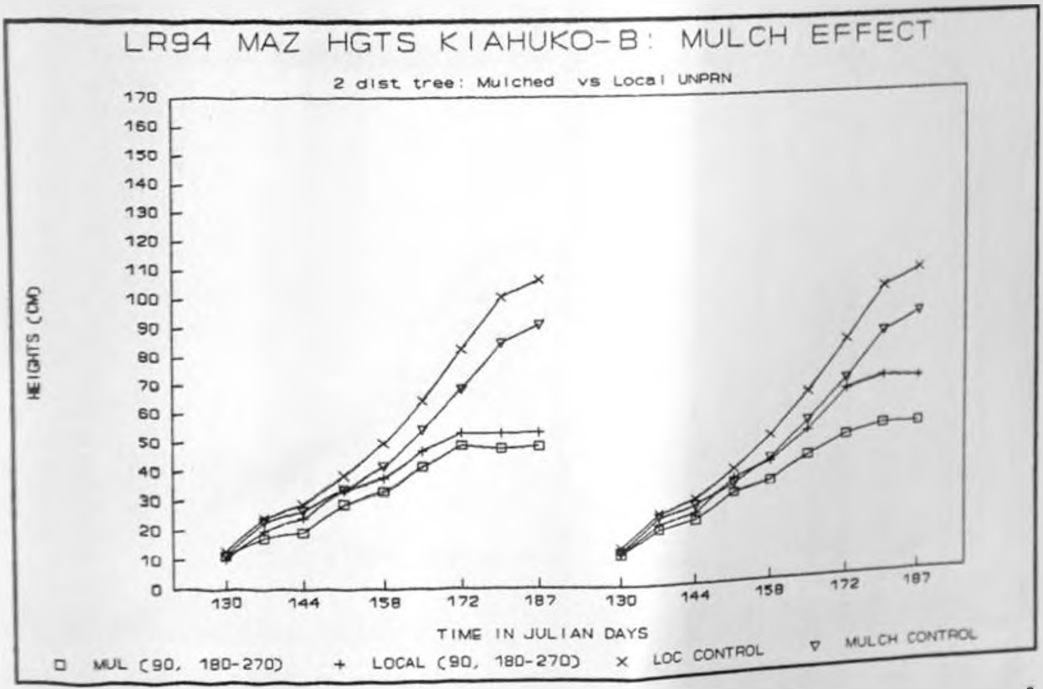

Fig. 107. Average maize heights at distances of 90 cm and 180-270 cm from unpruned *Grevillea robusta* trees in Mulched and Local treaments in AF and in NAF plots at Kiahuko-B on-farm for LR94.

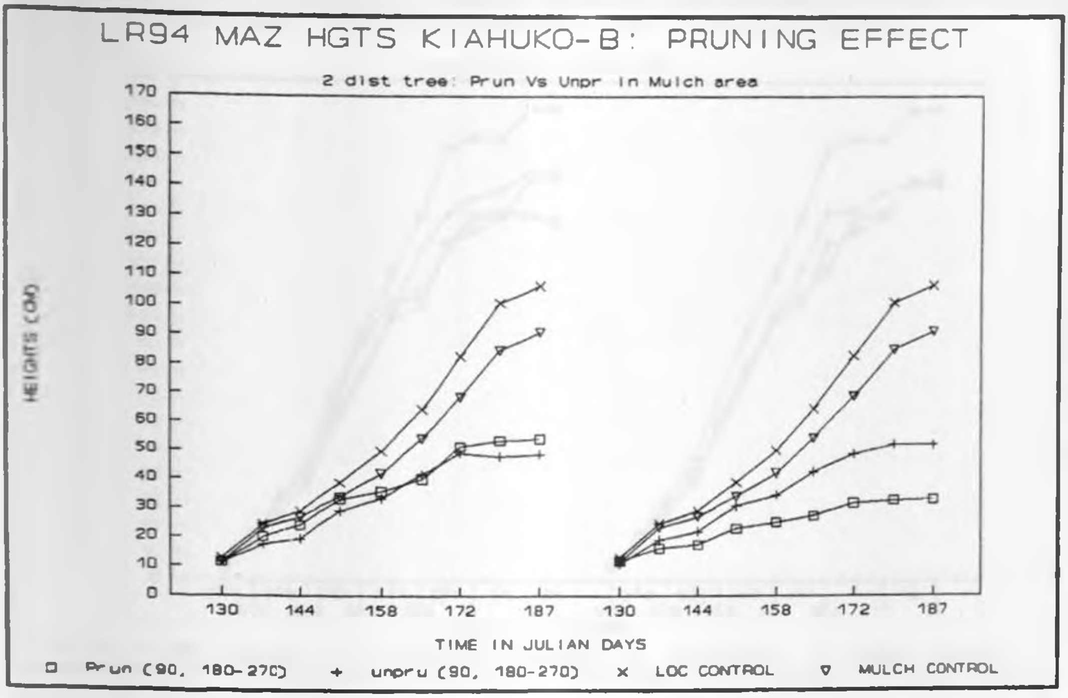

Fig. 108. Average maize heights, at distances of 90 cm (left) and 180-270 cm (right) from pruned and unpruned *Grevillea robusta trees* in Mulched plots in AF, and in NAF plots at Kiahuko-B on-farm for LR94.

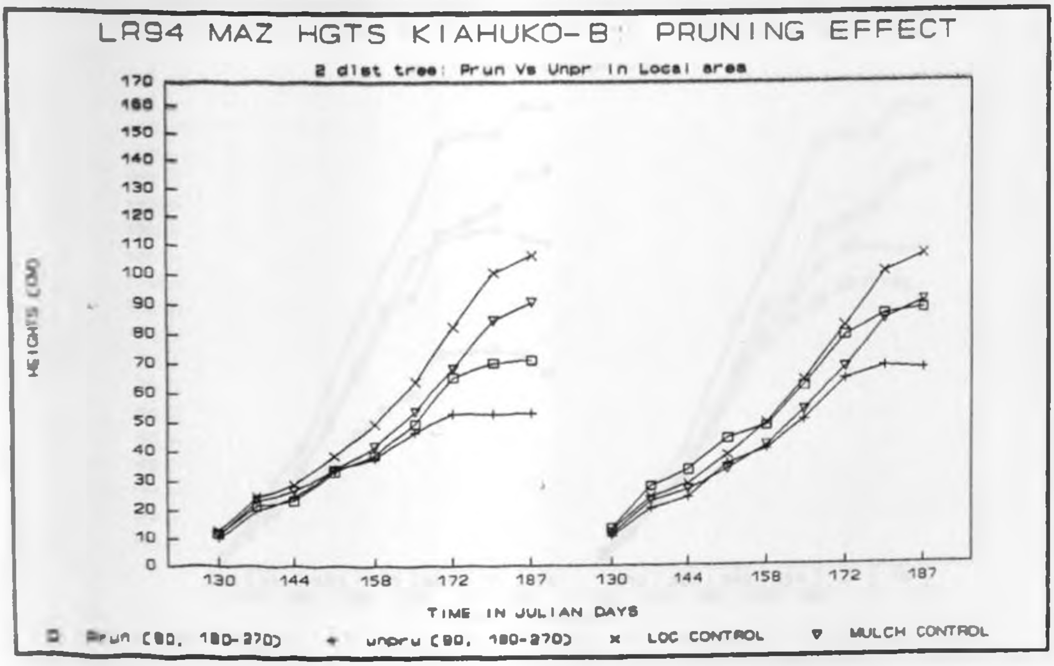

Fig. 109. Average maize heights, at distances of 90 cm (left) and 180-270 cm (right) from pruned and unpruned *Grevillea robusta trees* in Local plots in AF and in NAF plots at Kiahuko-B on-farm for LR94.

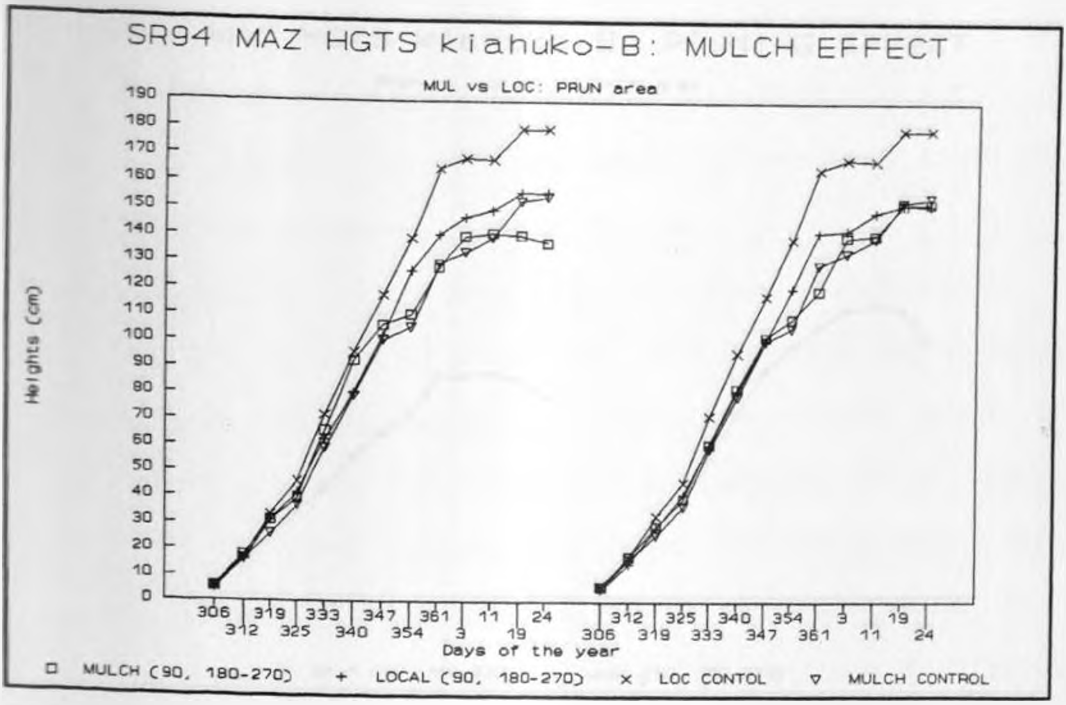

Fig. 110. Average maize heights at distances of 90 cm (left) and 180-270 cm (right) from pruned *Grevillea robusta trees* in Mulched and Local treaments in AF and in NAF plots at Kiahuko-B on-farm for SR94.

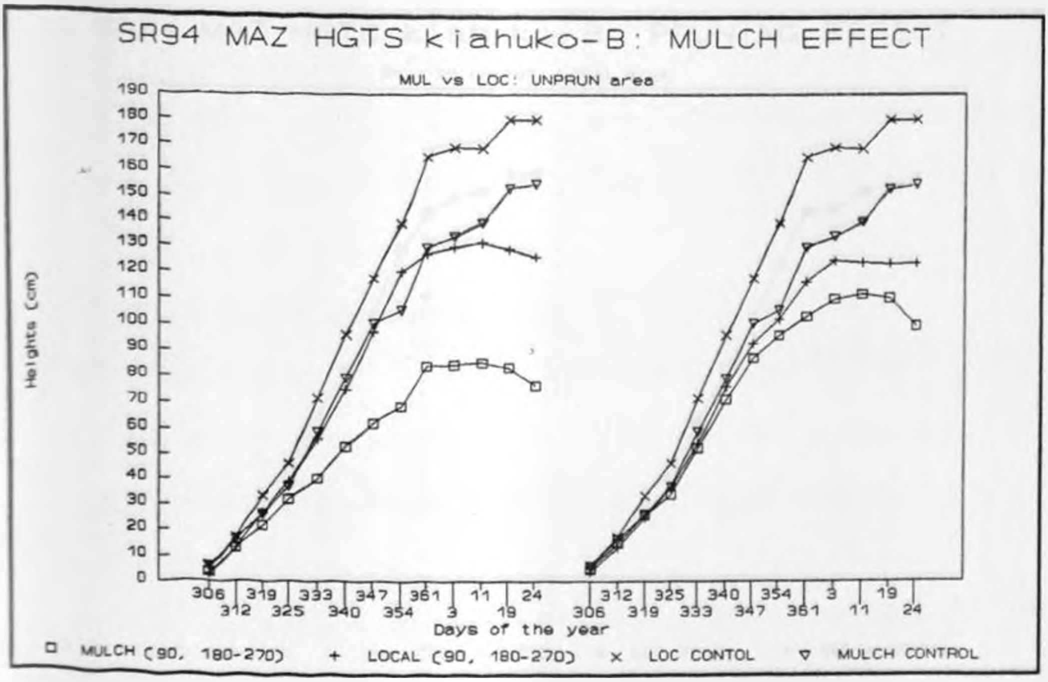

Fig. 111. **Average maize heights at distances of 90 cm (left) and 180-270 cm (right) from unpruned** *Grevillea robusta trees* in Mulched and Local treaments in AF and in NAF plots at Kiahuko-B on-farm for SR94.

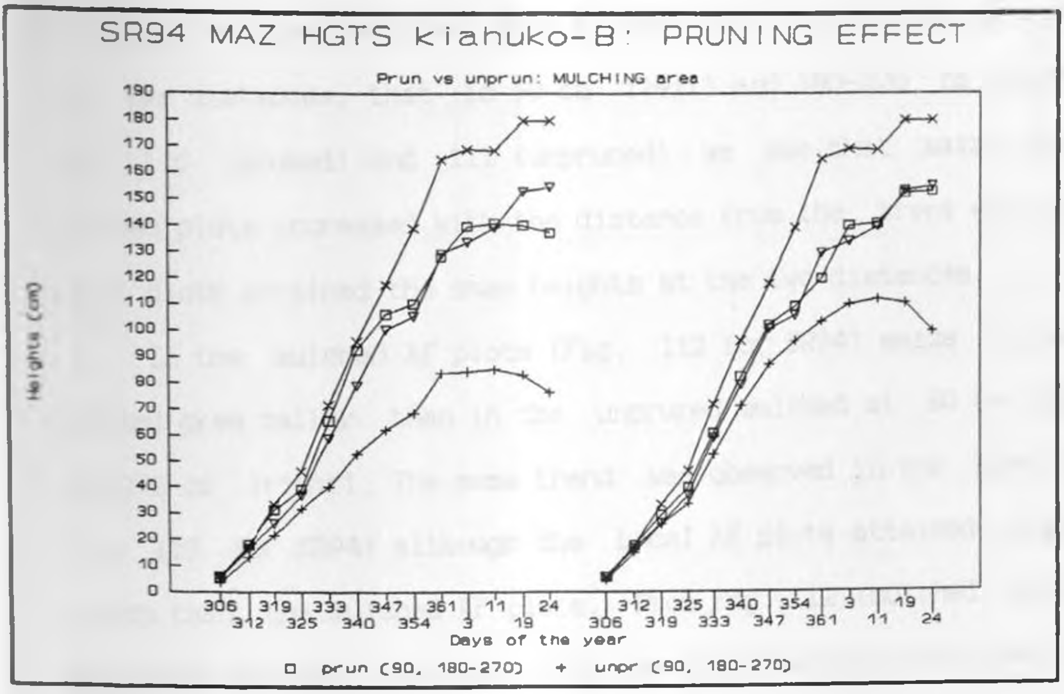

Fig. 112. Average maize heights at distances of 90 cm (left) and 180-270 cm (right) from pruned and unpruned *Grevillea robusta trees* in Mulched plots in AF and in NAF plots at Kiahuko-B on-farm for SR94.

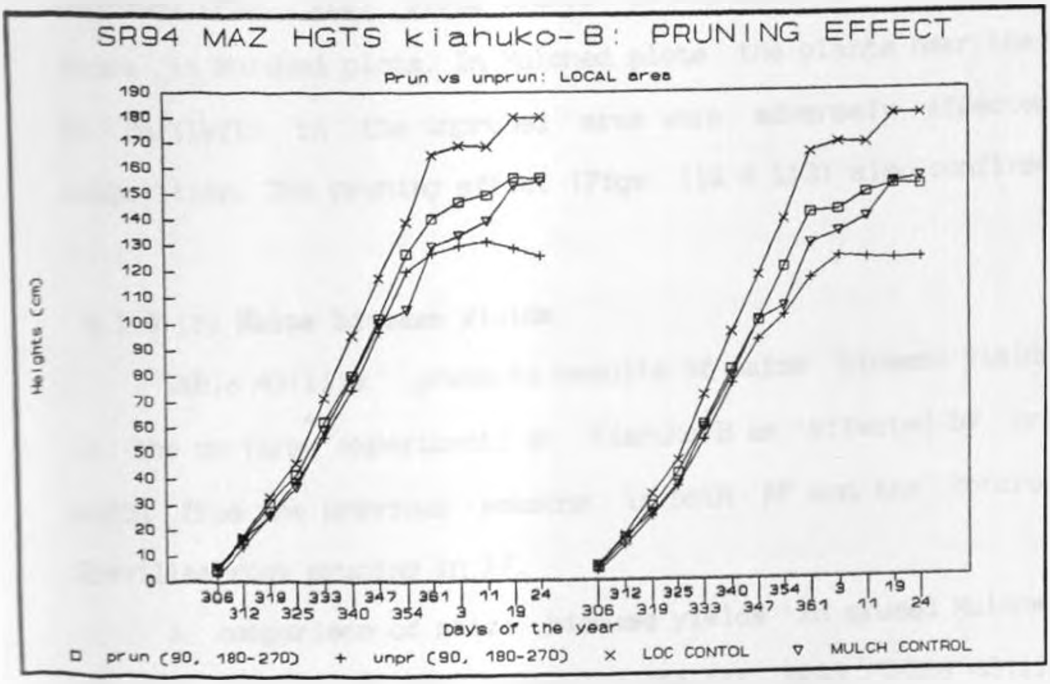

Fig. 113. Average maize heights at distances of 90 cm (left) and 180-270 cm (right) from pruned and unpruned *Grevillea robusta trees* in Local plots in AF and in NAF plots at Kiahuko-B on-farm for SR94.

maize in the Local unpruned grew taller than in the mulched unpruned at the two distances, that is 90 cm (left) and 180–270 cm (right). From Fig. 110 (pruned) and 111 (unpruned) we see that maize heights in mulched plots increased with the distance from the trees while those in Local plots attained the same heights at the two distances.

In the mulched AF plots (Fig. 112 for SR94) maize in the pruned mulched grew taller than in the unpruned mulched at 90 cm (left) and 180–270 cm (right). The same trend was observed in the Local AF plots (Fig. 113 for SR94) although the Local AF plots attained higher final yields than the mulched AF plots. From Fig. 112 (mulched plot) we see that maize heights increased with the distance from the trees. Maize in the Local AF plots attained the same heights at two distances from the trees (Fig. 113).

The mulch effect in the SR94 therefore showed that in unpruned (Fig. 111) plots plants in the Local plots grew taller than those in Mulched plots. In Mulched plots the plants near the trees, at 90 cm (left) in the unpruned area were adversely affected by tree competition. The pruning effect (Figs. 112 & 113) also confirmed this.

4.1.9 (c) Maize biomass yields

Table 43(ii)a presents results of maize biomass yields for SR93 in the on-farm experiments at Kiahuko-B as affected by crop residue mulch from the previous seasons, in both AF and the controls, and by Grevillea root pruning in AF.

A comparison of maize biomass yields in pruned Mulched plots in AF with those in Mulched control plots for SR93 (Table 43(ii)a)) gives a yield reduction of 1.4±0.7 t/ha in pruned Mulched plots. This substantial reduction in yield can be attributed to shading by the AF trees and this makes tree root pruning appreciably less effective under such conditions. The comparison of yields in Mulched control plots with those in unpruned Mulched plots in AF gives a reduction of 1.8±0.5 t/ha. which again is a substantial decrease we attribute to shading by the trees and competition for water between the crop and unpruned trees.

The comparison of yields in pruned Mulched with those in unpruned Mulched plot in AF gives a reduction of 0.4±0.6 t/ha. Here there was only a slight improvement, if any, in yields gained by root pruning in Mulched AF plots, possibly due to heavy shading that out played actors.

The comparison of yields in Local controls with those in pruned Local plot in AF gives a reduction of 3.1±0.9 t/ha. Again the difference is substantial and is due to heavy shading in AF which reduced the effects of other factors such as pruning.

Table 43(ii)b presents results of maize biomass yields for LR94 at Kiahuko-B on-farm in the control and AF plots.

A comparison of maize biomass yields for LR94 in pruned Mulched plots with those in Mulched control plots shows the latter gave more yields by 1.91±0.52 t/ha. This was a large difference, given the error margins, which we again attribute to heavy shading, which reduced the effect of root pruning in the pruned Mulched plots in AF. The comparison of yields in Mulched control with those in unpruned Mulched plot in AF for LR94 shows that the unpruned Mulched plots have hardly any yield, and this substantial difference is again due to heavy tree canopy shading, worsened by competition for water between the crop and unpruned trees.

The comparison of yields in pruned Mulched in AF with those in unpruned Mulched plot gives a reduction of 0.8±1.0 t/ha. Here there was substantial improvement in yields gained by root pruning in Mulched AF plots. but both yields remained low due to heavy shading that out played other actors.

The comparison of yields in Local controls with those in pruned Local plots in AF gives a reduction of 1.06±0.44 t/ha. Again the difference is substantial and is due to heavy shading in AF. The comparison with the Local unpruned yields gives an almost identical result.

As we have already pointed out, the previous seasons did not produce grain. An average grain yield of 0.61±0.39 t/ha was obtained from pruned Mulched plots in AF in SR94 while the pruned Local had 0.69±0.42 t/ha which gave a decrease of 0.08 t/ha and an error margin of 0.81 t/ha. Given the error margins, which are large, no or only slight improvement occurred when mulching (for the pruned maize grain yields). In the unpruned plots grain yields for SR94 were 0.07±0.07 t/ha in Mulched compared to 0.12±0.11 t/ha in Local plots, again a slight decrease when mulching in biomass yields of 0.05 t/ha with an error margin of 0.18 t/ha. so with little agronomical importance.

The reduction in grain yields in SR94 was also observed relative to the control plots (Table 44(ii)a). The control plots produced 1.43±0.59 t/ha for the Mulched and 1.60±0.50 t/ha for the Local control plots.

Among the control plots Mulched controls gave 0.17 t/ha more the Local controls. Given the error margin of 1.09 t/ha. we see here that no difference with a real meaning importance in grain yields was obtained by mulching.

Table 44(ii)b shows clearly that no improvement in cob splint yields for SR94 was obtained by both pruning and mulching in AF plots. and control plots with respect to mulching. Similarly the results for the maize stover biomass in Tables 43(ii)c and 43(ii)d have large error margins which covers all yield differences in both control plots and AF plots. The yield differences between and within plots are therefore marginal which proves that pruning and mulching gave no improvements in biomass yields in AF and the control plots.

The above analysis is strengthened by fully identical trends in SR94 cob splint (primary) yields, stover yields and then of course total biomass yields as given in Tables 44 (ii) b, c and d.

4.1.9 (d) Beans seed and biomass yields at Kiahuko-B on-farm

Table 43(ii)c presents results of bean seed and biomass yields for LR94 at Kiahuko-B on-farm in the control plots only, as seedlings in the AF did not germinate, possibly due to late planting, rodents (rats eating seeds before they germinated) and heavy shading. These

Table 44. On-farm yields (t/ha) (grain and biomass) at Kiahuko-A and Kiahuko-B: (i) SR94 maize biomass from live-fence experiment at Kiahuko-A, (ii) maize yields at Kiahuko-B on-farm: (a) SR94 maize grain yields, (b) SR94 maize cob splint or shelled cob), (c) SR94 maize stover yields and (d) SR94 total dry matter yields.

(i) SR94 maize biomass from live-fence experiment at Kiahuko-A				
Distance from live-fence (cm)	avg yields pruned	% of GC	avg yields unpruned	% of GC
0-120	1.06±0.35	58.2	0.79±0.47	43.4
120-300	0.96±0.20	52.8	0.93±0.28	51.1
300-600	1.05±0.24	57.6	0.80±0.37	44.0
GC	1.82±0.37			

(ii) Maize yields at Kiahuko-B

(a) SR94 maize grain yields

	pruned	% of M	% of L	unpruned	% of M	% of L
Mulched (AF)	0.61±0.39	42.7	38.1	0.07±0.07	4.9	4.4
Local (AF)	0.69±0.42	48.3	43.1	0.12±0.11	8.4	7.5

		% of M	% of L
Mulch contr (M)	1.43±0.59	100	112
Local contr (L)	1.60±0.50	89.3	100

(b) SR94 maize cob splint yields

	pruned	% of M	% of L	unpruned	% of M	% of L
Mulch (AF)	0.11±0.07	37.9	26.8	0.02±0.03	6.9	4.9
Local (AF)	0.14±0.09	48.3	34.1	0.03±0.02	10.3	7.3

		% of M	% of L
mulch contr (M)	0.29±0.12	100	70.7
Local contr (L)	0.41±0.12	141.4	100.0

(c) SR94 maize stover yields

	pruned	% of M	% of L	unpruned	% of M	% of L
Mulch (AF)	1.69±0.80	30.9	32.6	0.73±0.42	13.3	14.07
Local (AF)	2.40±0.73	43.9	46.2	1.94±0.58	35.5	37.38

		% of M	% of L
mulch contr (M)	5.47±2.20	100	105.4
Local contr (L)	5.19±0.93	94.9	100.0

(d) SR94 total biomass yields

	pruned	% of M	% of L	unpruned	% of M	% of L
Mulch (AF)	2.42±1.23	33.7	33.6	0.82±0.50	11.7	11.7
Local (AF)	3.23±1.16	44.9	44.8	2.08±0.63	28.9	28.8

		% of M	% of L
mulch contr (M)	7.19±2.20	100.0	99.7
Local contr (L)	7.21±1.36	100.3	100.0

control plots performed disastrously.

A comparison of bean seed yields in Mulched control plots with those in Local control shows that the former gave negligibly more yields by 0.02±0.04 t/ha. A comparison of bean biomass yields in Mulched control plots with those in Local control shows that the latter gave more yields by 0.05±0.20 t/ha which again is negligible.

4.1.10 Intercomparison of yields in the on-farm (Kiahuko-A & B and on-station (Matanya).

From Tables 43, 44 and Appendix Table A2.1 we can only compare results for SR93, LR94 and SR94. For the effect of *Grevillea robusta* root pruning we compare yields in pruned and unpruned trees. From Tables 43(ii)a and Appendix Table A2.1 we see that for SR93, the difference in maize biomass yields between pruned Mulched plot (AFM1) at Matanya (1.54±0.68 t/ha) and pruned Mulched at Kiahuko-B (1.4±0.4 t/ha) was 0.14±1.08 t/ha, which was appreciably less than the error margin and therefore two locations have supposed to have equal yields. The difference in the unpruned Mulched plots (0.47±0.33 and 1.0±0.2 t/ha) in the two locations was 0.53±0.53 t/ha which means that error margins of two locations just tough, so Kiahuko-B produced more biomass in the order of twice as much maize biomass in SR93 (Tables 43(ii)a and Appendix Table A2.1).

The differences in the pruned and unpruned Local plots in the two locations (for pruned: 0.83±0.37 and 0.7±0.3 t/ha; for unpruned: 0.8±0.27 and 1.4±1.2 t/ha) for SR93 were respectively 0.13±0.67 t/ha and 0.6±1.47 t/ha which due to large error margins means that the two locations must be supposed to have equal maize biomass in SR93, with a tendency for higher on-farm biomass in the unpruned case, like in the mulched comparison.

The differences in the Mulched control and Local control plots in the two locations for SR93 (for mulched: 1.97±0.76 and 2.8±0.3 t/ha; for

Local: 2.0±0.74 and 3.8±0.6 t/ha) were respectively 0.83±1.06 t/ha and 1.8±1.34 t/ha which again, although with large error margins, show a tendency of higher biomass yields on-farm in SR93. These differences were almost equal to those with the control plot (GC) at Kiahuko-A (Local control yields 3.7±0.6 t/ha). This shows that the SR 1993 low soil moisture affected Matanya and Kiahuko areas rather equally, but with a tendency of higher on-farm biomass.

From Tables 43 (ii)b and Appendix Table A2.1 we see that for LR94, the difference in maize biomass yields between pruned Mulched plot (AFM1) at Matanya (2.69±1.10 t/ha) and pruned Mulched plot at Kiahuko-B (0.11±0.08 t/ha) was 2.58±1.18 t/ha which was remarkably in favour of Matanya. Thus Matanya pruned Mulched plots produced a mulch higher maize biomass yield than Kiahuko-B. This difference may be attributed to heavier Grevillea shading at the Kiahuko-B AF than at Matanya. The difference in the unpruned Mulched plots (1.28±1.00 and 0.03±0.02 t/ha) in the two locations for LR94 was 1.25±1.02 t/ha which again remarkably in favour of Matanya.

The differences in the pruned (1.96±1.07 and 0.13±0.09 t/ha) and unpruned (2.15±0.80 and 0.09±0.03 t/ha) Local plots in the two locations for LR94 were respectively 1.83±1.16 t/ha and 2.06±0.83 t/ha which were again remarkably in favour of Matanya (Tables 43 (ii)b and Appendix Table A2.1).

The differences in the Mulched control (6.27±1.77 and 2.02±0.44 t/ha) and Local control (2.81±1.10 and 1.19±0.35 t/ha) plots in the two locations for LR94 were respectively 4.25±2.21 t/ha and 1.62±1.45 t/ha which are not negligible. We can therefore infer here that now Matanya had certainly higher maize biomass yields in LR94 than Kiahuko-B, due to heavy shading in AF at Kiahuko-B. This is opposite to the trend of SR93.

This already proves that even over a small distance, of a few kilometres, rainfall and therefore (biomass) yields can vary greatly under Laikipia conditions.

From Tables 44 (ii)a and Appendix Table A2.1 we see that for SR94, there was maize grain yields at Kiahuko-B while Kiahuko-A and Matanya plots produced only maize biomass. We therefore compared the total yields (including stover and unshelled cobs) at Kiahuko-B to the biomass at Matanya and Kiahuko-A. A comparison of maize biomass yields in pruned Mulched plot (AFM1) at Matanya (2.75±0.78 t/ha) to the pruned Mulched plot at Kiahuko-B (2.42±1.23 t/ha) shows that there was a small difference of 0.33±2.01 t/ha of biomass yields in favour of Matanya. This was really a negligible increase, given the error margins, indicating that the two locations had almost the same biomass in the mulched pruned AF plots. Heavy Grevillea shading at Kiahuko-B may have reduced the biomass yields to a level where it equalled the biomass yield at Matanya despite a supposedly good season at Kiahuko.

A comparison of maize biomass yields in unpruned Mulched plot (AFM2) at Matanya (1.32±0.75 t/ha) to the unpruned Mulched plot at Kiahuko-B (0.82±0.50 t/ha) shows that there was a difference of 0.5±1.25 t/ha yields in favour of Matanya. This was really a slight difference given the error margins but heavy shading affected Kiahuko-B biomass.

The differences in the pruned Local (2.17±0.77 and 3.23±1,16 t/ha) and unpruned Local (1.83±0.49 and 2.08±0.63 t/ha) plots in the two locations for SR94 were respectively 1.05±1.94 t/ha and 0.25±1.12 t/ha which differences are negligible in the unpruned case but in favour of Kiahuko-B for the pruned case, be it that the error margin is very large (Tables 44 (ii)d and Appendix Table A2.1).

The differences in the Mulched control (4.83±1.83 and 7.19±2.20 t/ha) and Local control (3.82±1.47 and 7.21±1.36 t/ha) plots in the two locations for LR94 were respectively 2.36±4.03 t/ha and 3.39±2.53 t/ha. The differences in control plots at the two locations were clearly in favour of the on-farm yields, the large error margins notwithstanding. Kiahuko-A controls had less biomass yield differences with Matanya, nevertheless appreciably less biomass yields than both Matanya and Kiahuko-B. To this comparison should be added that only Kiahuko-B on-farm maize yielded actual grain yields, of very much importance to the farmer.

4.2 Results of soil moisture

4.2.1 Relationship between observed and calculated volumetric soil moisture content (VSMC, θ %).

4.2.1 (a) Results of calibrations of neutron probes for Matanya soils.

The simultaneously obtained calibration results for the two instruments (CPN 501 and CPN 503) done for dry and wet seasons on 19/2/92 and 18/6/92 respectively are presented in Figs. 114 and 115 and regression equations 22 & 23.

$$\theta_{calc}=70.37*Cr-2.14,(r=0.982) \quad (22)$$

and

$$\theta_{calc}=27.20*Cr-10.74,(r=0.963) \quad (23)$$

where θ_{calc} is calculated VSMC and

Cr is count ratio, that is the ratio of the probe reading to the standard count.

These calibration equations were used to convert the weekly probe readings to VSMC. CPN 503 and its calibration equation (Eq. 23) were used only when CPN 501 broke down.

Tables 45a & 45b present observed and calculated soil moisture during dry and wet calibrations in 1992 using CPN 501 and 503. The relationship between observed and calculated VSMC were very high (r = 98.2 % for CPN 501 and r = 96.3 % for CPN 503). The positive per cent deviations of observed from calculated VSMC indicated that the calibration equation for CPN 501 (r= 98.2 %) slightly underestimated VSMC under dry conditions at 30 cm depth and below. The surface layers

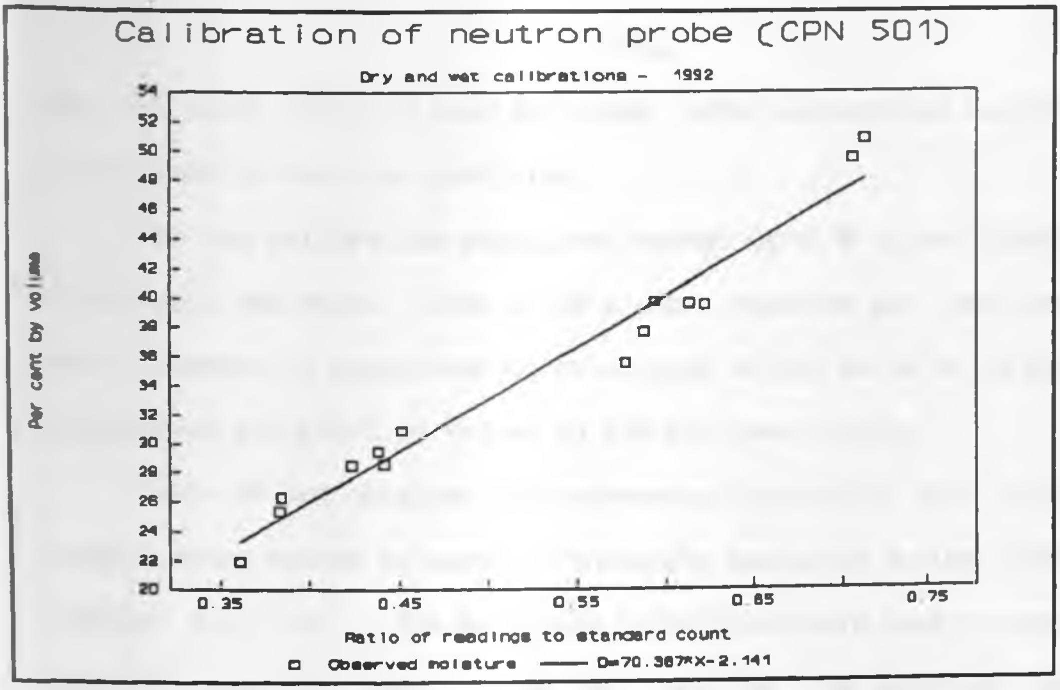

Fig. 114. Calibration of neutron probe (type CPN 501)

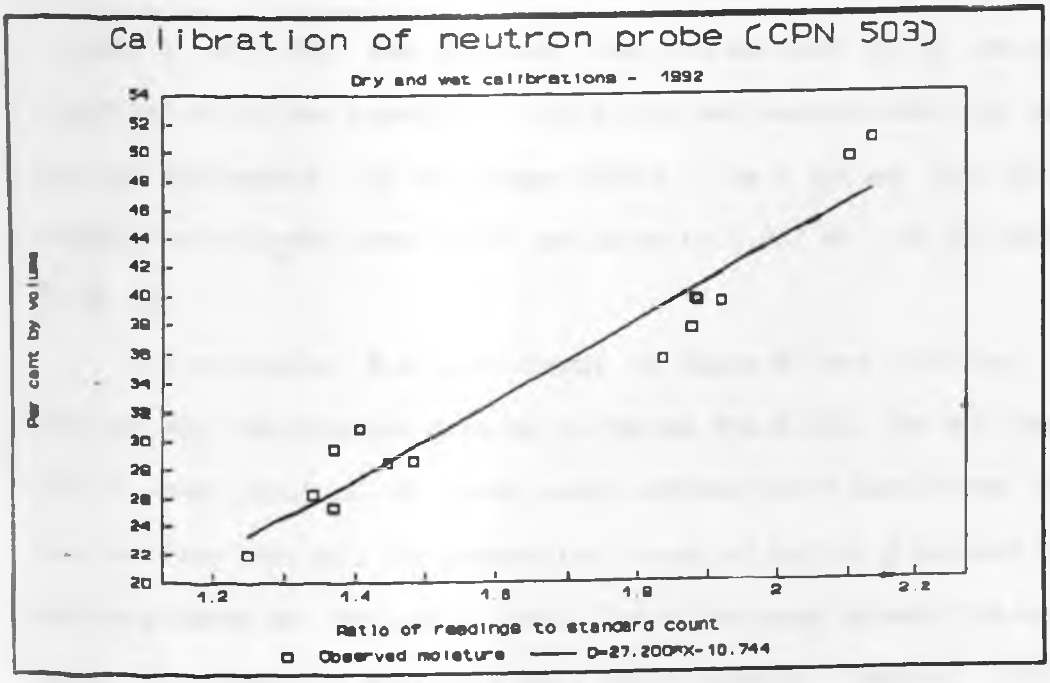

Fig. 115. Calibration of neutron probe (type CPN 503)

are left with few free hydrogen atoms after evaporation but there are those bound to the clay particles.

The two calibration equations overestimated θ in wet conditions at 90 cm depth and below (Table 45a & 45b). Negative per cent deviations were observed in comparison of calculated values below 90 cm during wet calibration and positive values in the shallower depths.

Table 46 was obtained by regressing gravimetric soil moisture on probe reading ratios at each of the seven measuring depths given above (section 4.2.1 (a)). The equations in Table 46 were used to estimate θ for each measuring depth in the soil profile. The equations gave more accurate θ than the single calibration equation (Eq. 22 or 23) used for the whole profile. The correlation coefficients, r, were very high. The highest r of 0.995 was obtained near the surface at 18 cm depth, a condition which was possible only during wet seasons when the clay soil swelled and sealed the shrinkage cracks. The r values were decreasing slightly with depth from 0.995 at 18 cm to 0.957 at 150 cm depths (Eq. 22 or 23).

The available θ at each depth in Table 47 was obtained from the dry and wet calibration data as in Tables 45a & 45b. The W.P. was taken as the lower limit of θ, taken under extremely dry conditions when the soil surface lost all its vegetative cover of mainly grass and the F.C. was considered as the upper limit. The difference between the upper and lower limits was the available soil water capacity (Gardner, 1988).

We notice from Table 47 that the layers 0–75 cm contain more than 50% of available water for the crop between the uncorrected maximum and minimum values of available water at the time of calibration. The bulk of the plant roots reside in this layer. The calibration curves (Eqs. 22 & 23 and Figs. 114 & 115) could therefore with reasonable accuracy

Table 45. Comparison of observed and calculated per cent VSMC (θ) and the radius of sphere of the importance. Q_J (Eq. 3), for the range of calculated VSMC (θ). (a) for CPN 501, (b) for CPN 503

Calib dates	Depth (cm)	Cr	Obs. θ	Calc θ	% deviat. Obs from calc	Q_J (cm)
(a) for CPN 501						
Dry 19.2.'92	18	0.361	21.95	23.26	-5.97	26.84
	30	0.423	28.52	27.62	+3.14	24.02
	60	0.385	26.35	24.95	+5.31	25.67
	90	0.384	25.34	24.88	+1.82	25.72
	120	0.441	28.62	28.89	-0.95	23.32
	150	0.438	29.48	28.68	+2.72	23.43
	170	0.451	30.93	29.59	+4.32	22.94
Wet 18.6.'92	18	0.706	49.44	47.54	+3.83	16.25
	30	0.712	50.77	47.99	+5.47	16.13
	60	0.593	39.72	39.60	+0.31	18.66
	90	0.577	35.53	38.40	-8.21	19.07
	120	0.614	39.56	41.04	-3.73	18.17
	150	0.622	39.50	41.66	-5.47	17.97
	170	0.587	37.63	39.18	-4.13	18.80
(b) for CPN 503						
Dry 19.2.'92	18	1.251	21.95	23.27	-6.01	26.83
	30	1.446	28.52	28.59	-0.26	23.48
	60	1.340	26.35	25.70	+2.45	25.19
	90	1.369	25.34	26.48	-4.50	24.70
	120	1.484	28.62	29.63	-3.53	22.92
	150	1.370	29.48	26.52	+10.05	24.68
	170	1.406	30.93	27.50	+11.09	24.10
Wet 18.6.'92	18	2.101	49.44	46.42	+6.12	16.55
	30	2.132	50.77	47.25	+6.94	16.33
	60	1.883	39.72	40.46	-1.87	18.36
	90	1.837	35.53	39.21	-10.35	18.79
	120	1.885	39.56	40.52	-2.44	18.34
	150	1.920	39.50	41.47	-4.99	18.03
	170	1.877	37.63	40.31	-7.11	18.41

estimate water requirement by the intercrop at every stage of its development.

The complications due to shrinkage cracks. as the Verto-luvic Phaeozem soils dry up during hot-dry seasons cause heterogeneity of the soils by reducing hydrogen atoms in the cracks as they become filled with air. It should be noted that a correction for constitutional

Table 46. Regression constants for observed and calculated VSMC (θ) at the measuring depths at Matanya. (θ_{calc}= a * Cr + b).

Depth (cm)	b	std err of θ_{est}	r	No obs.	a	std err of a
18	-9.62	1.58	0.995	6	83.77	4.12
30	-2.30	1.53	0.992	6	74.04	4.68
60	-0.55	1.43	0.988	6	70.30	5.39
90	-5.32	2.28	0.970	7	77.03	8.62
120	2.27	0.81	0.992	7	61.79	3.52
150	3.17	1.88	0.957	7	62.81	8.52
170	-0.87	1.58	0.973	7	69.69	7.40

Table 47 Calculations of available water from (a) observed (ring samples) and (b) calculated (regression line, Eq. 22 for CPN 501) soil moisture. (NB: 1 % vol. water = 1 mm of water per 10 cm soil depth).

(a) Observed (%)							
Depth (cm)	thick. (cm)	Field capac	Wilt. point	Avail water	mm water	cumul water	% vol of total available water
0-25	25	49.4	22.0	27.4	69	69	26.9
25-45	20	50.8	28.5	22.3	45	114	17.4
45-75	30	39.7	26.4	13.3	40	154	15.7
75-100	25	35.5	25.3	10.2	25	179	10.0
100-130	30	39.6	28.6	11.0	33	212	12.9
130-160	30	39.5	29.5	10.0	30	242	11.8
160-180	20	37.6	30.9	6.7	13	255	5.3
					Total		100.0

(b) Calculated (%)

Depth (cm)	thick. (cm)	Field capac	Wilt. point	Avail. water	mm water	cumul. water	% vol.
0–25	25	47.5	23.3	24.3	61	61	22.2
25–45	20	48.0	27.6	20.4	41	101	14.9
45–75	30	39.6	25.0	14.7	44	145	16.0
75–100	25	38.4	24.9	13.6	34	179	12.4
100–130	30	41.0	28.9	12.2	36	216	13.3
130–160	30	41.7	28.7	13.0	39	255	14.2
160–180	20	39.2	29.6	9.6	19	274	7.0
					Total		100.0

hydrogen was not applied because the montmorillonite content of our clay soils was not known. However, this correction is small for our type of soil (Ibrahim, 1992). The only correction applied was that for a change of bulk density with depth, which appeared also to be small (see below).

4.2.1 (b) Relationship between bulk density (Bd) and soil moisture at Matanya

We could propose the following from the results obtained by directly regressing bulk density (Bd) on soil moisture using calibration data (see Figs. 116–122 and Table 48):

(i) that on average the higher scatter of dry bulk density at lower VSMC (θ) than at higher VSMC (θ) must be due to contraction of the Verto-luvic phaeozem soils on drying thereby forming shrinkage cracks and lumps (clods) which get filled with air thus inducing heterogeneity in dry seasons and relatively more homogeneous soil under wet conditions.

(ii) dry bulk density slightly decreases with increasing VSMC (θ) due to swelling of the vertisols. For example, the change in bulk density at 18 cm and 170 cm with soil moisture content was relatively

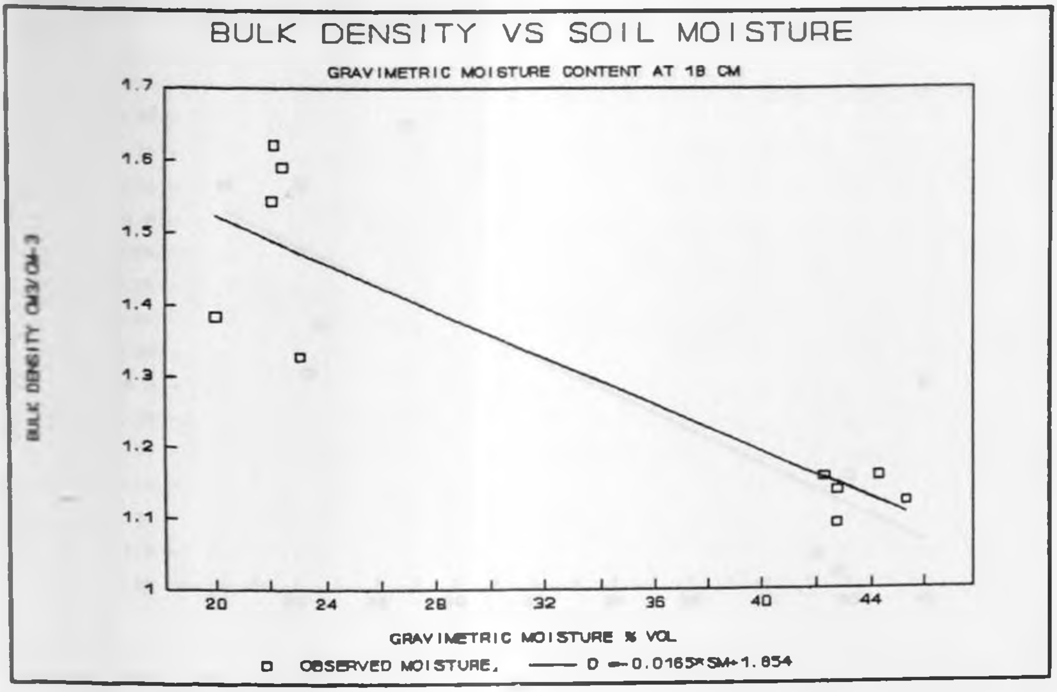

Fig. 116. Bulk density versus soil moisture at 18 cm depth

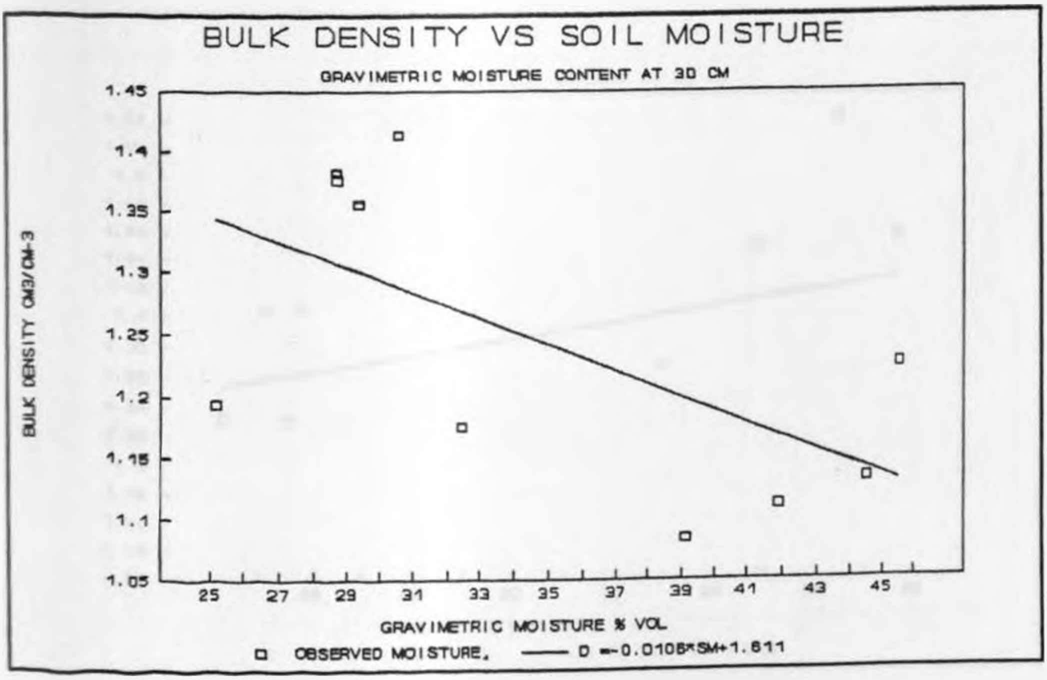

Fig. 117. Bulk density versus soil moisture at 30 cm depth

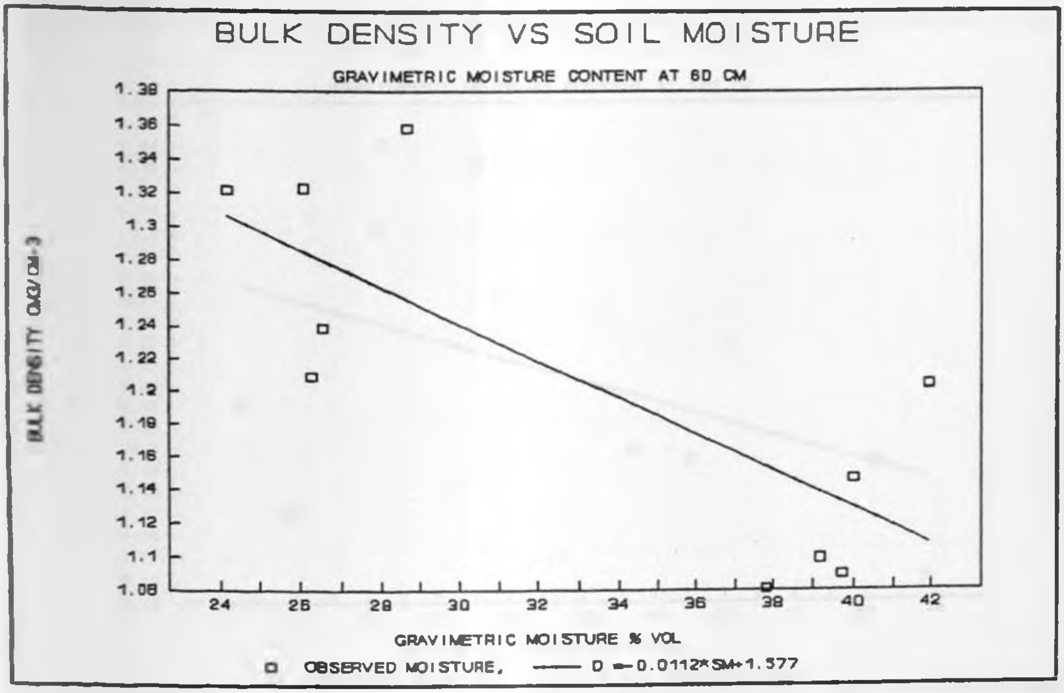

Fig. 118. Bulk density versus soil moisture at 60 cm depth

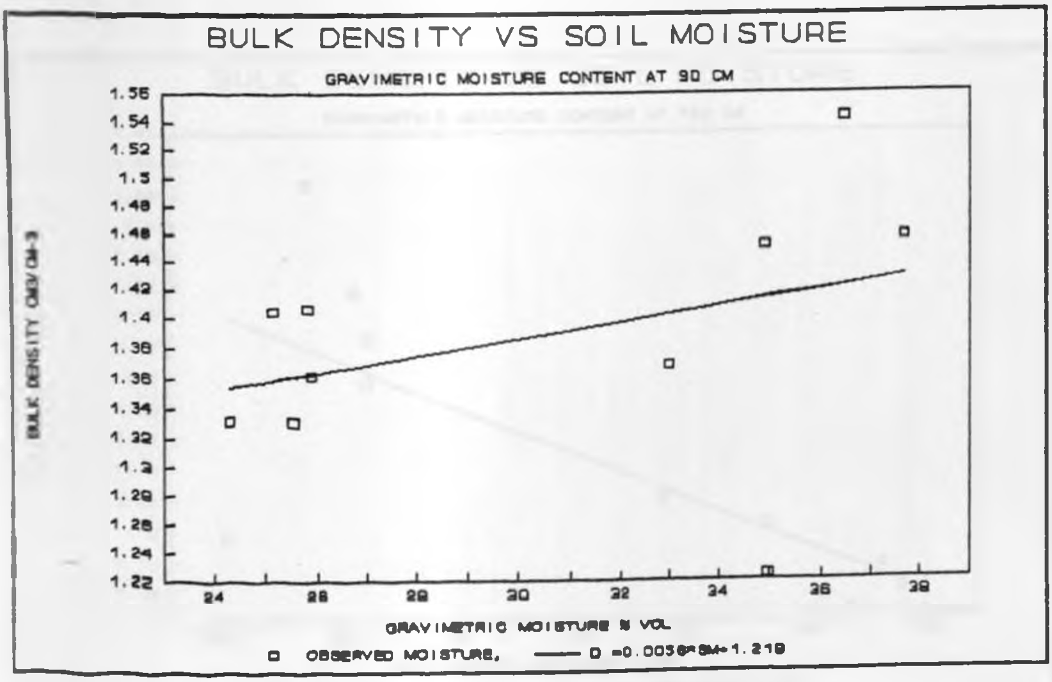

Fig. 119. Bulk density versus soil moisture at 90 cm depth

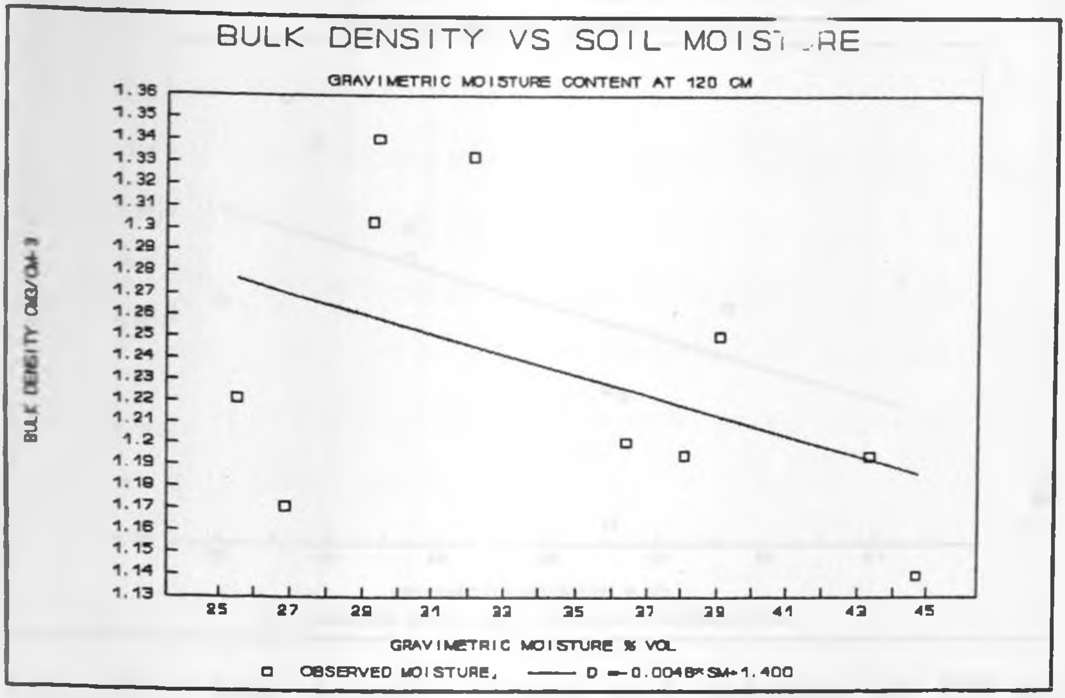

Fig. 120. Bulk density versus soil moisture at 120 cm depth.

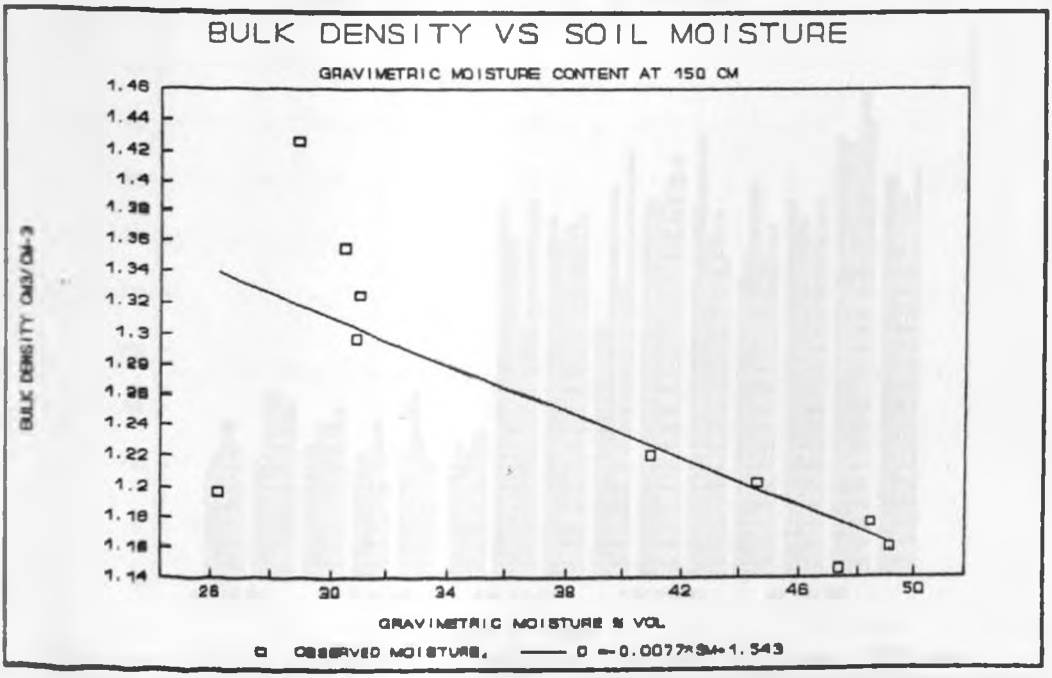

Fig. 121. Bulk density versus soil moisture at 150 cm depth

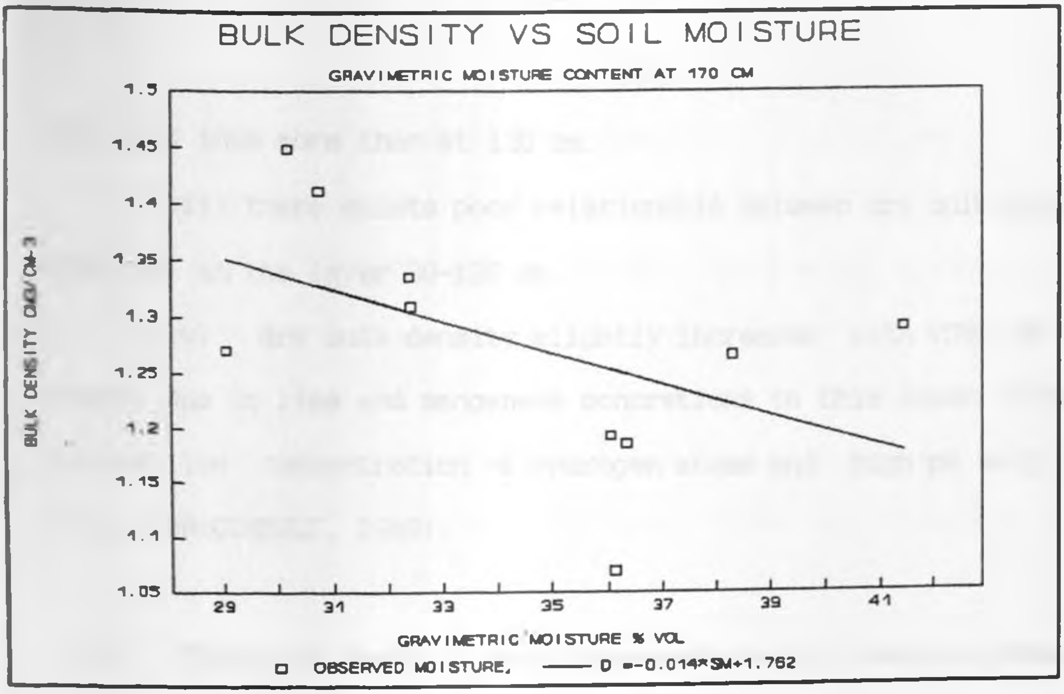

Fig. 122. Bulk density versus soil moisture at 170 cm depth

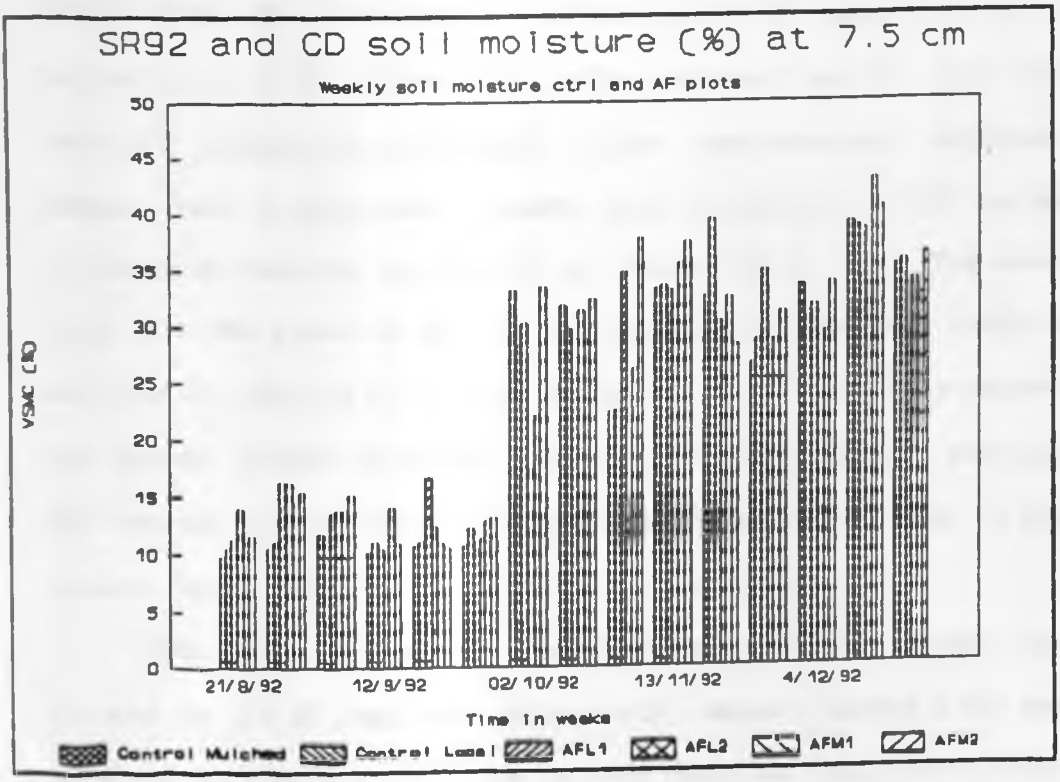

Fig. 123. Weekly VSMC (%) for the cool dry season and SR92 obtained from soil samples and oven-dried at a temperature of 110° C taken at 7.5 cm depth in AF and the control plots.

240% and 180% more than at 120 cm.

(iii) there exists poor relationship between dry bulk density and VSMC (θ) in the layer 30-120 cm.

(iv) dry bulk density slightly increases with VSMC (θ) at 90 cm depth due to lime and manganese concretions in this layer, because they contain low concentration of hydrogen atoms and high pH (e.g. Liniger, 1991, EUROCONSULT, 1989).

4.2.2 Choice of depth to start measurements with neutron probe.

The depth at which we start to take soil moisture measurements with a neutron meter (probe) depends on the sphere of importance, Q_s, of the probe. From Eq. 3 the radius of the sphere of importance is inversely proportional to θ. Tables 45a & 45b (columns 5 and 7) show that during very dry conditions in Matanya there was more soil moisture in the deeper than in shallower layers, with exceptions at 30 cm depth (see calibration results of 19.2.92 in Tables 45a & 45b). The reverse was true (in the first 30 cm) in the case of the very wet conditions (see calibration results of 18.6.92 in Tables 45a & 45b). This suggested that the deeper layers could not sufficiently reach dryness even during the dry periods. Q_s was therefore larger near the surface than in the deeper layers. Again the reverse was true for the wet period.

From Table 45a, we see that when the calculated θ near the surface dropped to 23.3% (smallest value in dry season) during a dry season, as occurred in February 1992, the minimum depth we could get accurate soil water measurements was 26.8 cm below the surface. The largest Q_s of about 26.8 cm could be obtained during extremely dry conditions only, when the soil surface would lose all its vegetation cover made up of mainly grass. In fact the wilting of such grass indicates the wilting point in the layers in which they root.

During the wet calibration exercise, we simulated an extremely wet seasons, which, though extremely rare, occurs in 1 out of 5 years, according to the local farmers. The lowest θ calculated under such very wet conditions was 38.4% (smallest value in wet season) at 90 cm depth. The Q_s calculated for this VSMC was 19.1 cm. The minimum depth the CPN 501 could measure accurately, had such conditions occurred, could be 19.1 cm below the surface.

Table 48. Relationship between dry bulk density (Bd) and VSMC (θ) obtained during calibration exercise. 10 samples at each depth (i.e. 5 for dry and 5 for wet calibrations), (Bd = c * θ + d).

Depth (cm)	Bd	std err of Bd_{est}	r	c	std err. of c
18	1.85	0.098	0.897	−0.017	0.003
30	1.61	0.104	0.626	−0.011	0.005
60	1.58	0.068	0.781	−0.011	0.003
90	1.22	0.086	0.351	0.006	0.005
120	1.40	0.066	0.469	−0.005	0.003
150	1.54	0.067	0.747	−0.008	0.002
170	1.76	0.102	0.504	−0.014	0.009
0−170	1.64	0.101	0.636	−0.011	0.002

The shallowest depth used by LRP in routine soil moisture measurement at their stations, including Matanya was 18 cm. This would be equivalent to a θ of 41.56 %, if the sphere of importance would touch the surface. In a semi-arid area like Matanya, this could be approached during a very good rainy season, when the soils are very wet. Otherwise, for most of the seasons this would not be correct. The neutron probe measurements taken at 18 cm depth were therefore subjected to 1.9% and 20.3% errors for wet and dry conditions respectively.

For continuity and convenience we continued taking neutron probe data from 18 cm depth and making appropriate adjustments in the 18 cm depth data for weekly soil sampling in the AF and NAF plots. In fact we should have used 30 cm in the dry season and 20 cm in the wet season.

4.2.3 Soil moisture sampling at Matanya

4.2.3 (a) VSMC at different depths and distance from *Grevillea robusta* trees.

(i) Variations of weekly VSMC with depth and distance from Pruned trees for 1992.

We examined VSMC for different years and six seasons, each for the seven depths already mentioned above and came to the conclusion that LR92 represents the driest season while SR92, the only season when we harvested maize grain yields and had the highest beans yields, represents the wettest season of our study period. For the bigger part of this section we present results of these two seasons but where desirable, we do make reference to the other four.

Fig. 123 gives weekly VSMC at a depth of 7.5 cm (surface) for the cool dry season (CD) and Short Rains of 1992 (SR92) as obtained from soil samples that were taken in experimental plots in AF and control and oven dried at a temperature of 110° C. The general picture here shows that the soil at 7.5 cm depth was very dry during CD and as expected quite wet during SR92. We can notice from this figure that the control plots were drier than the AF plots during CD, but became wetter during early periods of SR92. The dryness during CD may have been due to strong winds which desiccated the top soil in the unsheltered control plots. This also made CD have lower soil moisture at the surface than the hot dry season (January-early March) HD. This was also observed in 1993 data presented in Appendix Fig. A4 and Appendix Table A4. Relative weekly VSMC in AF show that pruned AF plots (AFM1 & AFL1) had less VSMC than unpruned. It should be noted here that soil samples were taken at the edges of each AF plots to avoid perforating the soil next to the trees and therefore interfering with the whole exercise. Pruning effects at this edges were not noticed.

Figs. 124-129 give variations of weekly VSMC with days of the year and distance from pruned *G. robusta* trees for the year 1992. These cover also weekly VSMC for LR92 and SR92 and two dry seasons (i.e. hot dry season (HD) of January-early March, LR92 and cool dry season (CD) from mid-June to end of September for the four depths of agronomic importance which have highest concentrations of bean and maize roots, namely 18, 30, 60 and 90 cm. From climatological estimates (e.g. Oteng'i, 1982) we here take HD to be DOY: 1-75, CD to be DOY: 168-274, LR to be DOY: 76-167 and SR to be DOY: 275-366. Calibration eqs. 22a & 22b were used to obtain calculated VSMC. Note that there were no data on DOY 276 as our neutron probe broke down and had to be repaired.

We see in Fig. 124-129 that at 94, 188 and 376 cm from pruned tree PT1, in upper part of AF, the VSMC was low at all the depths except 30 cm. The highest VSMC at 18 cm depth was recorded during LR92 between DOYs 122 and 157. At this time the intercrop which was planted on DOY 83 was in flowering phase (see section 4.1). The VSMC having passed the peak on DOY 129 was sharply dropping causing water stress which was evident on the plants by DOY 153. VSMC at 30 cm depth continued to be high for the three distances from PT1. The VSMC at 30 cm deviated very little from its mean values prior to DOY 280 even during LR92 rainy

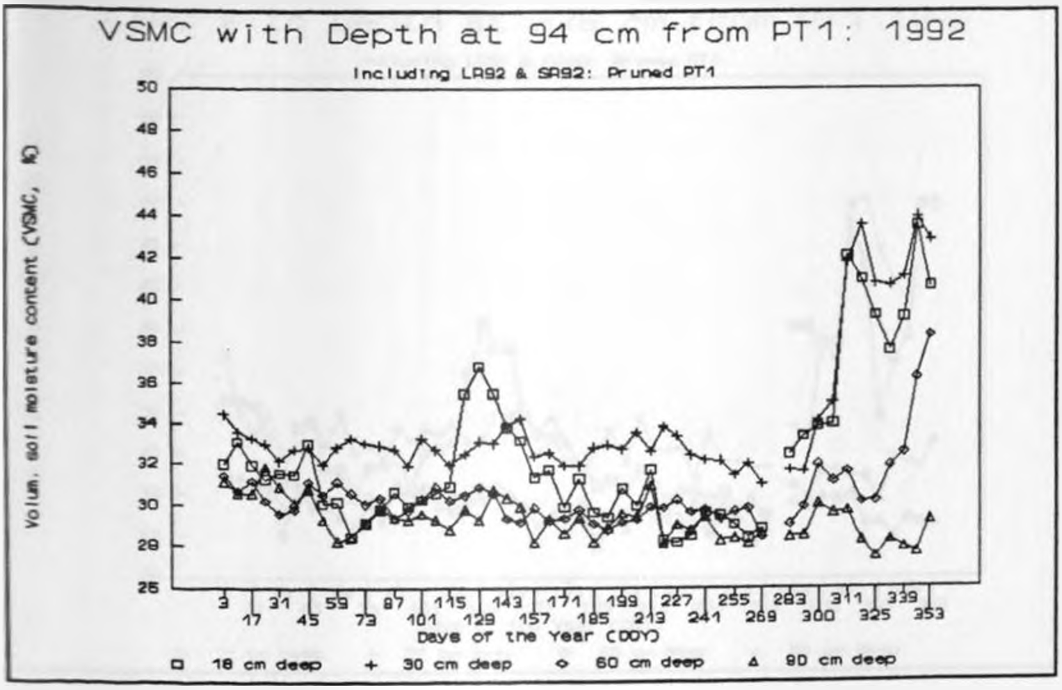

Fig. 124. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 94 cm from *G. robusta* trees, PT1, in pruned plot (AFM1).

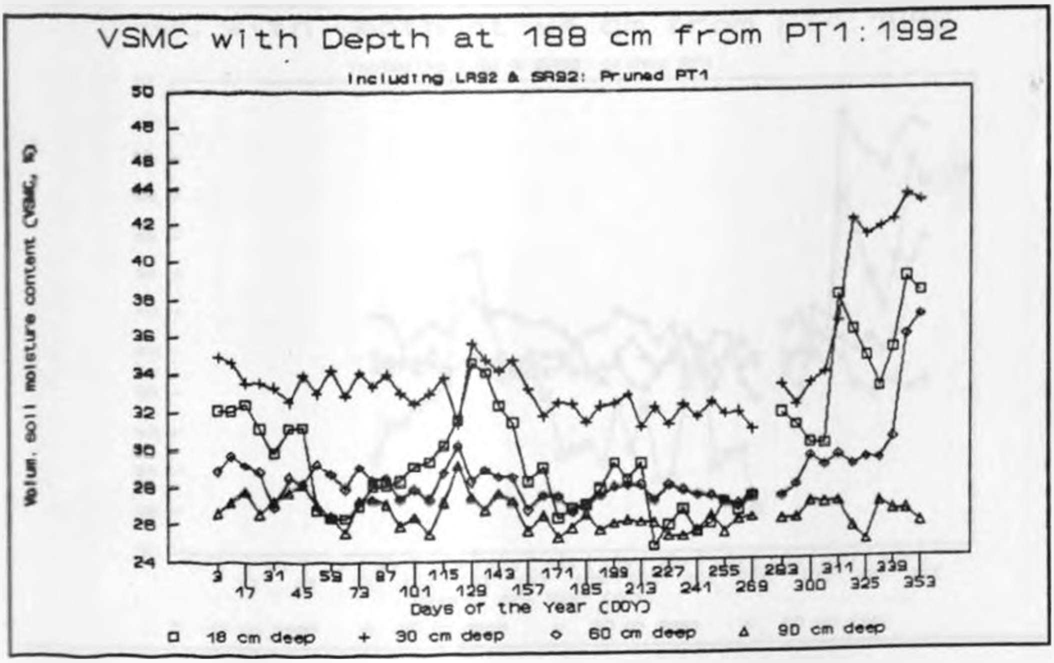

Fig. 125. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 188 cm from *G. robusta* trees, PT1, in pruned plot (AFM1).

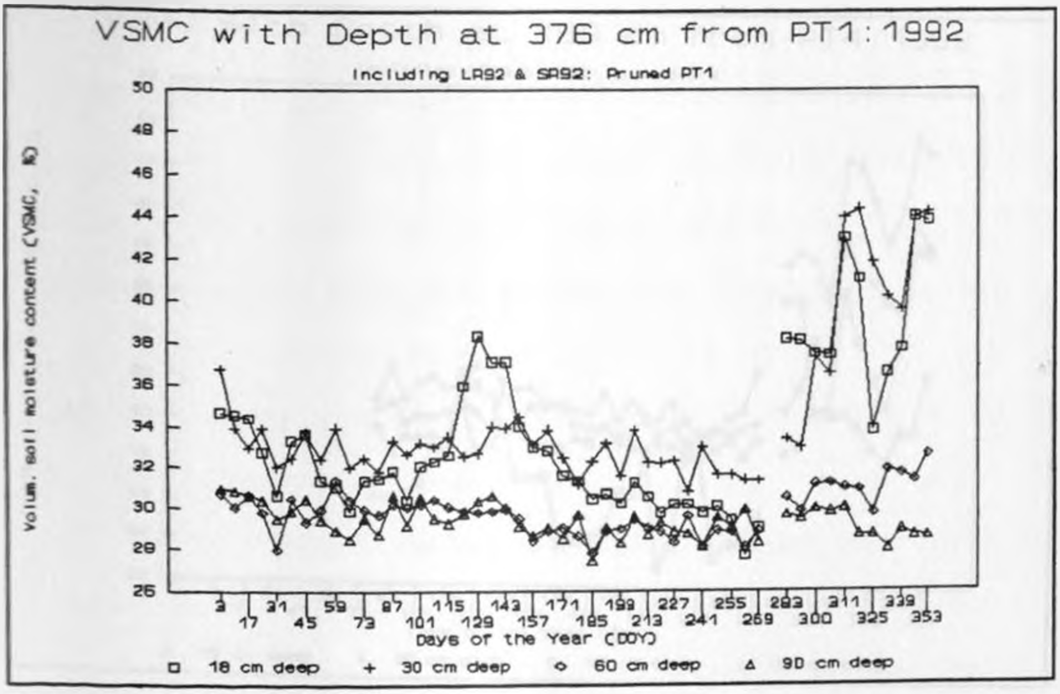

Fig. 126. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 376 cm from *G. robusta* trees, PT1, in pruned plot (AFM1).

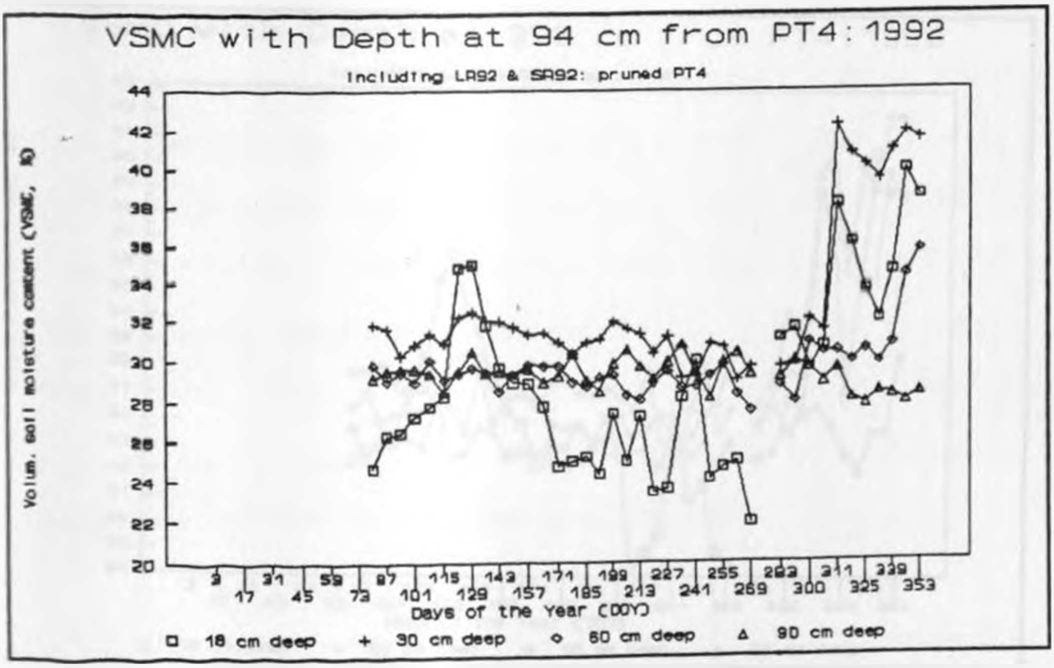

Fig. 127. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 94 cm from *G. robusta* trees, PT4, in pruned plot (AFM1).

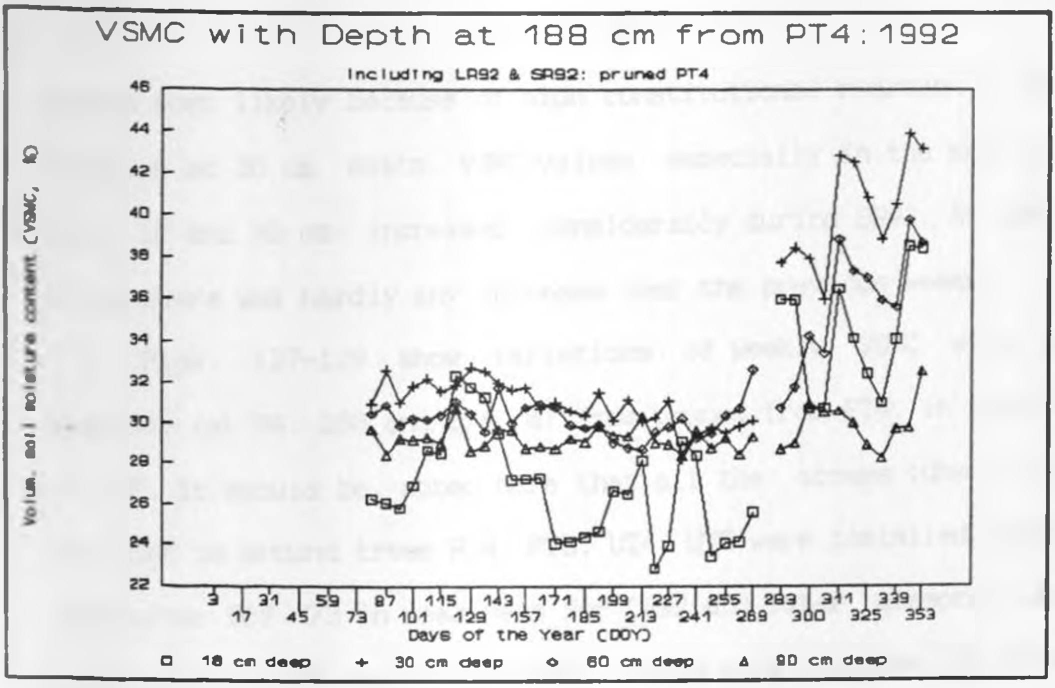

Fig. 128. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 188 cm from *G. robusta* trees, PT4, in pruned plot (AFM1).

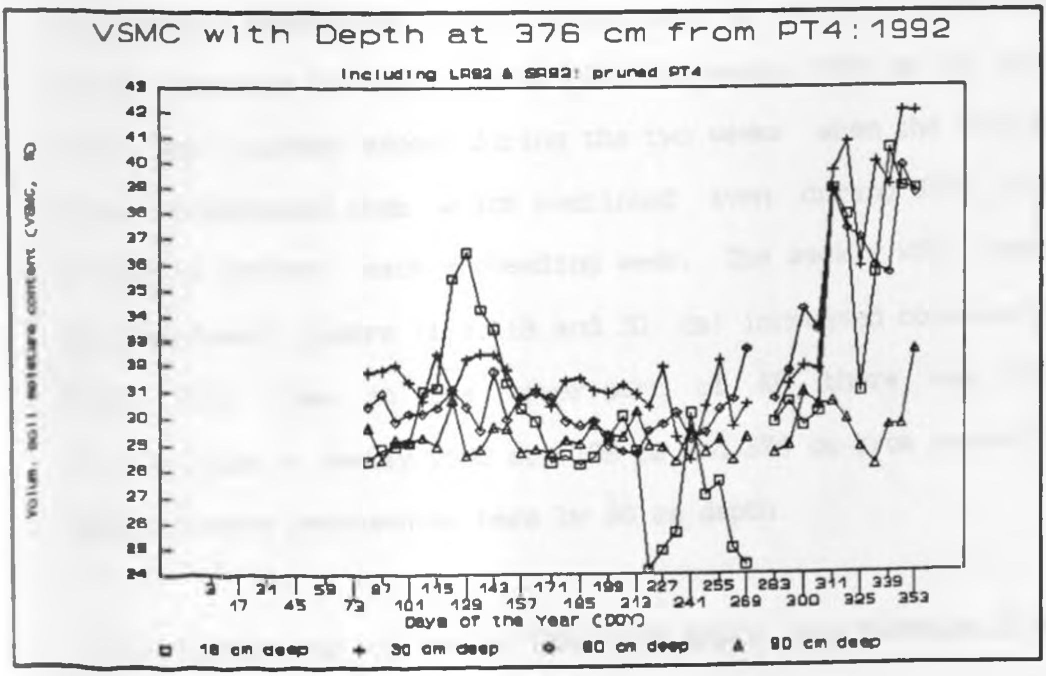

Fig. 129. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 376 cm from *G. robusta* trees, PT4, in pruned plot (AFM1).

season most likely because of high constitutional hydrogen in the clayey fraction at 30 cm depth. VSMC values especially in the shallow layers (i.e. 18 and 30 cm) increased considerably during SR92. At the depth of 90 cm there was hardly any increase over the previous weeks.

Figs. 127-129 show variations of weekly VSMC with depth and distance (at 94. 188 and 376 cm) from pruned from PT4. in the lower part of AF. It should be noted here that all the access tubes in the lower AF. that is around trees PT4. PT5. UT4. UT5 were installed later in year 1992 after DOY 73 in readiness for LR92 and later seasons. Like in the upper part of AF very high VSMC values were recorded at 18 cm depth during LR92 between DOYs 115 and 143 which peaked on DOY 136 and suddenly dropped. Six weeks prior to the period of highest values the weekly VSMC were very low and continued that way but with considerable fluctuation thereafter. High fluctuations at 18 cm were maximum values at the distance of 188 cm from PT4. The weekly VSMC at 30 cm depth was still the highest except during the two weeks when the values at 18 cm depth superseded them which continued even during SR92 and differed minimally between each succeeding week. The weekly VSMC especially in the shallower layers (i.e. 18 and 30 cm) increased considerably during SR92. This time in the lower part of AF there was considerable fluctuations in weekly VSMC at 188 cm and 376 cm from pruned PT4 in the deeper layers represented here by 90 cm depth.

(ii) Variations of weekly VSMC with depth and distance from unpruned trees for 1992.

Figs. 130-135 give variations of weekly VSMC as above but for unpruned *G. robusta* trees. We see in Fig. 130-132 that at 94. 188 and

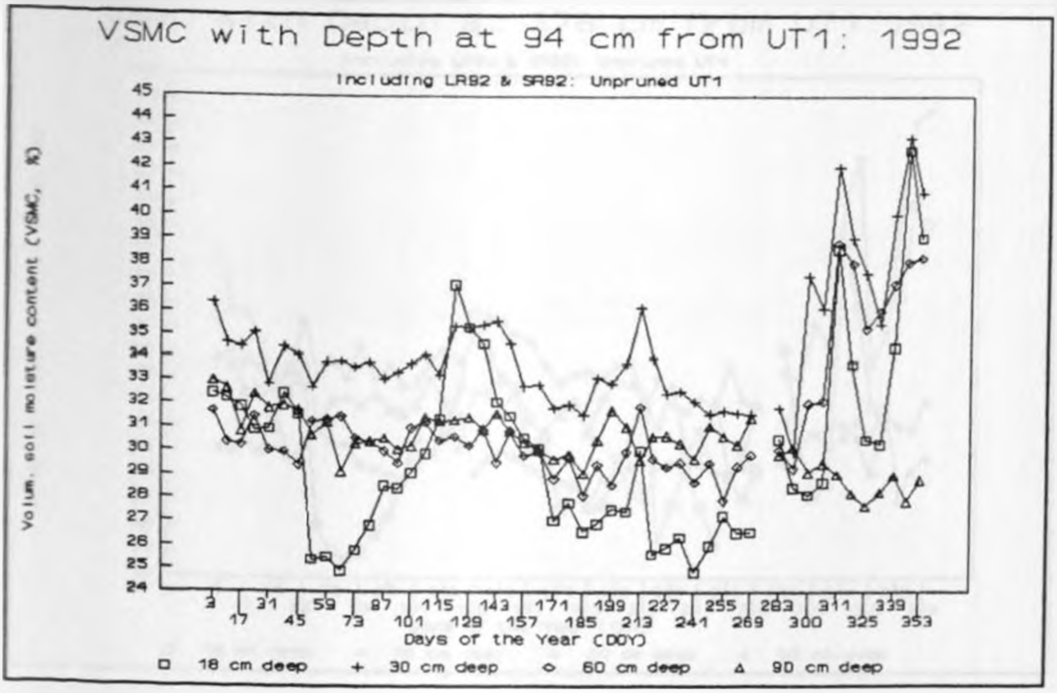

Fig. 130. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 94 cm from *G. robusta* trees, UT1, in unpruned plot (AFM2).

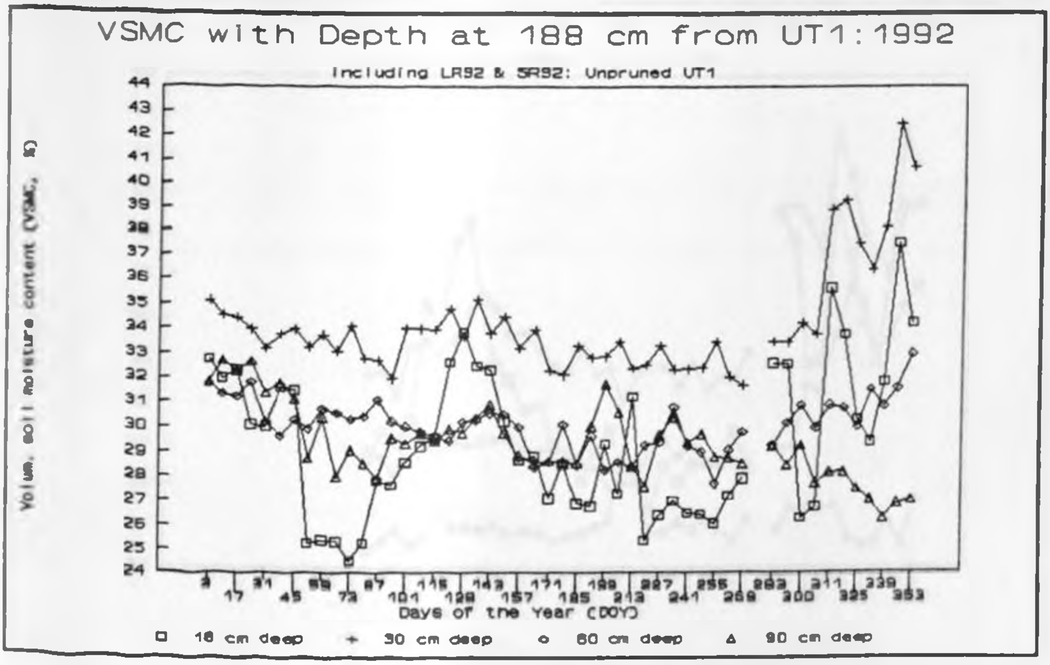

Fig. 131. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 188 cm from *G. robusta* trees, UT1, in unpruned plot (AFM2).

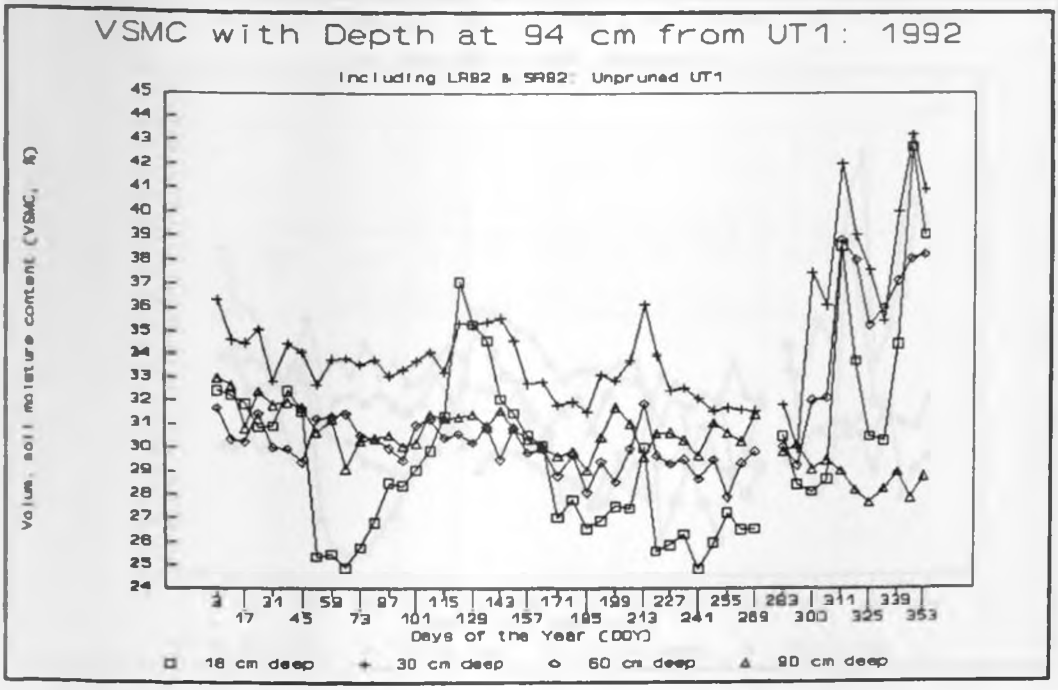

Fig. 130. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 94 cm from *G. robusta* trees, UT1, in unpruned plot (AFM2).

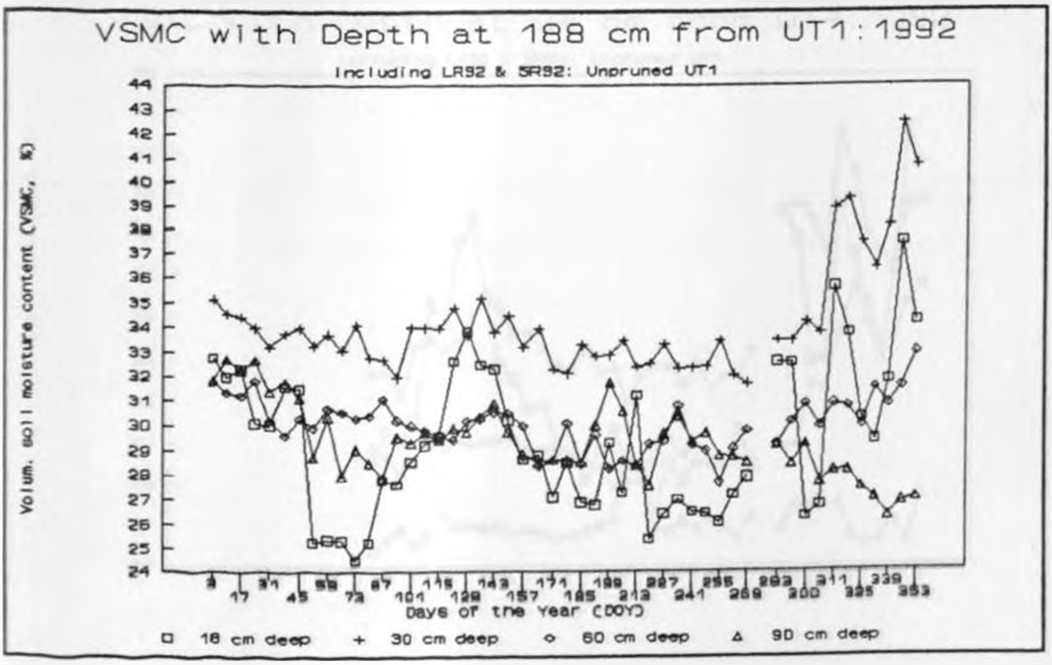

Fig. 131. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 188 cm from *G. robusta* trees, UT1, in unpruned plot (AFM2).

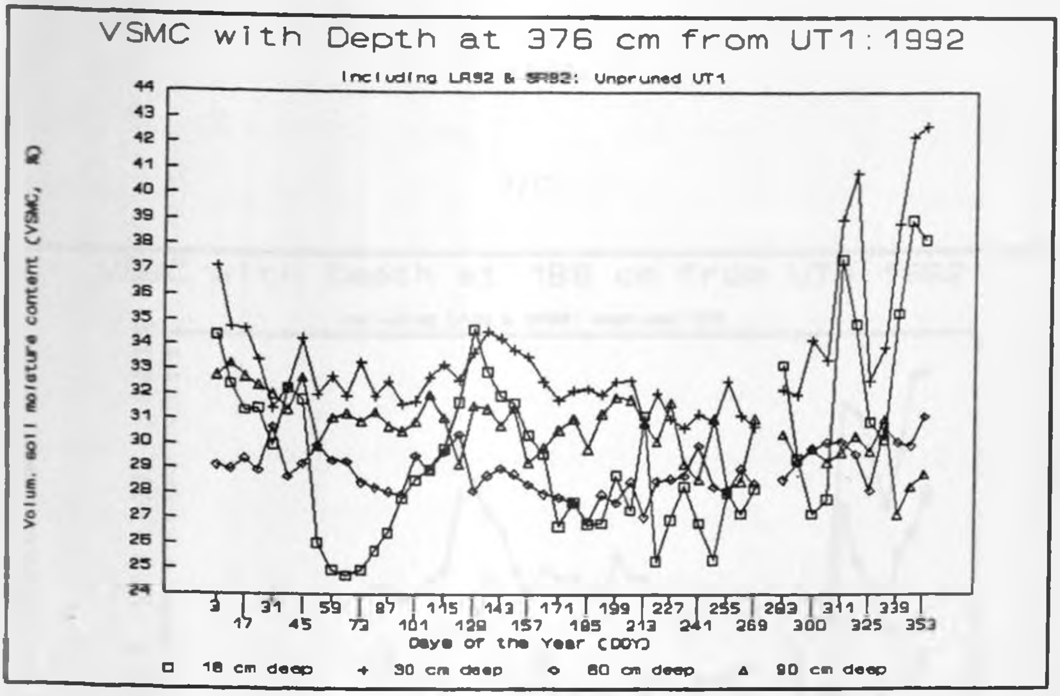

Fig. 132. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 376 cm from *G. robusta* trees, UT1, in unpruned plot (AFM2).

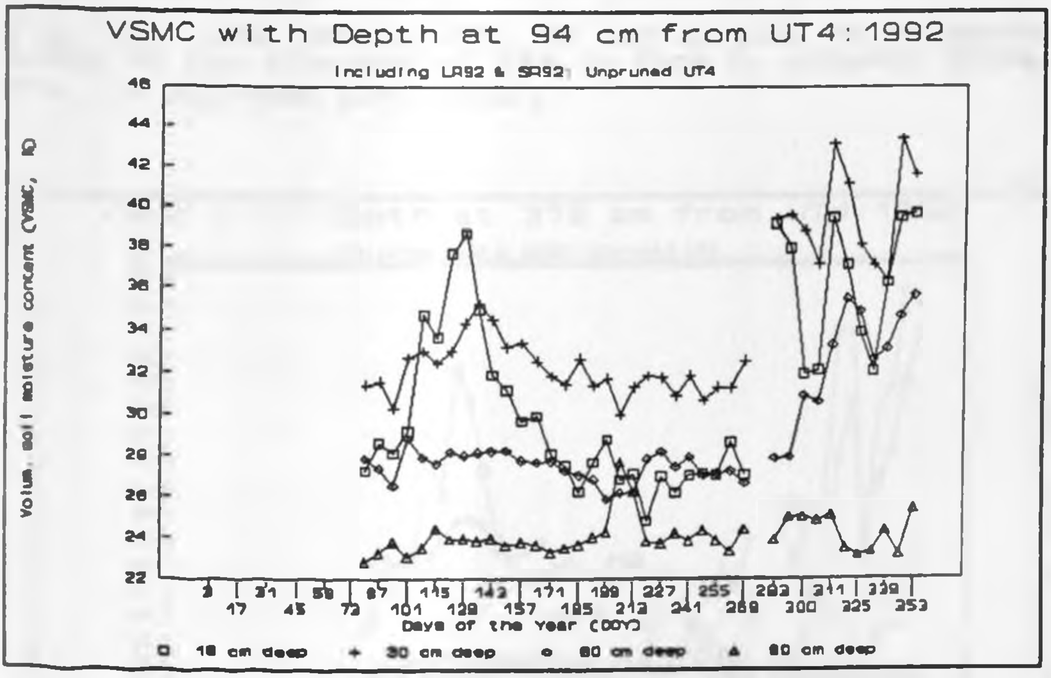

Fig. 133. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 94 cm from *G. robusta* trees, UT4, in unpruned plot (AFM2).

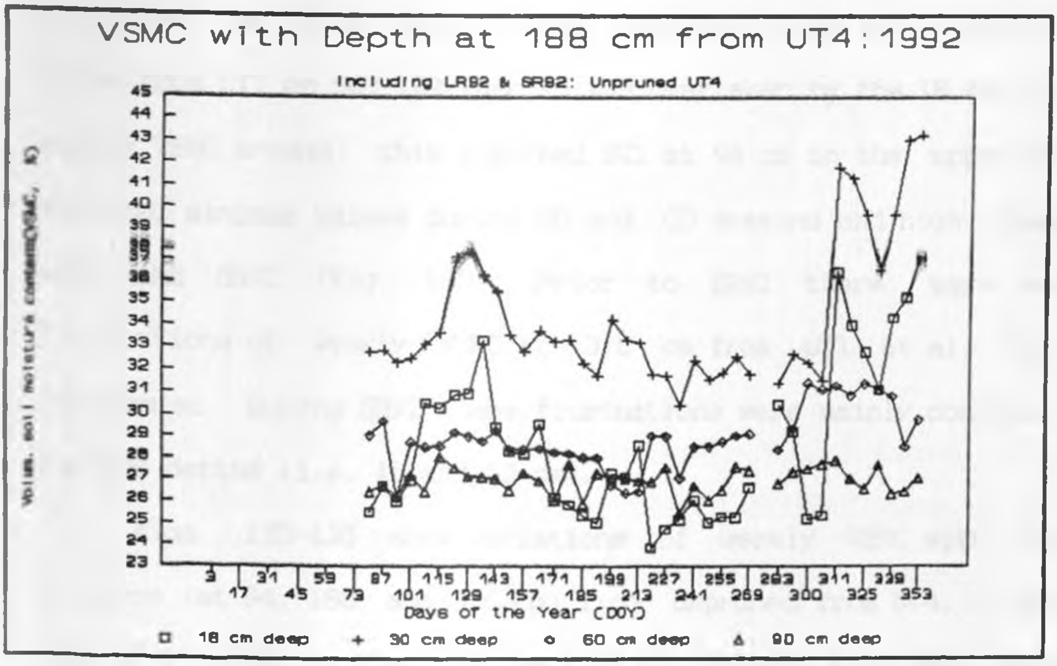

Fig. 134. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 188 cm from *G. robusta* trees, UT4, in unpruned plot (AFM2).

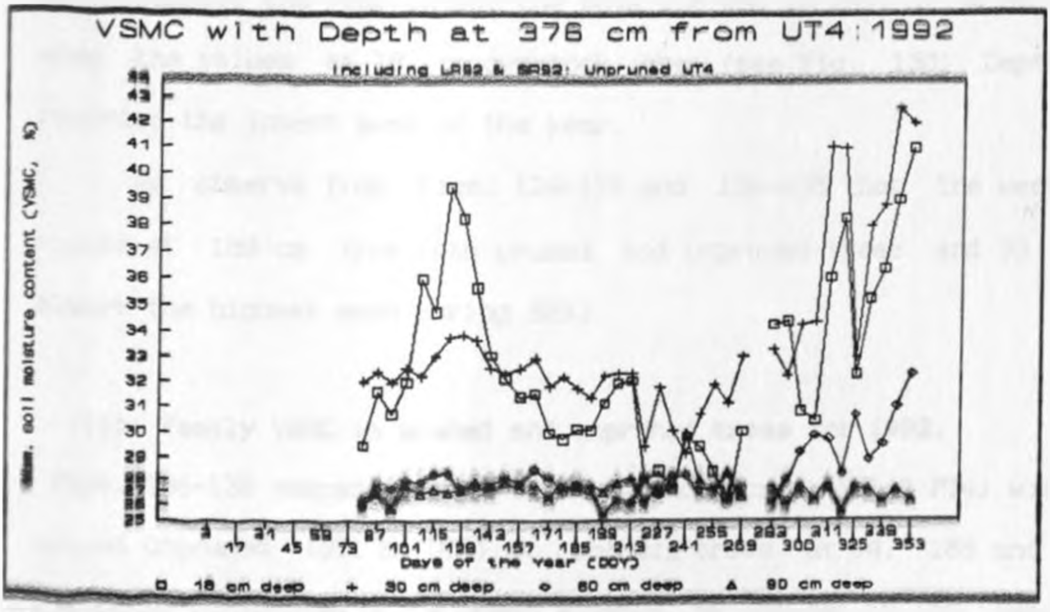

Fig. 135. 1992 weekly VSMC (%) for 18 till 90 cm depths taken at the distance of 376 cm from *G. robusta* trees, UT4, in unpruned plot (AFM2).

376 cm from unpruned tree UT1, in upper part of AF, the weekly VSMC at 18 and 30 cm depths prior to SR92 fluctuated more than in the pruned tree case. The 30 cm depth values continued to be the highest except at 94 cm from UT1 on DOY 122 when it was overtaken by the 18 cm value. The weekly VSMC around this unpruned UT1 at 94 cm in the upper part of AF attained minimum values during HD and CD seasons and high values during LR92 and SR92 (Fig. 130). Prior to SR92 there were very high fluctuations of weekly VSMC at 376 cm from UT1 at all the depths considered. During SR92 these fluctuations were mainly confined to the surface depths (i.e. 18 and 30 cm).

Figs. 133–135 show variations of weekly VSMC with depth and distance (at 94, 188 and 376 cm) from unpruned from UT4, in the lower part of AF. Like in the upper part of AF the very high VSMC values were recorded at 18 cm depth between DOYs 101 and 150, hence included the period experienced under UT4. The highest VSMC were again recorded at 30 cm throughout the year except the DOYs 108–136 in LR92 at 94 cm from UT4 when the values at 18 cm overtook them (see Fig. 130). Depth 90 cm recorded the lowest most of the year.

We observe from Figs. 124–129 and 130–135 that the weekly VSMC values at 188 cm from both pruned and unpruned trees and 30 cm were always the highest even during SR92.

(iii) Weekly VSMC in pruned and unpruned trees for 1992.

Figs. 136–138 compares weekly VSMC around pruned (PT1 & PT4) with that around unpruned (UT1 & UT4) *G. robusta* trees at 94, 188 and 376 cm distances in Mulched plots (AFM1 & AFM2). We can see in Fig. 136 that weekly VSMC at 94 cm from pruned PT1 was the highest for most of the

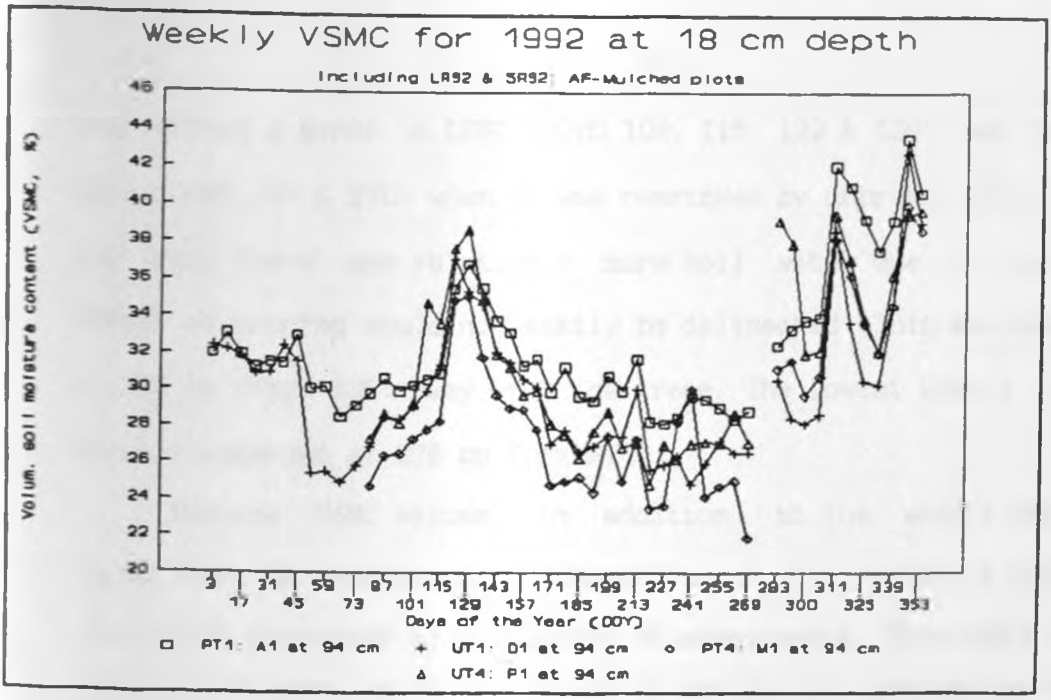

Fig. 136. 1992 weekly VSMC (%) for 18 cm depth taken at the distance of 94 cm from *G. robusta* trees (PT1, PT4, UT1 & UT4) in pruned and unpruned plots (AFM1 & AFM2).

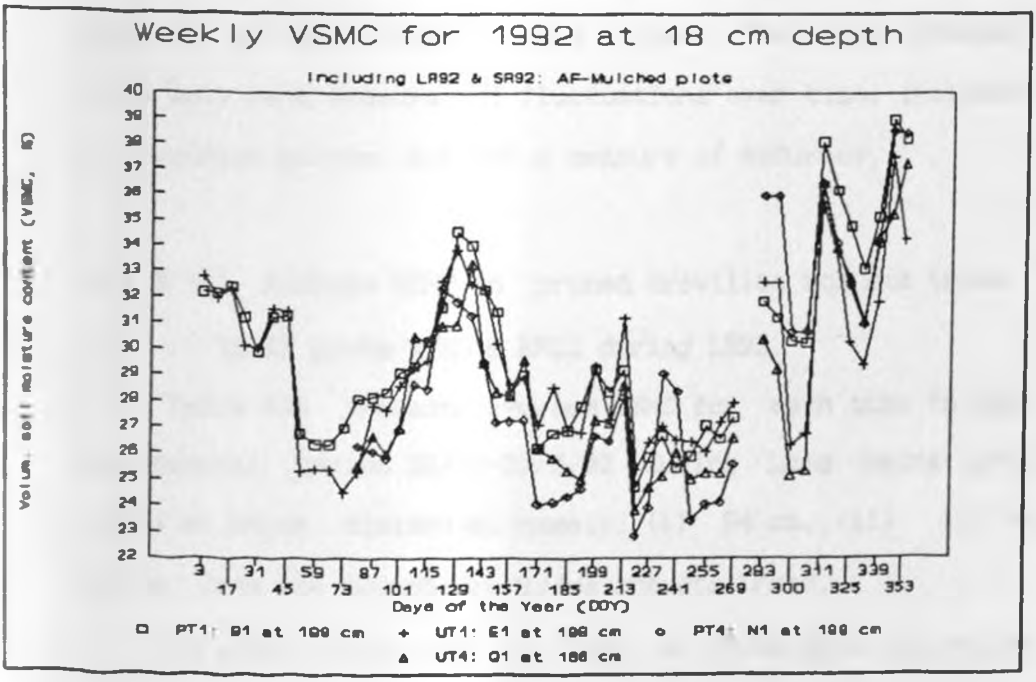

Fig. 137. 1992 weekly VSMC (%) for 18 cm depth taken at the distance of 188 cm from *G. robusta* trees (PT1, PT4, UT1 & UT4) in pruned and unpruned plots (AFM1 & AFM2).

year except a month in LR92 (DOYS 108, 115, 122 & 129) and two weeks in SR92 (DOYS 283 & 290) when it was overtaken by unpruned UT4. During LR92 and SR92 there was relatively more soil water due to rains and the effect of pruning could not easily be delineated. This was also observed at 376 cm (Fig. 138) away from the trees. The lowest weekly VSMC during HD were observed at 376 cm from PT4.

Average VSMC values, in addition to the weekly data we gave above, may be considered an integration of soil moisture behaviour for the period concerned at the depths of measurement. This means that their averages as given in Tables 49 and 50 are giving indications of average soil moisture as a function of distance to the trees. Accuracy limits are those combinations from the values averaged, where each value has a maximum error of ±10%, but of course each measurement done in one weekly sampling is independent of the others. Therefore standard deviations would only be a measure of fluctuations over time, including those due to measuring errors, but not a measure of accuracy.

4.2.3 (b) Average VSMC in pruned Grevillea robusta trees in AF plots AFM1 & AFL1 during LR92.

Table 49a presents average VSMC for each tube in the AF for the experimental period 20/3/-29/5/92 during Long Rains growing season (LR92) at three distances, namely; (i) 94 cm, (ii) 188 cm, and (iii) 376 cm, from the pruned *Grevillea robusta* trees.

We see in Table 49a (i) that, at 94 cm from the pruned trees, the largest average VSMC of 33.11 was observed at 170 cm depth in tube A3 around Grevillea tree PT3 in the middle part of the agroforestry plot (AF). The soil moisture in such a depth may not be of any use to the intercrop whose maximum rooting density hardly goes below 60 cm. PT3 was situated on the border between mulched (AFM1) and Local (AFL1) plots (see Fig. 9). The smallest VSMC of 24.78 was observed at 18 cm depth in tube M2 in the lower part of AFL1.

Intercomparisons of the tubes at 94 cm from the pruned trees in the first four layers, that is 18, 30, 60 and 90 cm depths (see Table 49a(i)) we notice that the largest VSMC of 32.78 was recorded in tube A3 around PT3 at 30 cm depth at the AFM1/AFL1 border while the smallest VSMC of 24.78 was recorded at 18 cm depth in tube M2 around pruned PT5. Tube A1 at PT1 had generally high average VSMC, that is 32.05 at 18 cm depth, 32.66 at 30 and 30.17 at 60 cm depths. In comparison M2 had generally the lowest VSMC values especially in the first four depths which had maximum intercrop root density. Considering all the seven depths higher values were found in the first four depths and at below 90 cm depth which was beyond the beans rooting depth and only reached by few maize roots. The lowest VSMC values were at 90 cm depth. On the whole we observe from Table 49 that at 94 cm from the pruned Grevillea trees VSMC was higher at the deeper layers for M2 but not per se for the other trees. The surface layers above 90 cm, except 30 cm depth with an average VSMC of 31.37, had lower VSMC than the deeper layers. The maximum average VSMC of 31.96 was observed in the deeper layers at 120 cm depth, the minimum at the top.

We see in Table 49a(ii) that at 188 cm from the pruned trees the average VSMC of 33.03 recorded at 30 cm depth in tube B1 around PT1 was the largest for that distance in pruned area at the first four depths. The smallest VSMC at 188 cm was recorded at 18 cm in tube N2 around PT5 in AFL1. Tubes B1, B2 and B3 in the upper part of AF had generally high VSMC values in the first three depths. In comparison tubes around PT4 and PT5 tended to have lower values in the upper layers than those tubes around PT1, PT2 and PT3. Again for the seven depths high average VSMC values were found in the first three depths and below 90 cm depth which was of little agronomic value to the intercrop especially beans. The lowest VSMC values were at 90 cm depth. On the whole we observe from Table 49a(ii) that at 188 cm from the pruned Grevillea trees the deeper layers had more soil moisture than the shallower layers. Again, and even more pronounced, the exception was 30 cm depth with an average of 32.18. The same inference may be observed in Figs. 124-129 and 130-135. The other values are close to the average with 60 and 90 cm somewhat lower. The lower VSMC in the layers 60-90 cm depths are due to soil texture. We earlier pointed out in chapter 2 that these layers are composed of alkaline soils mainly of lime. These soils have a tendency to retain fewer hydrogen atoms and drains fairly fast during dry rainy seasons, hence more useful to crop in terms of soil water conservation.

We observe in Table 49a(iii) at 376 cm from the pruned trees that both the largest and smallest average VSMC of 33.60 and 28.61 respectively were recorded in tube O1 around Grevillea tree PT4 in the lower part of mulching plot (AFM1) at 120 and 90 cm depths respectively (see Fig. 9). Intercomparisons of the tubes at 376 cm from the pruned trees for the first four depths shown in Table 49a(iii) the highest VSMC of 33.25 was recorded at 18 cm depth in tube C1. The smallest VSMC of 28.61 was recorded at 90 cm in tube O1 around PT4 in AFM1. Most tubes recorded average VSMC of more than 30% in the depths shallower than 90 cm. Most soil water had drained gravitationally into the deeper layers where it was of little agronomic value. Of the four depths of agronomic importance the 18 and 30 cm depths had higher moisture content than 60 and 90 cm depths. The tubes around PT4 and PT5 had higher VSMC at 18 and

60 cm depths than in the layers 90 and 150 cm deeper.

4.2.3 (c) Average VSMC in unpruned Grevillea robusta trees in AF plots AFM2 & AFL2 during LR92

Table 49b presents average VSMC for each tube for LR92 at the same three distances, namely: (i) 94, (i) 188, and (i) 376 cm, from the unpruned *Grevillea robusta* trees.

We see in Table 49b (i) that, at 94 cm from the unpruned trees the average VSMC of 34.14 recorded at 30 cm depth in tube D2 was the largest for the first four layers shallower than 90 cm inclusive. The soil moisture at 60 cm and above is of great agronomic value for both maize and beans. The smallest VSMC in the first four layers was 25.77 observed at 90 cm depth in tube P1 around UT4 in the lower part of AFM2. Again average VSMC less than 30 was recorded at 60 and 90 cm depths in all the tubes. On the whole we again observe from Table 49b(i) that at 94 cm from the unpruned Grevillea trees VSMC was higher at the deeper layers for all the tubes.

We see in Table 49b (ii) that at 188 cm from the unpruned trees the average VSMC of 34.16 recorded at 30 cm depth in tube Q1 around UT4 was the largest for that distance in unpruned area in the first four depths. The smallest VSMC at 188 cm was recorded at 90 cm in tube E3 around UT3 in AFM2. In comparison tubes around UT2 and UT3 had generally lower values in the upper layers than the rest of the tubes. Again higher VSMC values were found below 90 cm depths although such values have little agronomic value to maize/beans intercrop, especially the beans. Again relatively low VSMC values were found at 60 and 90 cm depths. On the whole we observe from Table 49b(ii) that at 188 cm from the unpruned Grevillea trees the deeper layers had more soil moisture than the shallower layers.

We observe in Table 49b(iii) at 376 cm from the unpruned trees that the largest and smallest average VSMC of 33.40 and 28.25 respectively were recorded in tubes R2 at 30 cm depth and R1 at 90 cm. The two tubes were at 376 cm from Grevillea trees UT5 and UT4 respectively (R2 same tube as F3 around UT3). Again most tubes recorded average VSMC of more than 30.00% in the depths of agronomic significance shallower than 90 cm.

Table 49. Average VSMC at different depths and distances from *Grevillea robusta* trees. (a) pruned (AFM1 & AFL1). (b) unpruned (AFM2 & AFL2) plots for LR92 (period: 20/3/-29/5/92).

(a) Pruned AF (AFM1 & AFL1)

(i) Average of tubes at 94 cm

	Depths						
tube	18	30	60	90	120	150	170
A1 avg	32.05	32.66	30.17	29.79	32.10	30.90	31.18
A2 avg	31.13	31.93	29.14	29.76	31.11	31.24	30.51
A3 avg	29.13	32.78	29.73	30.12	31.64	30.73	33.11
M1 avg	30.01	31.91	30.13	30.22	32.48	30.38	27.67
M2 avg	24.78	27.57	28.71	29.61	32.49	29.19	31.22
Avg tub	29.42	31.37	29.58	29.90	31.96	30.49	30.74

(ii) Average of tubes at 188 cm

tube	18	30	60	90	120	150	170
B1 avg	30.62	33.03	28.78	27.66	32.04	30.68	30.96
B2 avg	31.78	32.37	29.13	29.74	30.18	30.86	29.95
B3 avg	30.54	31.85	30.01	30.05	32.64	30.31	31.29
N1 avg	29.50	32.23	31.02	30.08	31.97	29.84	30.34
N2 avg	27.94	31.43	30.52	29.40	31.97	30.17	31.64
Avg tub	30.08	32.18	29.89	29.38	31.76	30.37	30.84

(iii) Average of tubes at 376 cm

tube	18	30	60	90	120	150	170
C1 avg	33.25	32.67	30.01	29.87	30.59	30.30	30.92
C2 avg	29.35	32.11	30.62	29.58	31.32	32.42	33.33
C3 avg	30.66	33.18	28.67	28.64	32.64	31.28	30.30
O1 avg	32.03	32.13	30.50	28.61	33.60	30.37	30.77
O2 avg	30.66	33.06	28.81	28.64	32.67	31.20	30.24
Avg tub	31.19	32.63	29.72	29.07	32.17	31.11	31.11

(b) Unpruned AF (AFM2 & AFL2)

(i) Average of tubes at 94 cm

	Depths						
tube	18	30	60	90	120	150	170
D1 avg	31.16	33.58	30.42	30.82	30.80	30.68	30.21
D2 avg	32.61	34.14	29.72	29.70	30.72	31.39	29.88
D3 avg	32.58	32.99	28.44	29.17	29.62	29.71	31.75
P1 avg	32.57	33.02	28.90	25.77	29.09	28.63	30.61
P2 avg	33.60	33.85	28.37	29.55	30.58	29.81	28.17
Avg tub	32.50	33.52	29.17	29.00	30.16	30.04	30.12

(ii) Average of tubes at 188 cm

tube	18	30	60	90	120	150	170
E1 avg	30.05	33.14	30.23	29.72	30.41	29.91	30.80
E2 avg	29.47	32.25	28.19	29.75	29.06	29.86	29.41
E3 avg	27.52	32.59	28.64	24.95	24.89	28.99	31.78
Q1 avg	30.69	34.16	29.59	28.19	30.01	29.19	30.59
Q2 avg	31.33	33.53	29.04	30.88	29.36	29.91	29.86
Avg tub	29.81	33.13	29.14	28.70	28.75	29.57	30.49

(iii) Average of tubes at 376 cm

tube	18	30	60	90	120	150	170
F1 avg	30.09	32.50	29.15	30.88	29.05	29.82	31.51
F2 avg	31.29	32.34	28.52	29.52	29.75	30.04	29.84
F3* avg	32.84	33.40	27.92	31.35	29.83	30.16	31.17
R1 avg	33.82	32.88	28.70	28.25	29.04	29.98	31.46
R2* avg	32.84	33.40	27.92	31.35	29.83	30.16	31.17
Avg tub	32.18	32.90	28.44	30.27	29.50	30.03	31.03

* same tube serving two tree replications UT5 and UT3

Because averages are close to each other, and standard deviations meaning that fluctuations and errors remains (see earlier remarks).

4.2.3 (d) Average VSMC in pruned Grevillea robusta trees in AF plots AFM1 & AFL1 during SR92

Table 50a presents seasonal average VSMC for each tube in the AF as discussed above but this time for the experimental period 9/10/92-29/1/93 within the SR92.

We see in Table 50a(i) that, at 94 cm from the pruned trees, the largest average VSMC of 40.28 was recorded at 30 cm depth in tube A1 around Grevillea tree PT1 in the mulched plot. We can see in Figs. 124-129 and Figs. 130-135 that the 30 cm depth had the highest soil moisture throughout the year in dry as well as wet seasons at all distances from the trees, except a few weeks in LR92 as pointed out above. The smallest VSMC of 28.25 was observed at 150 cm depth in tube M2 in the lower part of AFL1 around PT5.

As for LR92 we generally observe low average VSMC values in SR92 at 90 cm depth and high values at 30 cm depths. Tubes A1 at PT1 and M1 at PT4 had generally high average VSMC at all depths. In comparison M2 had generally the lowest VSMC values especially at 60-90 cm layer and 150-170 cm layers. Considering all the seven depths higher values were found in the first four depths and also below 90 cm depth. Depth 90 cm had the lowest VSMC values. The first four depths had higher average VSMC than the deeper layers with 30 cm depth recording the highest of 36.80 followed by 18 cm depth which had 35.52 and then 60 cm depth with 32.10. This was unlike the LR92 when the deeper layers had more soil water than the shallower layers. No wonder then that we had the best season in SR92 since more soil water was confined to the shallower layers.

We see in Table 50a (ii) that at 188 cm from the pruned trees the average VSMC of 41.39 recorded at 30 cm depth in tube N1 around PT4 was the largest for that distance in pruned area in the first four depths. The smallest average VSMC at this distance from the trees was of 28.03 recorded at 90 cm in tube B1 around PT1 in AFM1 in the upper part of AF. Like for the other cases all the tubes recorded their highest VSMC at 30 cm depth. Like at 94 cm distance the lowest VSMC values were at 90 cm depth. Again unlike LR92 we observe from Table 50a (ii) that at 188 cm from the pruned Grevillea trees the shallower layers had more soil moisture than the deeper layers. Again 30 cm depth with an average of 35.98 was more pronounced than any other depth.

We observe in Table 50a (iii) at 376 cm from the pruned trees that both the largest average VSMC of 41.19 was recorded at 30 in tube C1 around Grevillea tree PT1 in the upper part of mulching plot (AFM1). The smallest value of 28.91 was recorded at the 90 cm depth in tube C2 around PT4 in lower part of AFL1 (see Fig. 9).

In general we observe that the tubes at 376 cm from the pruned trees for the first four depths of more agronomic significance had highest VSMC for SR92 in the layers above 90 cm. This are the layers of more agronomic importance for both maize and beans.

4.2.3 (e) Average VSMC in unpruned Grevillea robusta trees in AF plots AFM2 & AFL2 during SR92

Table 50b presents averages of VSMC for the tubes in AF plots having root unpruned *Grevillea robusta* trees (AFM2 & AFL2), during the SR92.

At 94 cm from unpruned *Grevillea robusta* the largest VSMC of 40.50 was observed at 30 cm in tube P1 around unpruned tree UT4 in mulched plot (see Table 50b(i)). The smallest VSMC of 25.68 was observed also in tube P1 but at 90 cm depth. The layers above 60 cm had more soil moisture than those below, the 30 cm depth as again being pronounced like in the case of the pruned area.

When we compare the whole unpruned area (AFM2 & AFL2) at 94 cm the largest average VSMC of 39.23 of all tubes was recorded at 30 cm depth. The smallest value of 27.98 was recorded at 90 cm depth. Both of these depths are agronomically important to the maize/beans intercrop particularly maize as it can root down to past 90 cm depth.

The results of averages of tubes in AFM2 and in AFL2 of 32.09 and 31.90 respectively indicate that there was more soil moisture in AF mulched than in the AF Local plots at 94 cm from the unpruned *Grevillea robusta* trees.

On the whole there was more soil moisture in the shallower layers at 94 cm from the unpruned trees than in the deeper soil layers.

At 188 cm from unpruned *Grevillea robusta* trees the largest VSMC of 39.26 was again recorded at 30 cm but in tube Q1 around unpruned tree UT4, in the lower part of mulching plot (AFM2) (see Table 50b(ii)). The lowest value of 27.13 was observed in tube E2 around unpruned tree UT2 in the upper part of the Local plot AFL2. For the whole unpruned area (AFM2 & AFL2) at 188 cm the largest VSMC of 38.59 was again recorded at 30 cm depth. This time the smallest value of VSMC of 28.18 was recorded at 150 cm depth, the depth of least agronomic importance to the intercrop. The averages of tubes in AFM2 and in AFL2 of 31.96 and 31.17 respectively indicate that there was more soil moisture in AF mulched than in the AF Local plots at 188 cm from the unpruned *Grevillea robusta* trees although these values are marginally different and may not explain yield differences in the mulched and Local treatments. This difference is so small that it must be considered negligible. In such cases yield differences may be explained through soil moisture distribution within the growing season as given in section 4.2.3 (a), in response to rainfall occurrences.

At 376 cm from unpruned *Grevillea robusta* trees the largest VSMC of 38.99 was obtained in tube R1 around UT4 in mulching plot (AFM2) and the smallest of 28.38 in tube F1 around UT1 also in mulching plot (AFM2) (see Table 50b(iii)). Again for the whole unpruned area 30 cm depth had the largest VSMC of 38.39.

From the foregoing we learn that SR92 tubes had more soil moisture than the LR92 tubes at all the three distances from the *Grevillea robusta* trees. The 30 cm depth had most pronounced soil moisture amounts throughout the year 1992. The marginal differences in average VSMC between pruned and unpruned seemed to be amplified in yield differences between the two treatments.

Table 50. Average VSMC at different depths and distances from *Grevillea robusta* trees. (a) pruned (AFM1 & AFL1). (b) unpruned (AFM2 & AFL2) plots for SR92 (period: 9/10/92-29/1/93) and (a) Pruned AF (AFM1 & AFL1).

(i) Average of tubes at 94 cm

	Depths						
tube	18	30	60	90	120	150	170
A1 avg	39.44	40.28	34.52	29.83	32.29	29.31	30.32
A2 avg	36.64	36.44	30.95	29.68	31.35	30.51	29.97
M1 avg	35.95	38.97	33.33	30.24	31.75	30.34	29.39
M2 avg	30.06	31.50	29.59	29.26	32.00	28.25	29.94
Avg tub	35.52	36.80	32.10	29.76	31.85	29.60	29.90

(ii) Average of tubes at 188 cm

tube	18	30	60	90	120	150	170
B1 avg	36.56	40.37	33.18	28.03	33.93	30.28	29.70
B2 avg	36.45	37.01	30.64	28.66	30.58	29.04	30.14
N1 avg	36.54	41.39	37.32	31.94	30.48	29.72	29.48
N2 avg	33.28	35.98	34.51	29.19	32.06	28.64	30.77

All tubes	35.71	38.69	33.91	29.45	31.76	29.42	30.02

(iii) Average of tubes at 376 cm

tube	18	30	60	90	120	150	170
C1 avg	40.77	41.19	33.58	30.73	32.28	29.43	29.88
C2 avg	34.01	36.72	34.43	29.73	32.14	30.14	31.58
O1 avg	37.06	38.71	34.74	30.24	32.87	30.50	29.77
O2 avg	34.70	39.02	33.09	28.91	33.60	30.11	29.62
All tubes	36.63	38.91	33.96	29.90	32.72	30.04	30.21

(b) Unpruned AF (AFM2 & AFL2)

(i) Average of tubes at 94 cm

	Depths						
tube	18	30	60	90	120	150	170
D1 avg	35.34	38.63	35.19	28.82	31.04	29.24	29.28
D2 avg	36.34	39.59	36.31	28.76	30.13	27.94	26.97
P1 avg	37.95	40.50	33.61	25.68	28.22	26.46	29.35
P2 avg	35.16	38.22	30.01	28.66	30.28	29.31	28.93
Avg tub	36.20	39.23	33.78	27.98	29.92	28.24	28.63

(ii) Average of tubes at 188 cm

tube	18	30	60	90	120	150	170
E1 avg	34.72	39.12	33.33	29.13	31.20	27.84	29.54
E2 avg	34.63	37.31	30.23	28.68	29.27	28.92	27.13
Q1 avg	34.74	39.62	33.00	28.44	29.14	27.34	30.22
Q2 avg	34.65	38.30	31.17	29.71	28.96	28.63	28.78
Avg tub	34.68	38.59	31.93	28.99	29.64	28.18	28.92

iii) Average of tubes at 376 cm

tube	18	30	60	90	120	150	170
F1 avg	35.59	38.72	32.28	31.19	30.83	28.38	29.58
F2 avg	35.01	37.02	31.26	28.55	29.24	29.81	29.17
R1 avg	37.65	38.99	31.81	28.58	30.33	29.39	30.33
R2 avg	35.62	38.83	30.89	30.87	30.46	29.40	30.16
Avg tub	35.97	38.39	31.56	29.80	30.22	29.25	29.81

4.2.4 Intercomparison of the VSMC in the mulch and Local AF in the whole soil profile for the six seasons

4.2.4 (a) Soil moisture distribution in the whole soil profile

Table 51 presents averages of tubes in the (i) mulched and Local pruned (AFM1 & AFL1); and (ii) mulched and Local unpruned (AFM2 & AFL2)

Grevillea robusta tree plots for the entire soil profile (18-170 cm) for the six seasons already discussed above.

We see in this Table 51 that. with the exception of few seasons. the mulch plots had more soil moisture than the Local plots in the AF at all the three distances from either pruned or unpruned *Grevillea robusta* trees. even though Table 51 includes VSMC at the deeper layers of little agronomic importance and hence should be considered together with Figs. 124-129 and 130-135 to explain yield differences.

We can therefore notice that in pruned plots (AFM1 & AFL1) 17 out of 18 (i.e. 94.44 %) of the cases (i.e. mulching versus Local) the mulched area had more soil moisture than the Local area. In unpruned area 10 out of 18 (i.e. 55.56 %) of the cases the mulch area had more soil moisture than the Local in AF.

Table 51. Intercomparisons of VSMC averages in AF mulched with AF Local plots for the 18-170 cm soil profile and distance from *Grevillea robusta trees* for the six seasons: (a) pruned (b) unpruned trees.

Treatments (a) Pruned	seasons					
	LR92	SR92	LR93	SR93	LR94	SR94
(i) 94 cm distance						
Mulching (AFM1)	30.83	33.28	34.34	30.41	31.16	33.93
Local (AFL1)	30.27	31.15	31.31	29.47	29.70	31.77
(ii) 188 cm distance						
Mulching (AFM1)	30.62	33.49	35.49	30.80	31.41	33.07
Local (AFL1)	30.65	31.92	32.66	30.20	30.42	33.04
(iii) 376 cm distance						
Mulching (AFM1)	31.12	33.70	35.68	30.77	31.72	33.90
Local (AFL1)	30.92	32.70	34.23	30.20	31.51	33.70

(b) Unpruned						
(i) 94 cm distance						
Mulching (AFM2)	30.45	32.09	31.85	29.90	30.63	33.16
Local (AFL2)	30.78	31.90	32.40	30.14	29.91	32.99
(ii) 188 cm distance						
Mulching (AFM2)	30.48	31.96	32.74	29.69	29.84	33.24
Local (AFL2)	29.58	31.17	33.24	29.85	29.61	31.73
(iii) 376 cm distance						
Mulching (AFM2)	30.51	32.40	33.42	30.21	30.26	34.42
Local (AFL2)	30.70	31.88	33.13	30.21	30.40	33.48

There was apparently more soil moisture in LR93 and SR94 (columns 3 & 6 in Table 51) than SR92. However, the LR93 and SR94 soil moisture was mainly confined to the deeper layers as periods between each rainfall occurrences were large and gave enough time for the soil water to be used up in the layers holding the roots (see section 4.2.4 (b)). Hence agronomically the two seasons could not produce crop yields making SR92 stand out as the only season we had maize grain yields.

The above shows that our earlier exercise (section 4.2.3 (a)) on agronomically important depths and the agronomically important deviations was giving a picture in which the consequences of rainfall distribution were correctly covered. The calculations with averages over the whole profile and season are masking what is available to the crops. However, it also shows that varieties of maize with higher rooting depths would do better in seasons with irregular rainfall that percolates into deeper layers.

4.2.4 (b) Effects of mulching on VSMC

Figs. 139 & 140 present the results on the effect of mulch on VSMC at 94, 188 and 376 cm from pruned and unpruned *Grevillea robusta trees* during the six seasons.

As expected the pruned mulch plot (AFM1) (Fig. 139) had more VSMC than the pruned Local plot (AFL1) at all distances from the *Grevillea robusta trees* during the six seasons. There was a lot of moisture in the soil, mainly confined in the deeper layers where it could not be reached by intercrop roots during LR93, hence there was no maize yields. This points to the fact that rainfall distribution was not even throughout the season as it gave a lot of time for deep percolation to take place. In fact 36.7 and 17.3 mm of rain fell on 18/4/93 and 19/4/94 respectively thereafter there was no rain until 21/5/93 when 61.3 mm was received and then 12.0 mm on 11/6/93. For the intercrop planted on 14/4/93, these showers were rather fairly heavy but erratic and could not help crop growth.

Similarly high VSMC were recorded during SR94 but no grain yields for maize in the intercrop. Rainfall was not evenly distributed to support maize growth to maturity. The intercrop of for SR94 was planted, as already mentioned, on 10/10/94. A look at weekly soil moisture for the years 1993 and 1994, of the type discussed above in section 4.2.3(a), showed the response of soil moisture changes to rainfall occurrences within LR93 and SR94. Reasonably heavy rains of 14.0, 6.8 and 55.5 mm fell on 20/10/94, 21/10/94 and 22/10/94 respectively. These were followed by fairly heavy rains between 27/10/94 and 4/11/94 of 23.8 on 5/11 and 11/11/94 each and 43.8 mm on 13/11/94 raising people's hopes of a good season which it never became as long dry spell which followed

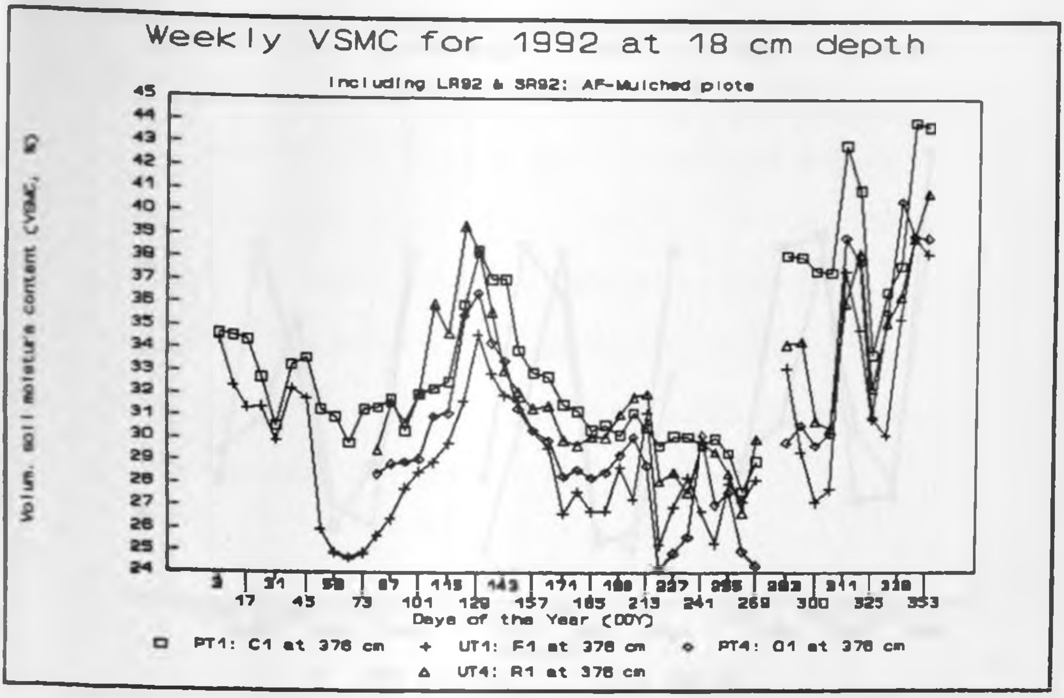

Fig. 138. 1992 weekly VSMC (%) for 18 cm depth taken at the distance of 376 cm from *G. robusta* trees (PT1, PT4, UT1 & UT4) in pruned and unpruned plots (AFM1 & AFM2).

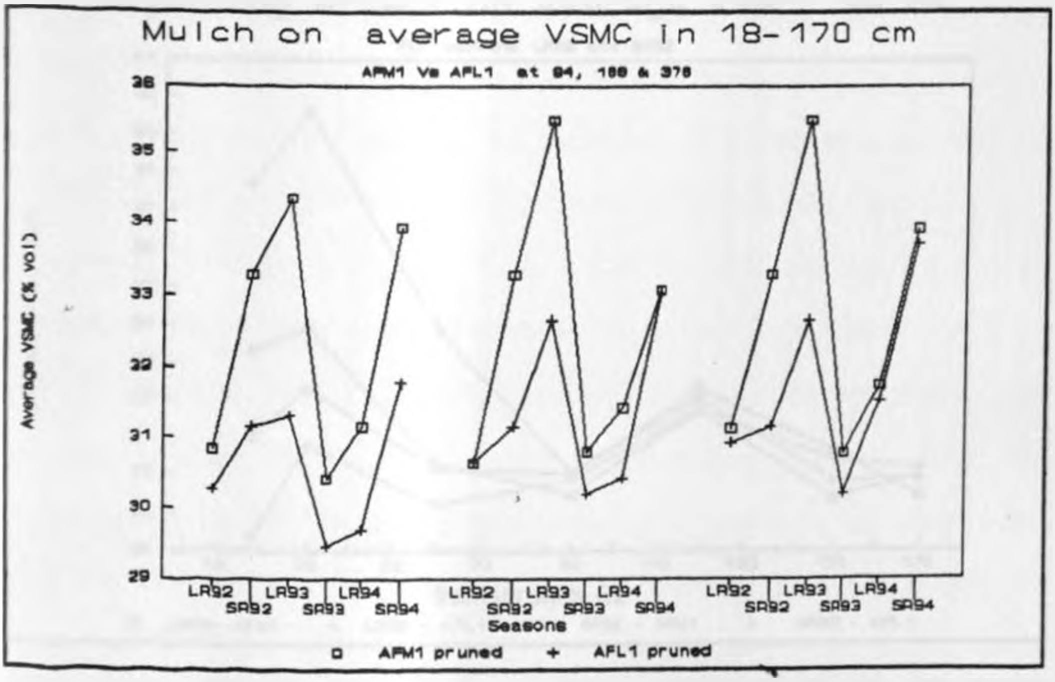

Fig. 139. Mulch effect on soil moisture in pruned plots (AFM1 & AFL1)

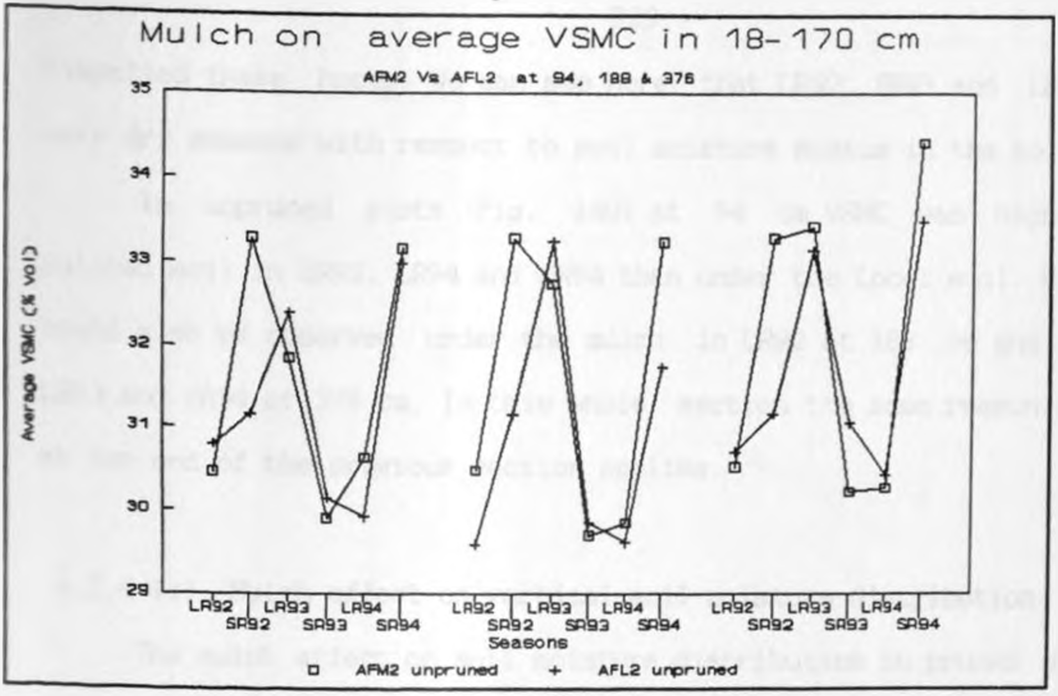

Fig. 140. Mulch effect on soil moisture in unpruned plots (AFM2 & AFL2)

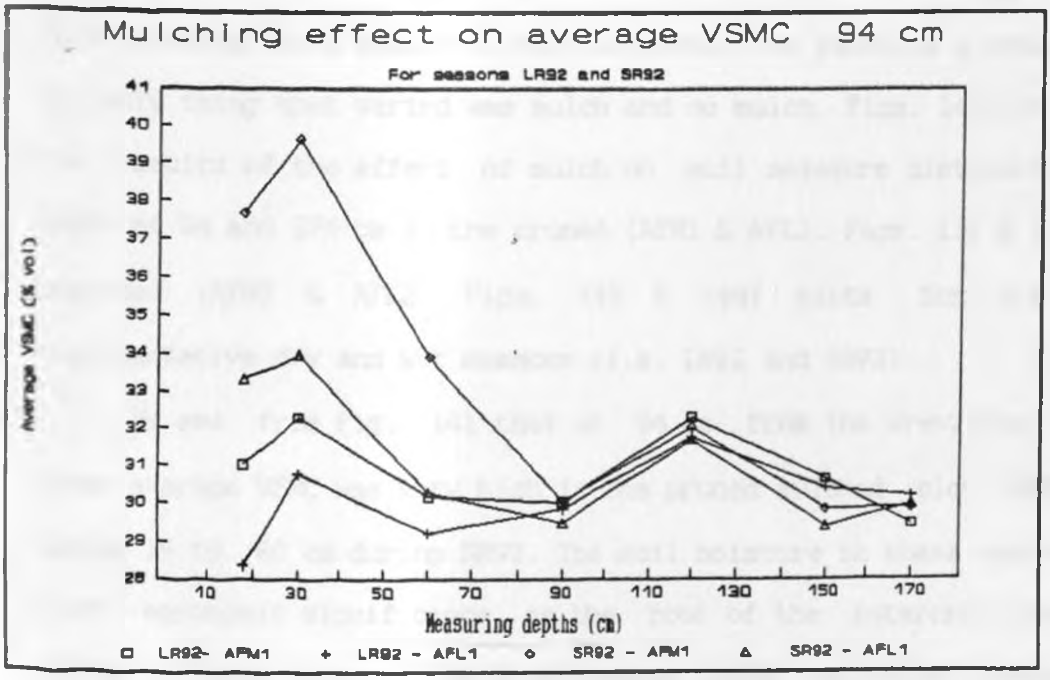

Fig. 141. Mulch effect on soil moisture at 94 cm from Grev. in LR92 & SR92 in pruned plots.

dispelled these hopes. We can see here that LR92. SR93 and LR94 were very dry seasons with respect to soil moisture status in the soil.

In unpruned plots (Fig. 140) at 94 cm VSMC was higher under mulched soil in SR92. LR94 and SR94 than under the Local soil. High VSMC could also be observed under the mulch in LR92 at 188 cm and in SR92. LR93 and SR94 at 376 cm. In this whole section the same reasoning given at the end of the previous section applies.

4.2.4 (c) Mulch effect on vertical soil moisture distribution

The mulch effect on soil moisture distribution in pruned area was obtained by comparing the soil moisture in pruned Mulched plot (AFM1) with that in the pruned Local (AFL1) as given in Table 48 and 49 the averages of all tubes in each treatment for LR92 and SR92. In that case root pruning being common in the two plots was taken as a constant and the only thing that varied was mulch and no mulch. Figs. 141-144 present the results of the effect of mulch on soil moisture distribution with depth at 94 and 376 cm in the pruned (AFM1 & AFL1. Figs. 130 & 131) and unpruned (AFM2 & AFL2. Figs. 143 & 144) plots for the chosen representative dry and wet seasons (i.e. LR92 and SR92).

We see from Fig. 141 that at 94 cm from the *Grevillea robusta* trees average VSMC was very high in the pruned mulched plot (AFM1) from depths 18 to 60 cm during SR92. The soil moisture in these depths is of great agronomic significance as the root of the intercrop components reside in these layers. The drier season (LR92) had higher average VSMC in the deeper layers than the wetter season SR92. although the difference was small. The high moisture in the deeper layers is of little agronomic value to crop like beans with shallow roots. The soil

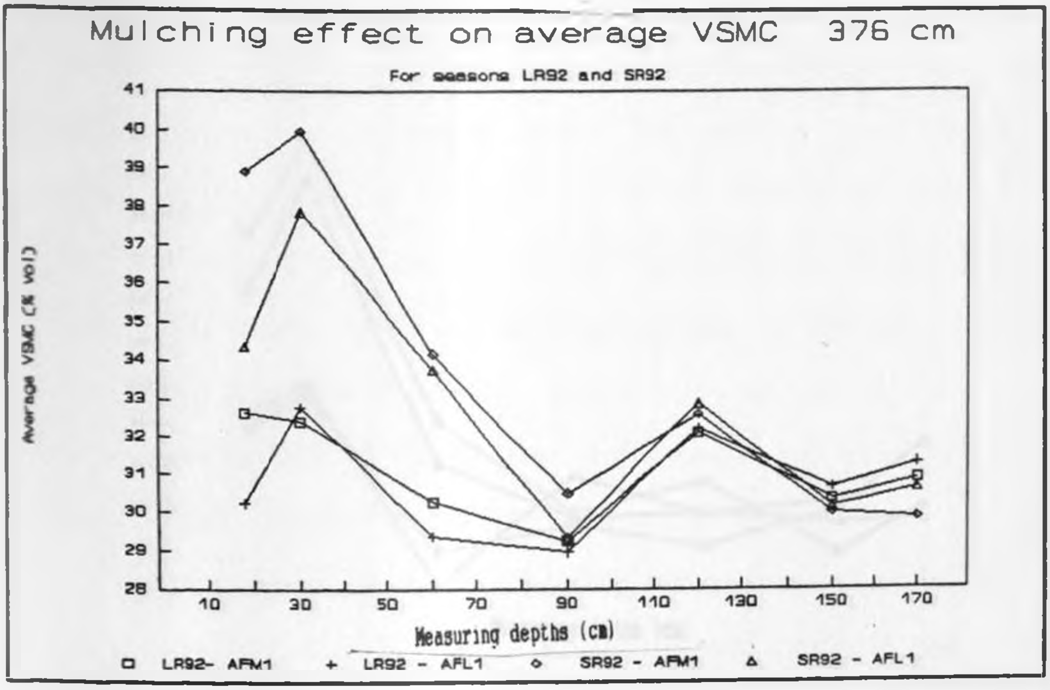

Fig. 142. Mulch effect on soil moisture at 376 cm from Grev in LR92 & SR92 in pruned plots.

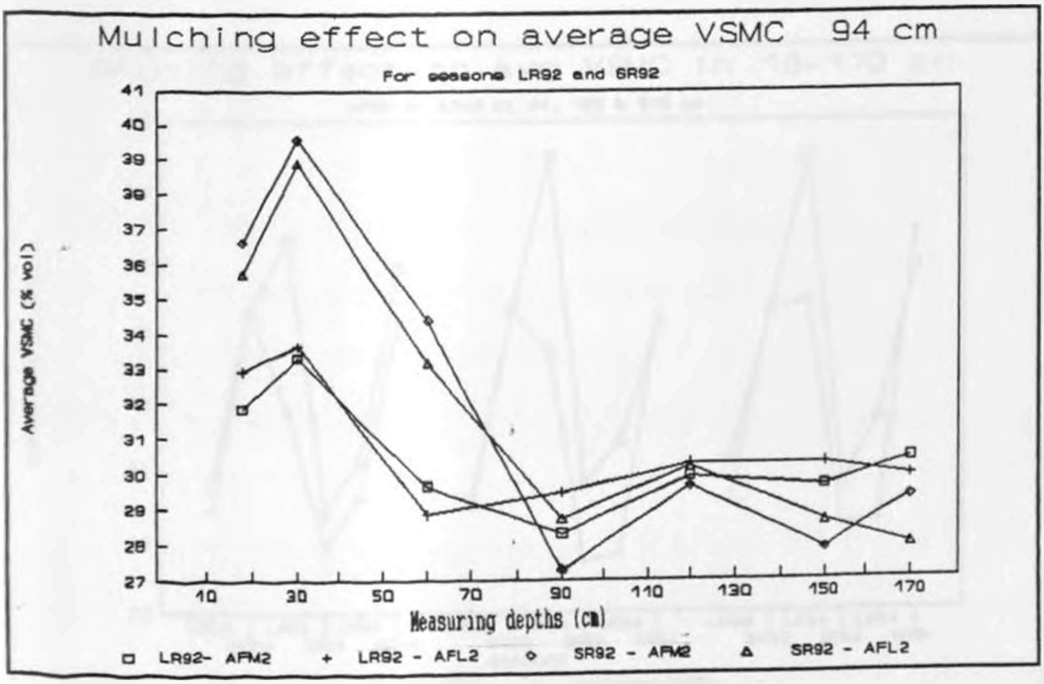

Fig. 143. Mulch effect on soil moisture at 94 cm from *Grevillea robusta* trees in LR92 & SR92 in unpruned plots.

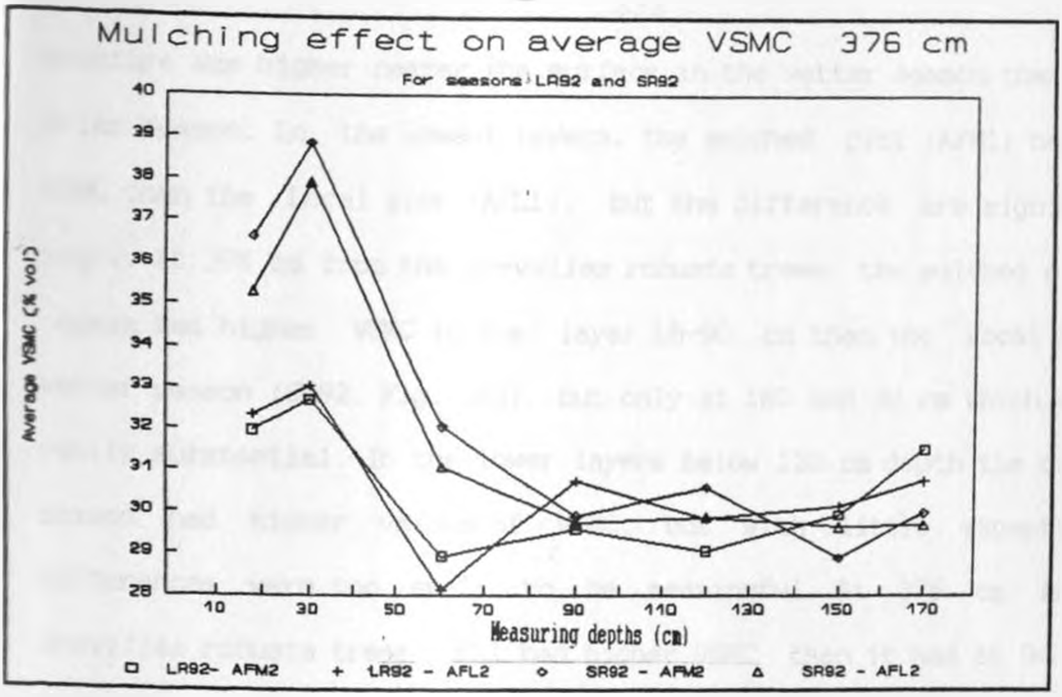

Fig. 144. Mulch effect on soil moisture at 376 cm from *Grevillea robusta* trees Grev. in LR92 & SR 92 in unpruned plots.

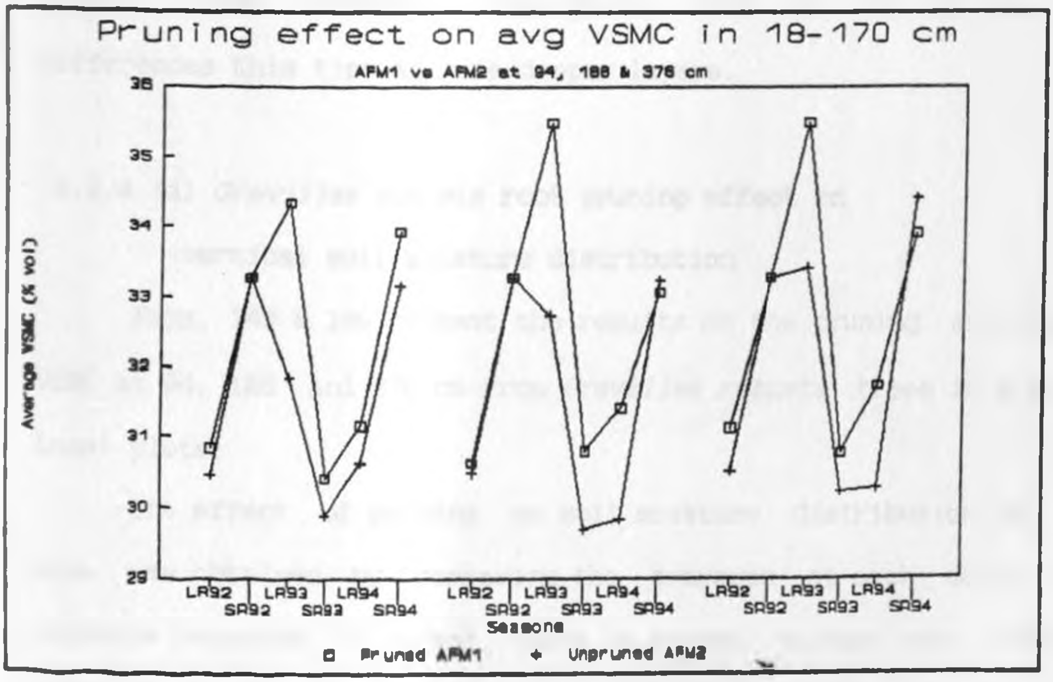

Fig. 145. Pruning effect on soil moisture in mulched plots for six seasons at 94, 188 & 376 cm from *Grevillea robusta* trees.

moisture was higher nearer the surface in the wetter season than in the drier season. In the lowest layers. the mulched plot (AFM1) had higher VSMC than the Local plot (AFL1). but the difference are significantly small. At 376 cm from the *Grevillea robusta* trees. the mulched plot again had higher VSMC in the layer 18-90 cm than the Local for the wetter season (SR92. Fig. 142). but only at 180 and 30 cm which was really substantial. In the lower layers below 120 cm depth the drier season had higher values of VSMC. but with little exception the differences were too small to be meaningful. At 376 cm from the *Grevillea robusta* trees AFL1 had higher VSMC than it had at 94 cm. at most of the two lowest depths.

Similar trends could be observed in unpruned plots (AFM2 & AFL2) (Figs. 143 & 144) although the VSMC in the two plots were for each season rather comparable throughout, with at 94 cm the highest differences this time at some deeper layers.

4.2.4 (d) *Grevillea robusta* root pruning effect on vertical soil moisture distribution

Figs. 145 & 146 present the results on the pruning effects on the VSMC at 94. 188 and 376 cm from *Grevillea robusta* trees in mulched and Local plots.

The effect of pruning on soil moisture distribution in mulched area was obtained by comparing the averages at each depth of soil moisture recorded by access tubes in pruned Mulched plot (AFM1) with averages of the tubes in the unpruned Mulched (AFM2) as were worked out from Tables 49 and 50 (see Fig. 9) for all tubes in each treatment for LR92 and SR92. In that case mulching is common in the two plots and was moisture was higher nearer the surface in the wetter season than in the drier season. In the lowest layers, the mulched plot (AFM1) had higher VSMC than the Local plot (AFL1). but the difference are significantly small. At 376 cm from the *Grevillea robusta* trees. the mulched plot again had higher VSMC in the layer 18-90 cm than the Local for the wetter season (SR92, Fig. 142). but only at 180 and 30 cm which was really substantial. In the lower layers below 120 cm depth the drier season had higher values of VSMC. but with little exception the differences were too small to be meaningful. At 376 cm from the *Grevillea robusta* trees AFL1 had higher VSMC than it had at 94 cm. at most of the two lowest depths.

Similar trends could be observed in unpruned plots (AFM2 & AFL2) (Figs. 143 & 144) although the VSMC in the two plots were for each season rather comparable throughout, with at 94 cm the highest differences this time at some deeper layers.

4.2.4 (d) *Grevillea robusta* root pruning effect on vertical soil moisture distribution

Figs. 145 & 146 present the results on the pruning effects on the VSMC at 94, 188 and 376 cm from *Grevillea robusta* trees in mulched and Local plots.

The effect of pruning on soil moisture distribution in mulched area was obtained by comparing the averages at each depth of soil moisture recorded by access tubes in pruned Mulched plot (AFM1) with averages of the tubes in the unpruned Mulched (AFM2) as were worked out from Tables 49 and 50 (see Fig. 9) for all tubes in each treatment for LR92 and SR92. In that case mulching is common in the two plots and was

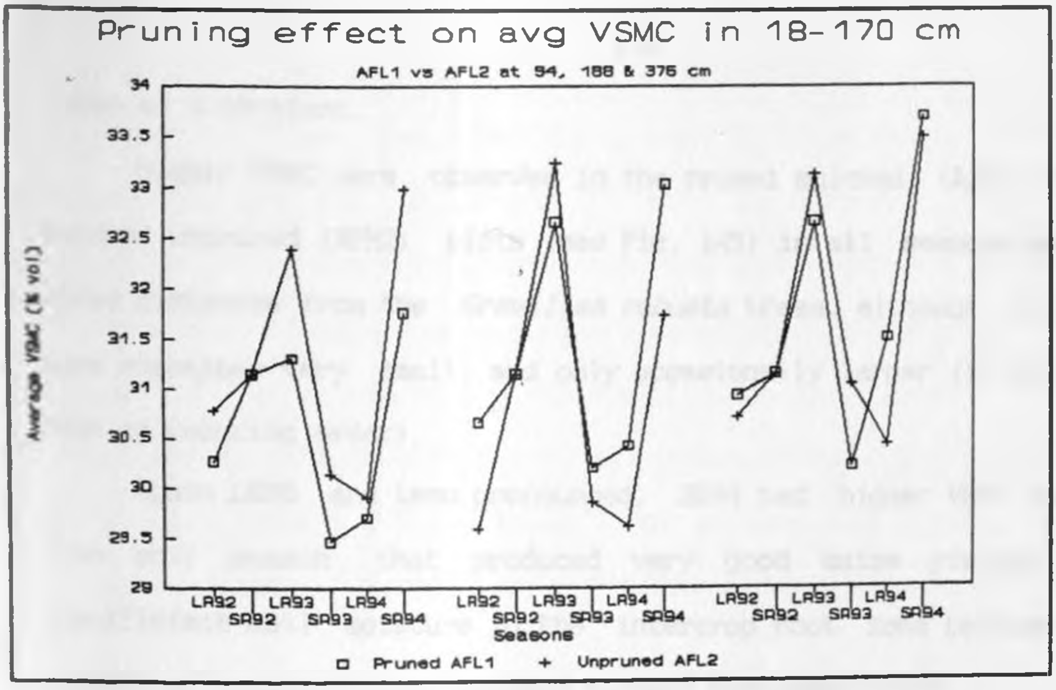

Fig. 146. Pruning effect on soil moisture in Local plots for six seasons at 94, 188 & 376 cm from *Grevillea robusta* trees.

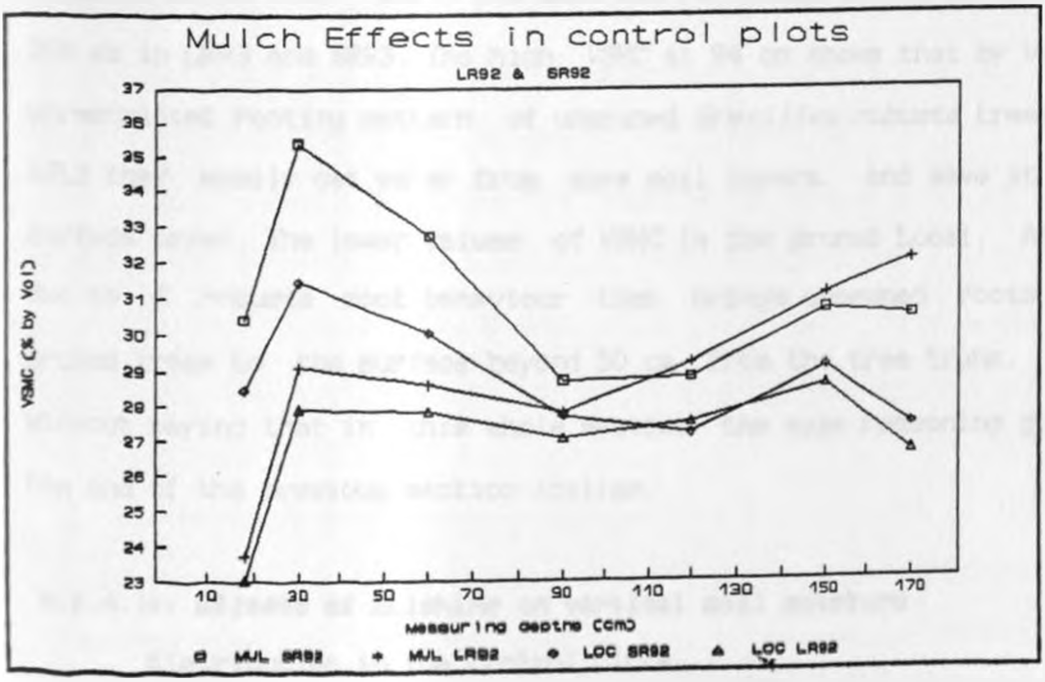

Fig. 147. Mulch effect on soil moisture in control plots for LR92 & SR92 seasons

taken as a constant.

Higher VSMC were observed in the pruned mulched (AFM1) than the mulched unpruned (AFM2) plots (see Fig. 145) in all seasons and at the three distances from the *Grevillea robusta* trees. although differences were sometimes very small. and only occasionally larger (in LR93. LR94. SR94 in reducing order).

Again LR93 and less pronounced. SR94 had higher VSMC than SR92 (the only season that produced very good maize yields) due to insufficient soil moisture in the intercrop root zone because of the problem of rainfall distributions already discussed above.

A comparison of Local plots for all the seasons revealed that AFL1 had lower VSMC than AFL2 especially closer to the *Grevillea robusta* trees at 94 cm (Fig. 146). The same was reflected at 188 cm in LR93. at 376 cm in LR93 and SR93. The high VSMC at 94 cm shows that by virtue of unrestricted rooting pattern of unpruned *Grevillea robusta* trees in the AFL2 they easily get water from more soil layers. and save it in the surface layer. The lower values of VSMC in the pruned Local. AFL1. was due to *G. robusta* root behaviour that brings unpruned roots of the pruned trees to the surface beyond 50 cm from the tree trunk. It goes without saying that in this whole section the same reasoning given at the end of the previous section applies.

4.3.4 (e) Effects of mulching on vertical soil moisture distribution in the control plots

Fig. 147 presents the results of the effects of mulching on vertical soil moisture distribution in the control non-agroforestry plots for the representative seasons (LR92 & SR92). Comparing LR92 and

SR92 which behaved differently with respect to soil moisture distribution we see that VSMC was highest at 30 cm depth and quite low at 18, 90 and 120 cm depths in both the seasons. Here again, as expected, there was more moisture in the soil under the mulch than in the unmulched (Local). As we have already seen, the wetter season had higher VSMC values nearer the surface than the drier season while in the deeper depths the mulched plots among each other and the Local among each other become rather equal, the mulched plot being higher in moisture content. This has been explained already several times above.

4.2.4 (f) Root pruning effect on soil moisture distribution with depth

For this part we present only results for the 94 and 376 cm distances from the *Grevillea* trees. We deliberately left out results for 188 cm distance from the trees as we noticed that the variations there were within the limits for 94 and 376 cm distances.

Figs. 148-151 present the results of the effect of *Grevillea robusta* root pruning on soil moisture distribution with depth at 94 and 376 cm in the mulched (AFM1 & AFM2, Figs. 148 & 149) and Local (AFL1 & AFL2, Figs. 150 & 151) plots for the chosen typical dry and wet seasons (i.e. LR92 and SR92).

We could observe a small positive effect of pruning at 18 cm and a larger effect from 90 cm depths till 150 cm at the distances of 94 cm from the *Grevillea robusta* trees in the wetter season (Fig. 148). In the drier season the higher positive effect of pruning could be felt in the 90 and 120 cm depths as the VSMC were higher in the AFM1 than in the AFM2, but a smaller negative effect occurred at 18 and 30 cm. At 376 cm

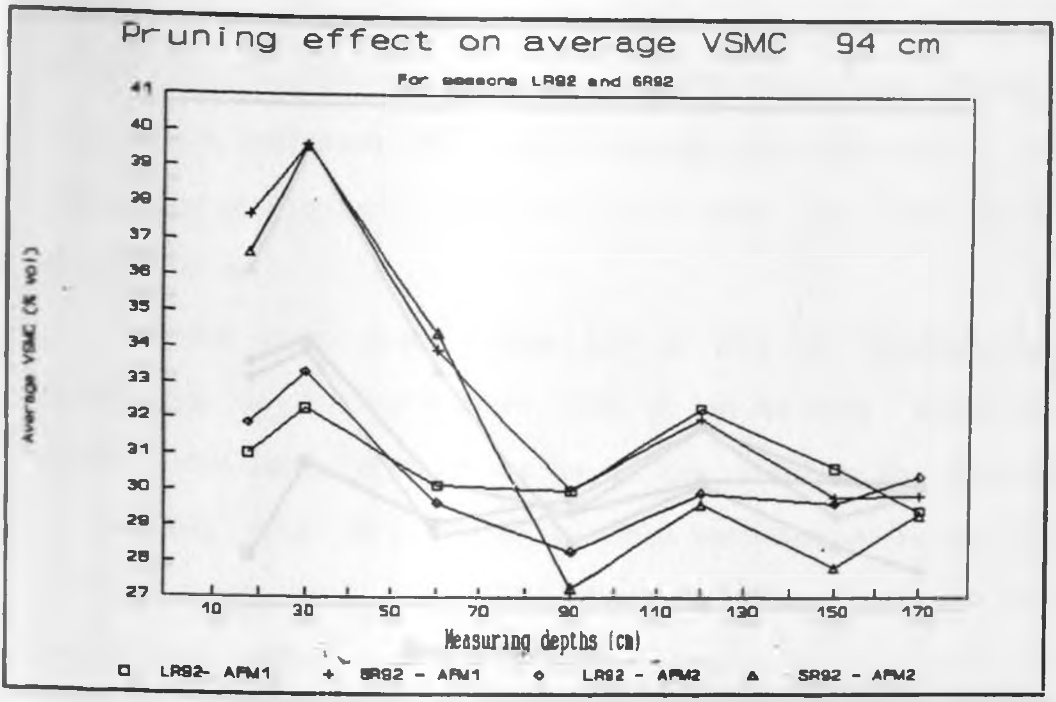

Fig. 148. Pruning effect on soil moisture at 94 cm from Grev in mulched plots- LR92 & SR92. AFM1 in the pruned plot and AFM2 in the unpruned plot.

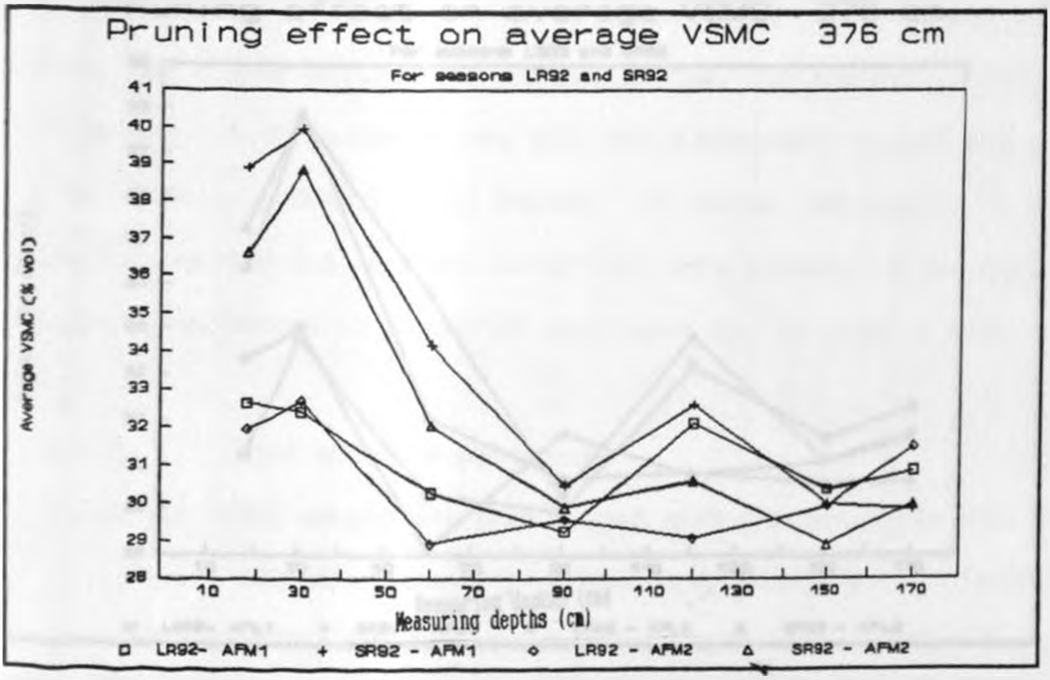

Fig. 149. Pruning effect on soil moisture at 376 cm from Grev in Mulched plots - LR92 & SR92. AFM1 is the pruned plot and AFM2 is the unpruned plot.

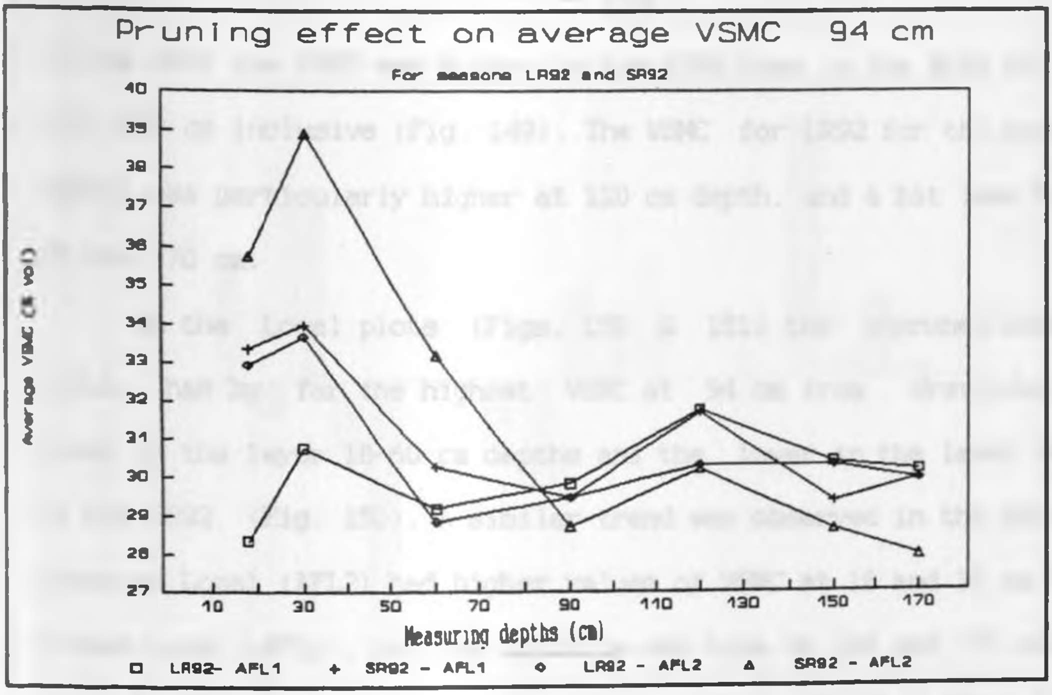

Fig. 150. Pruning effect on soil moisture at 94 cm from Grev in Local plots -LR92 & SR92. AFL1 is the pruned plot and AFL2 is the unpruned plot.

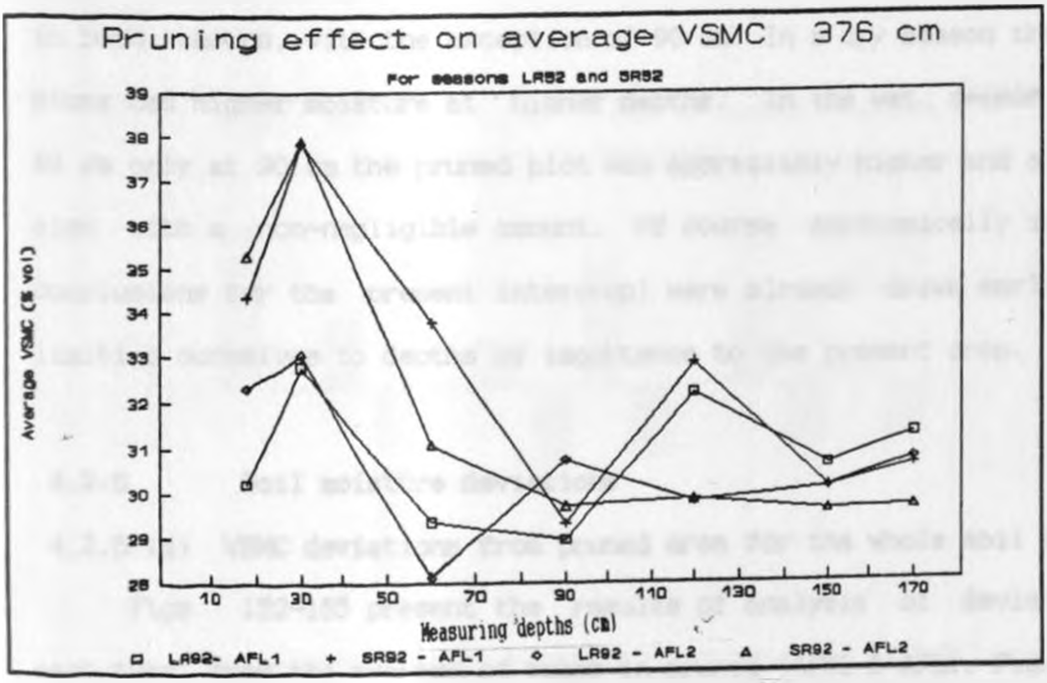

Fig. 151. Pruning effect on soil moisture at 376 cm from Grev in Local plots - LR92 & SR92. AFL1 is the pruned plot and AFL2 is the unpruned plot.

in the SR92 the VSMC was higher in the AFM1 than in the AFM2 all the way till 150 cm inclusive (Fig. 149). The VSMC for LR92 for the pruned plot (AFM1) was particularly higher at 120 cm depth, and a bit less higher at 60 and 170 cm.

In the Local plots (Figs. 150 & 151) the unpruned Local plot (AFL2) had by far the highest VSMC at 94 cm from *Grevillea robusta* trees in the layer 18-60 cm depths and the lower in the layer 90-170 cm in the SR92 (Fig. 150). A similar trend was observed in the LR92 as the unpruned Local (AFL2) had higher values of VSMC at 18 and 30 cm than the pruned Local (AFL1), but the opposite was true at 120 and 170 cm depths.

At 376 cm from the *Grevillea robusta* trees (Fig. 151) the situation changed as the AFL2 had comparable VSMC with AFL1 at 30 cm but exceeded it at 18 cm in both seasons, while it was lower at 60 cm also in both seasons, with the exception of 90 cm. In a dry season the pruned plots had higher moisture at higher depths. In the wet season, beyond 60 cm only at 90 cm the pruned plot was appreciably higher and at 170 cm also with a non-negligible amount. Of course agronomically important conclusions for the present intercrop) were already drawn earlier when limiting ourselves to depths of importance to the present crop.

4.2.5 Soil moisture deviations

4.2.5 (a) VSMC deviations from pruned area for the whole soil profile

Figs. 152-155 present the results of analysis of deviations of each tube from the average of tubes in pruned (AFM1 & AFL1, Figs. 152 & 153) and unpruned (AFM2 & AFL2, Figs. 154 & 155) for the whole soil profile for the representative seasons (LR92 & SR92). In the forthcoming presentation it is understood that only depths till 90 cm inclusive were

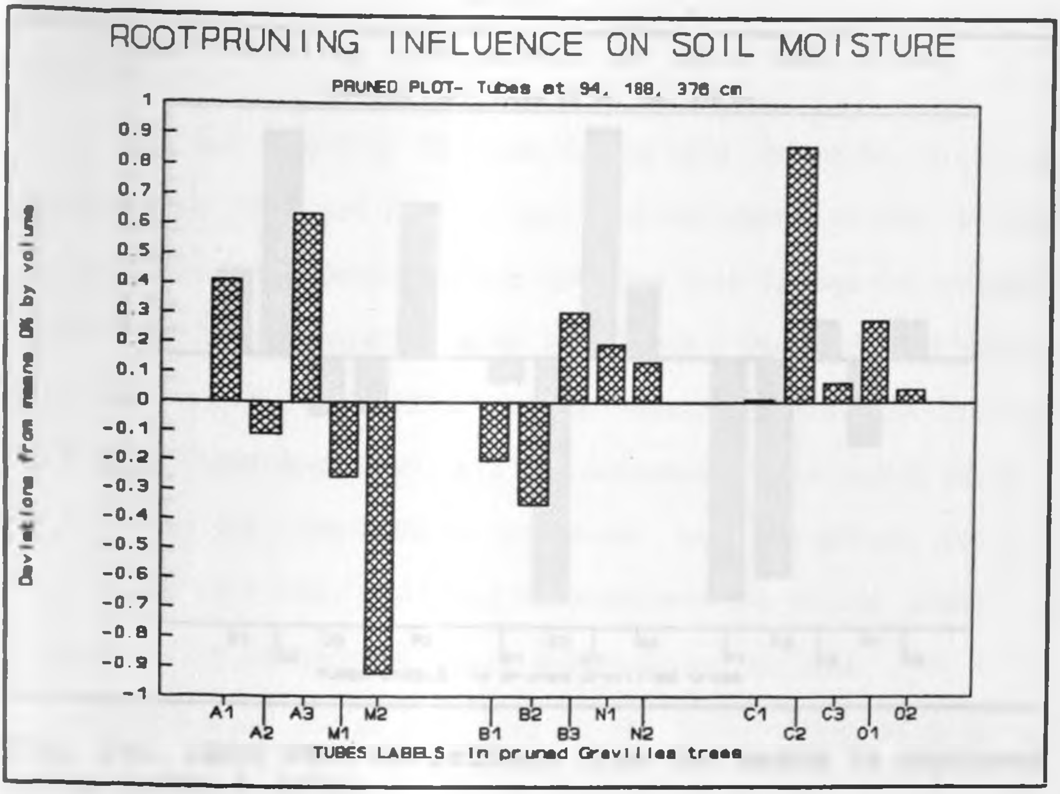

Fig. 152. LR92 VSMC deviations from the means in pruned plots (AFM1 & AFL1) for whole profile

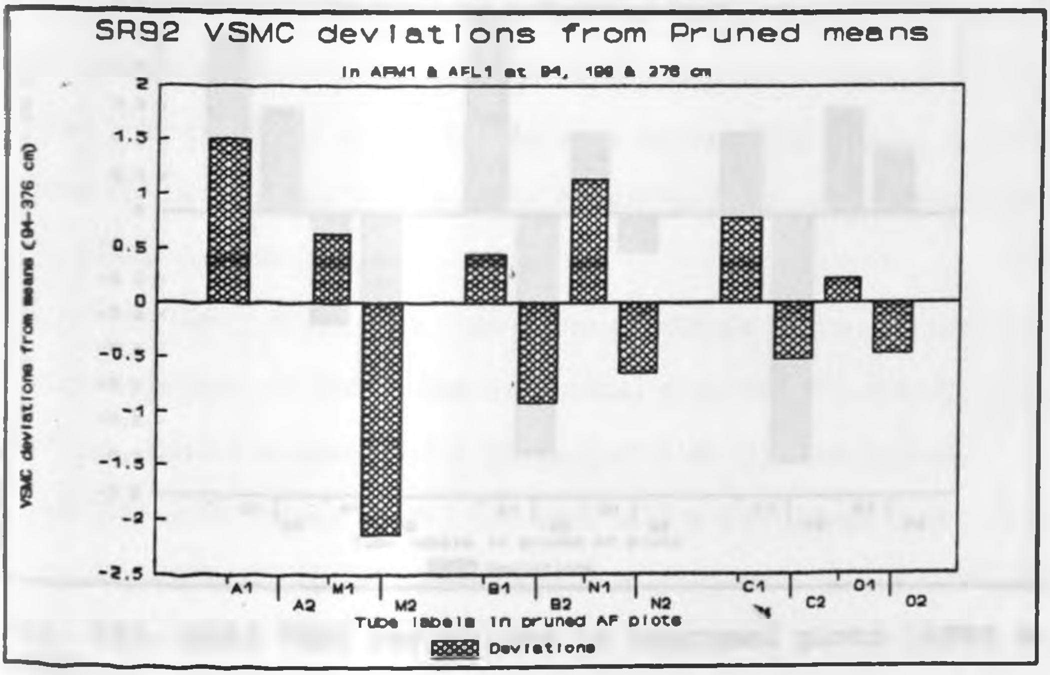

Fig. 153. SR92 VSMC deviations from means in pruned plots (AFM1 & AFL1).

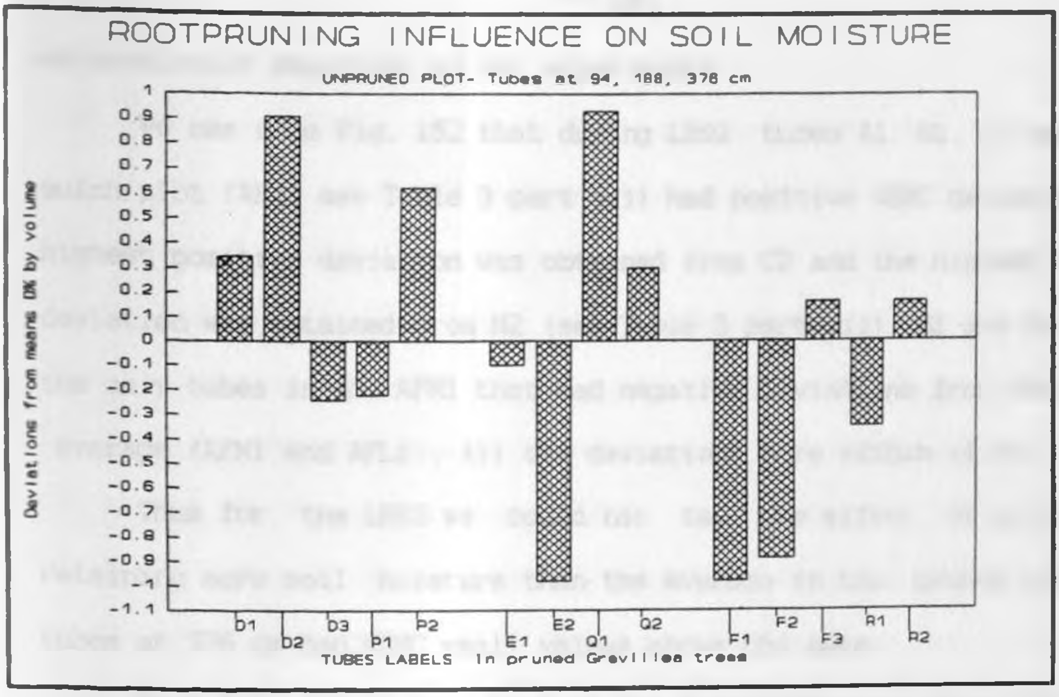

Fig. 154. LR92 VSMC deviations from the means in unpruned plots (AFM2 & AFL2)

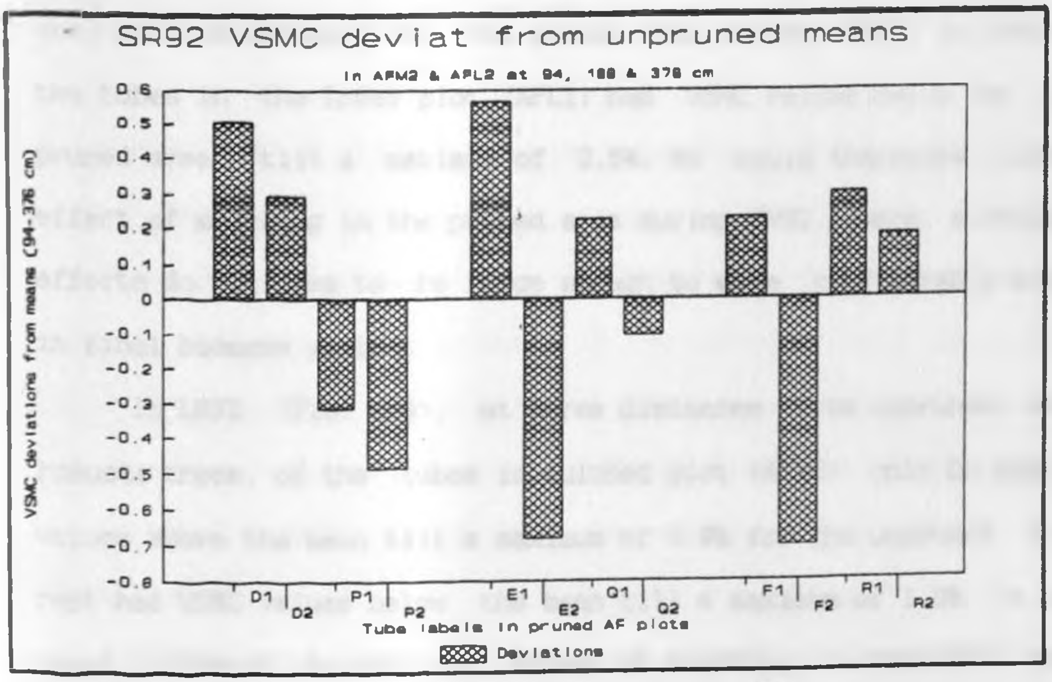

Fig. 155. SR92 VSMC deviations in unpruned plots (AFM2 & AFL2).

agronomically important in our experiments.

We see from Fig. 152 that during LR92 tubes A1, N1, C1 and O1 in mulch plot (AFM1 see Table 3 part iii) had positive VSMC deviations. The highest positive deviation was obtained from C2 and the highest negative deviation was obtained from M2 (see Table 3 part iii). M1 and B1 were the only tubes in the AFM1 that had negative deviations from the pruned average (AFM1 and AFL1). All the deviations were within ±1.0%.

Thus for the LR92 we could not tell the effect of mulching in retaining more soil moisture than the average in the pruned plots. All tubes at 376 cm had VSMC small values above the mean.

From Fig. 153 we see that at the three distances from the pruned *Grevillea robusta* trees all the tubes (i.e. A1, M1, B1, N1, C1 & O1) in the mulched plots registered VSMC values till a maximum of 1.5% above the profile averages for the pruned area during SR92. In contrast all the tubes in the Local plot (AFL1) had VSMC values below the mean for pruned area, till a maximum of 2.5%. We could therefore discern the effect of mulching in the pruned area during SR92 season, although these effects do not seem to be large enough to make considerable difference in final biomass yields.

In LR92 (Fig. 154), at three distances from unpruned *Grevillea robusta* trees, of the tubes in mulched plot (AFM2) only D1 and Q1 had values above the mean till a maximum of 0.9% for the unpruned area. The rest had VSMC values below the mean till a maximum of 1.0%. It was once again difficult to tell the effect of mulching in the LR92 season in unpruned area.

In SR92 (Fig. 155), 5 out of 6 tubes in mulching plot had values above the average for the unpruned area, but the deviations are around

0.5% at maximum (AFM2 & AFL2). The 5 tubes were D1, E1, Q1, F1 and R1 (see Fig. 7 and Table 3). Only P1 in mulching area had negative value. Most tubes which had VSMC values below the mean were in the Local (or unmulched) plot (AFL2).

We therefore infer from the results of the two seasons (LR92 and SR92) that during the period of high rainfall the crop residue mulch effectively conserved some soil moisture but could not do so during the dry season in the unpruned plot. This was due to the fact that during the dry period the crop residue mulch could not cover the soil sufficiently since some of it was eaten by termites and ants whereas some was easily blown away by wind and got redistributed. More-over, if run-off prevention is with this type of mulch more important than evaporation reduction, rainfall distribution is again the most determining factor.

4.2.5 (b) VSMC deviations from the means at each depth during LR92 and SR92

We relied here mostly on the behaviour of the access tubes (i.e. above or below the mean values) in the mulching plots as criteria for the success of crop residue mulch to conserve soil moisture in this environment. The positive per cent deviations from the mean values at the concerned depth in mulching was considered as a basis for mulch effectiveness.

Figs. 156-158 & 168-170 present results of analysis of per cent deviations of VSMC from the mean values at three distances: 94, 188 and 376 cm from the pruned and unpruned *Grevillea robusta* trees, and the per cent deviations of the tubes in the pruned area from the means of the entire AF plot at each depth.

We see from Figs. 156-158 that during LR92, of the tubes in the pruned area at 18 cm depth, all those in mulched plot (AFM1: A1: M1: B1: C1: O1) had per cent VSMC above the mean values except tube N1 (see Fig. 9 and Table 3). At 30 cm depth all the tubes in AFM1, except C1, were above average. At 60 cm depth all the tubes in AFM1, except B1, were above average. At 90 cm tubes A1, B1 and O1 had small, large and medium negative per cent deviations respectively.

At 94 cm from pruned *Grevillea robusta* trees the largest positive per cent deviation of +8.9 was registered around PT1 by tube A1 at 18 cm depth. The largest negative per cent deviation of -15.8 was recorded around tree PT5 by tube M2 at 18 cm depth. The lowest deviations were generally registered at 90 and 120 cm depths.

At 188 cm from pruned *Grevillea robusta* trees the largest positive per cent deviation of +5.8 was registered around PT2 by tube B2 at 18 cm depth while the largest negative deviation of -7.2 was recorded around tree PT5 by tube N2 again at 18 cm depth. The lowest deviations were again registered at 90 and 120 cm depths.

At 376 cm away the largest positive per cent deviation of +6.6 was registered around PT1 by tube C1 at 18 cm depth while the largest negative value of -6.0 was recorded around tree PT2 by tube C2 again at 18 cm depth.

This confirms that, as expected, mulching was more effective in the layers closer to the surface than in the deeper depths. We notice here that tube M2 at 94 cm from PT5 had been consistent in registering negative deviations at all depths except, though marginally, at 120 cm depth.

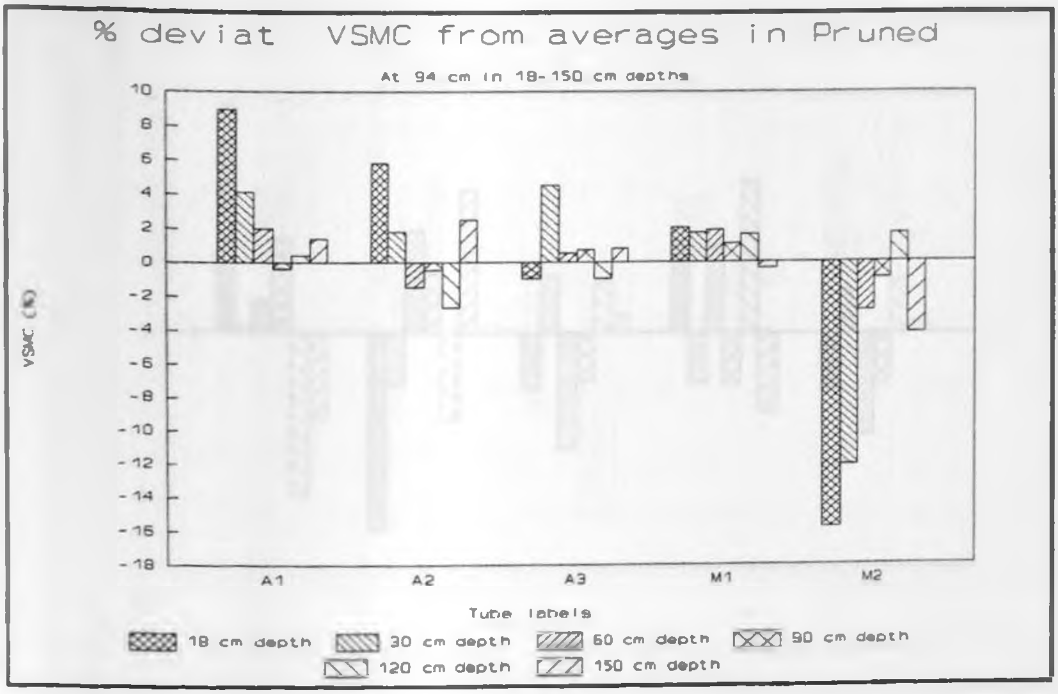

Fig. 156. LR92 per deviation of VSMC in pruned.

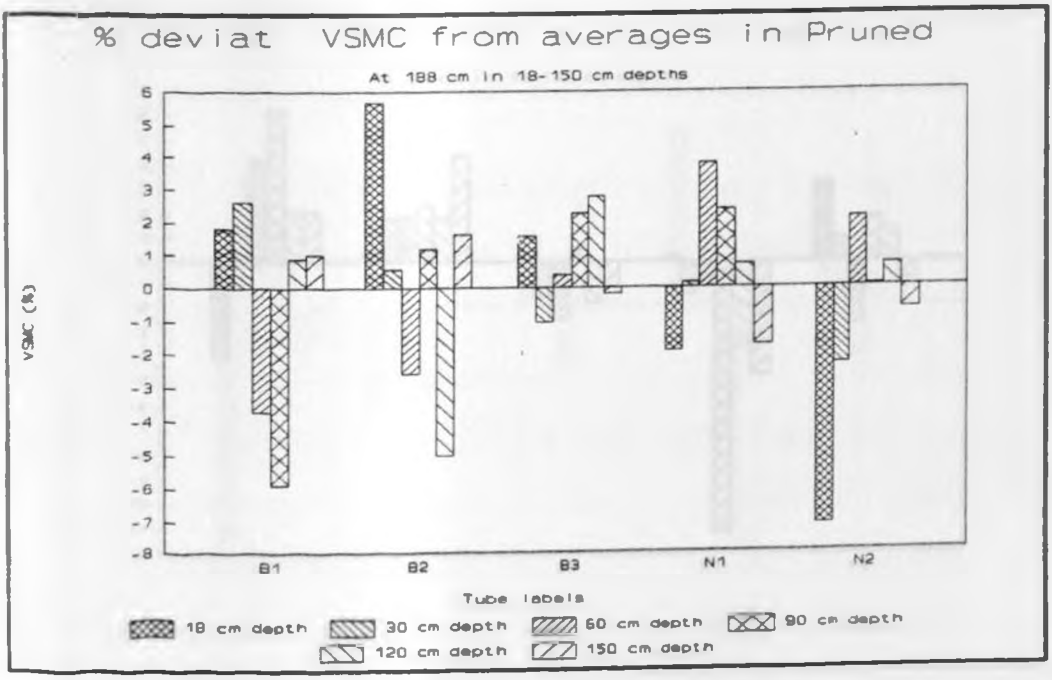

Fig. 157. LR92 per cent deviation in pruned plots.

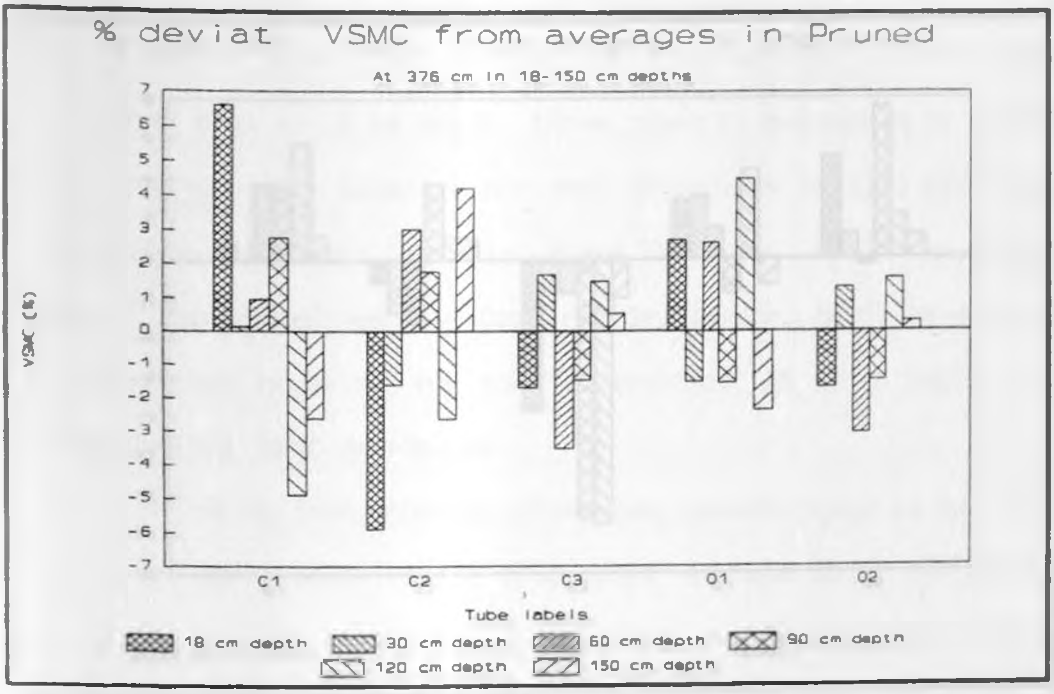

Fig. 158. LR92 per cent deviations in pruned.

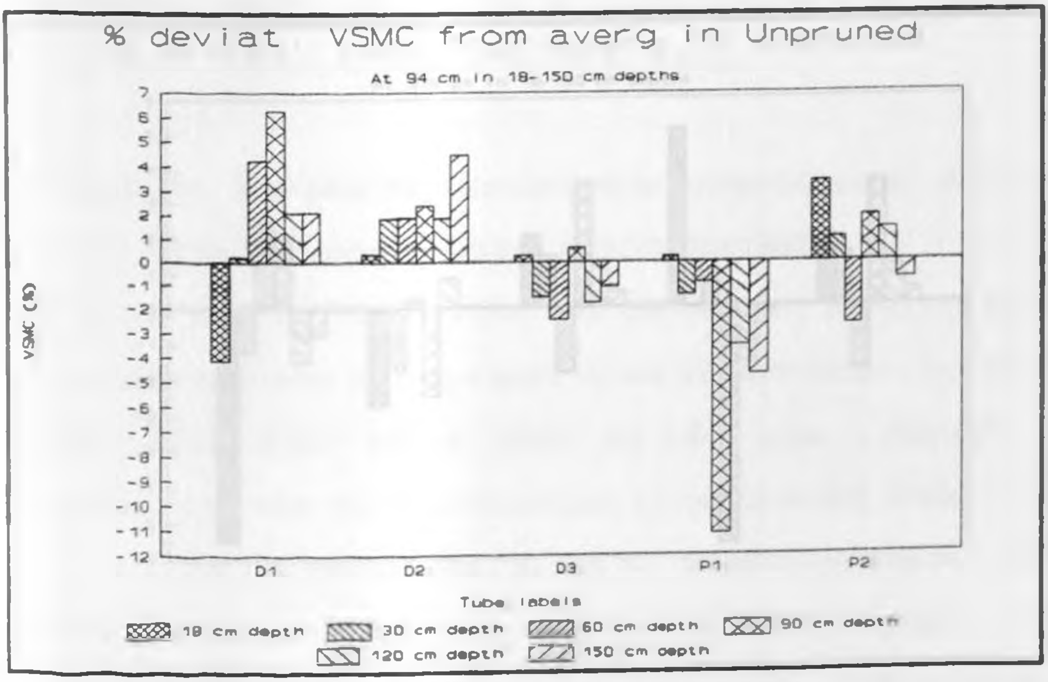

Fig. 159. LR92 per cent deviations in unpruned.

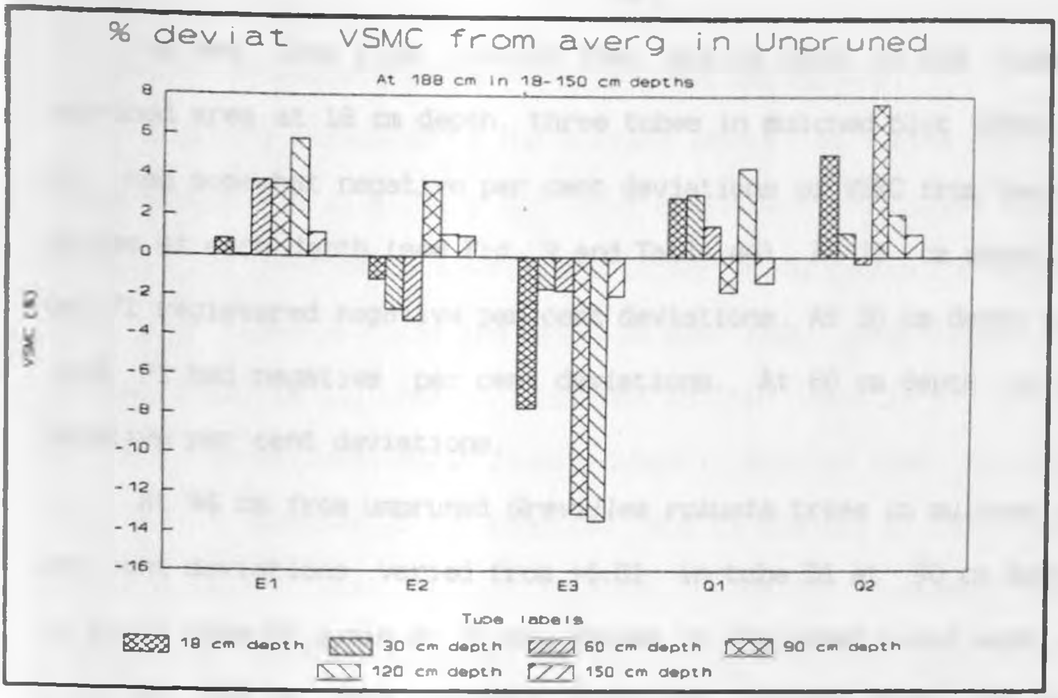

Fig. 160. LR92 per cent deviations in unpruned.

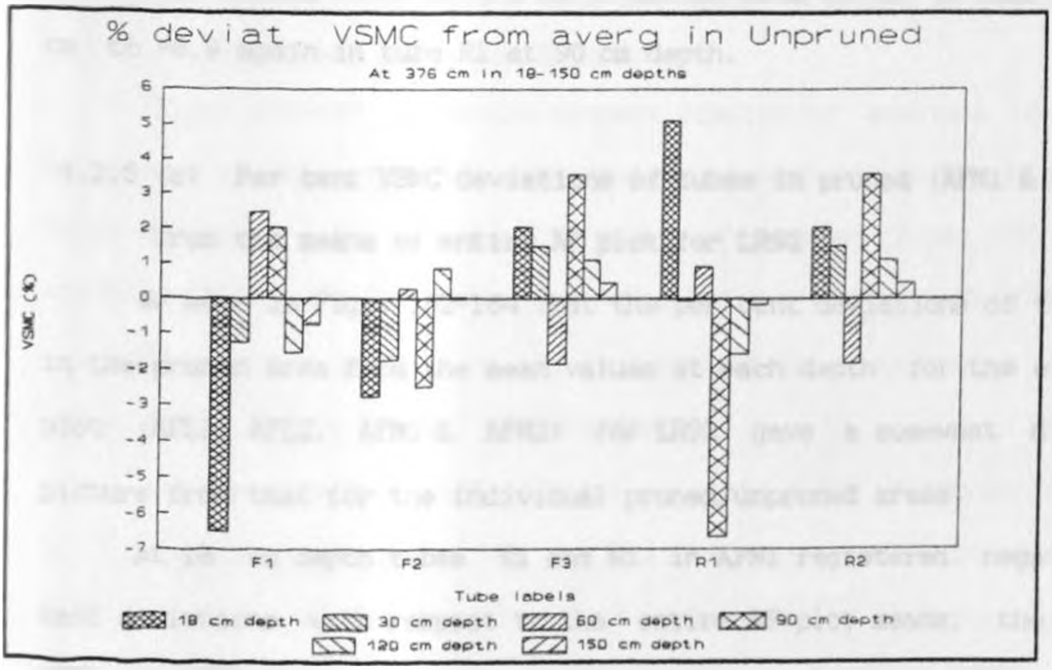

Fig. 161. LR92 per cent deviations in unpruned.

We see from Figs. 159-161 that during LR92. of the tubes in the unpruned area at 18 cm depth, three tubes in mulched plot (AFM2: D1: F1: P1) had somewhat negative per cent deviations of VSMC from the means values at each depth (see Fig. 9 and Table 44). At 18 cm depth tubes D1 and F1 registered negative per cent deviations. At 30 cm depth tubes F1 and P1 had negative per cent deviations. At 60 cm depth only P1 had negative per cent deviations.

At 94 cm from unpruned *Grevillea robusta* trees in mulched plot the per cent deviations varied from +6.01 in tube D1 at 90 cm depth to -11.02 in tube P1 again at 90 cm. Values in unmulched plots were lower.

At 188 cm from unpruned *Grevillea robusta* trees the per cent deviations varied from -13.89 in tube E3 around UT3 at 120 cm to +7.8 in tube Q2 around UT5. At 376 cm it varied from +5.23 in tube R1 at 18 cm to -6.9 again in tube R1 at 90 cm depth.

4.2.5 (c) Per cent VSMC deviations of tubes in pruned (AFM1 & AFL1) from the means of entire AF plot for LR92

We see in Figs. 162-164 that the per cent deviations of the tubes in the pruned area from the mean values at each depth for the entire AF plot (AFL1, AFL2, AFM1 & AFM2) for LR92 gave a somewhat different picture from that for the individual pruned/unpruned areas.

At 18 cm depth tubes M1 and N1 in AFM1 registered negative per cent deviations with respect to the entire AF plot means. the rest in AFM1 and AFM2 had positive per cent deviations. At 30 cm depth all the three tubes around PT4 (i.e. M1. N1 and O1) at 94. 188 and 376 cm and C1 at 376 cm. from PT1 (Figs. 159-161) had (relatively small) negative per cent VSMC with respect to the entire AF plot. At 90 cm depths tube

O1 around PT4 registered negative per cent deviations.

Limiting ourselves to the surface layers, we notice here that two tubes around PT5 (i.e. M2 & N2) have consistently recorded large negative per cent deviations in the 18 and 30 cm depths. A comparison with the tubes in unpruned area we see that fewer tubes in pruned mulched (that is 13) than in unpruned mulched (that is 17) had negative per cent deviations. Again fewer tubes in mulched than in Local plots (that is 17 against 21 for unpruned and 13 against 17 for pruned) had negative values. This is also true for 18 and 30 cm depths. Thus mulch enabled the tubes in mulched plots to record more soil moisture at higher depths than the average values for the entire plots.

4.2.5 (d) Per cent deviations from the means in pruned AF plots (AFM1 and AFL1) for SR92

Figs. 165-167 & 168-170 present results of analysis of per cent deviations of VSMC from the mean values of each depth during SR92 at three distances: 94, 188 and 376 cm from the pruned (Figs. 165-167) and unpruned (Figs. 176-178) *Grevillea robusta* trees. Figs. 171-173 present the VSMC per cent deviations of the tubes in the pruned area from the means of the entire AF plot at each depth.

We see from Figs. 165-167 that all the tubes in pruned AFM1 (A1, B1, C1, M1, N1 & O1) around PT1 and PT4 had registered positive per cent VSMC deviations with respect to mean values at 18 cm depth. At 30 cm depth tube O1 recorded per cent VSMC below the average value. Tube B1 (Fig. 166) had negative values at 60 and 90 cm while C1. (Fig. 167) had negative values at 90 cm with respect to the entire AF plant, though negligibly small.

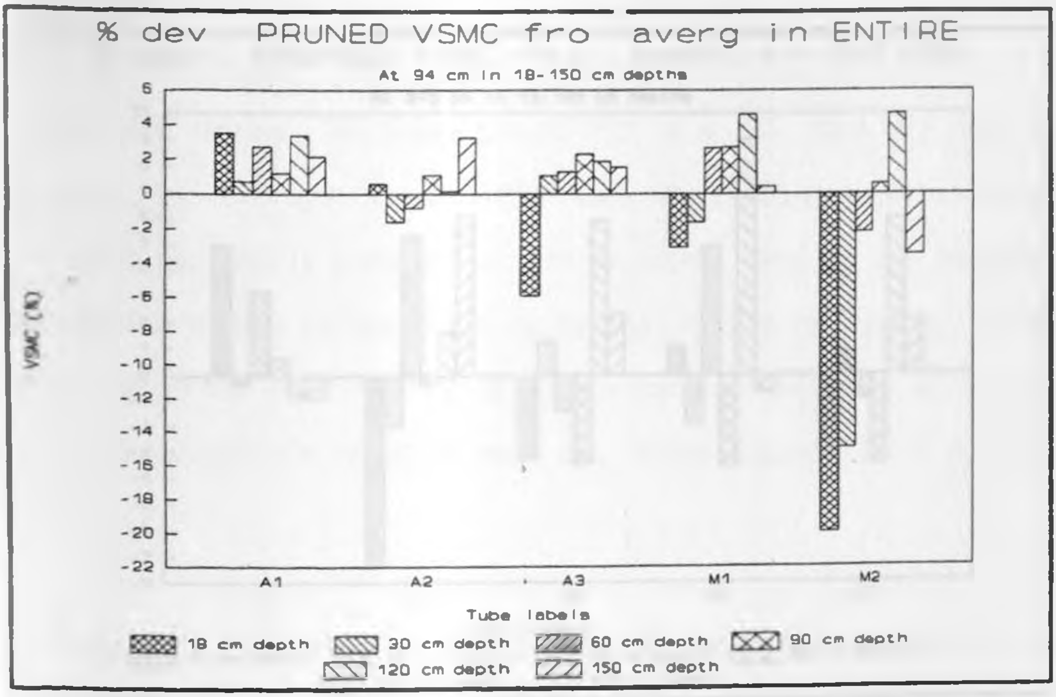

Fig. 162. LR92 per cent deviations of pruned in Entire at 94 cm from Grevillea robusta trees.

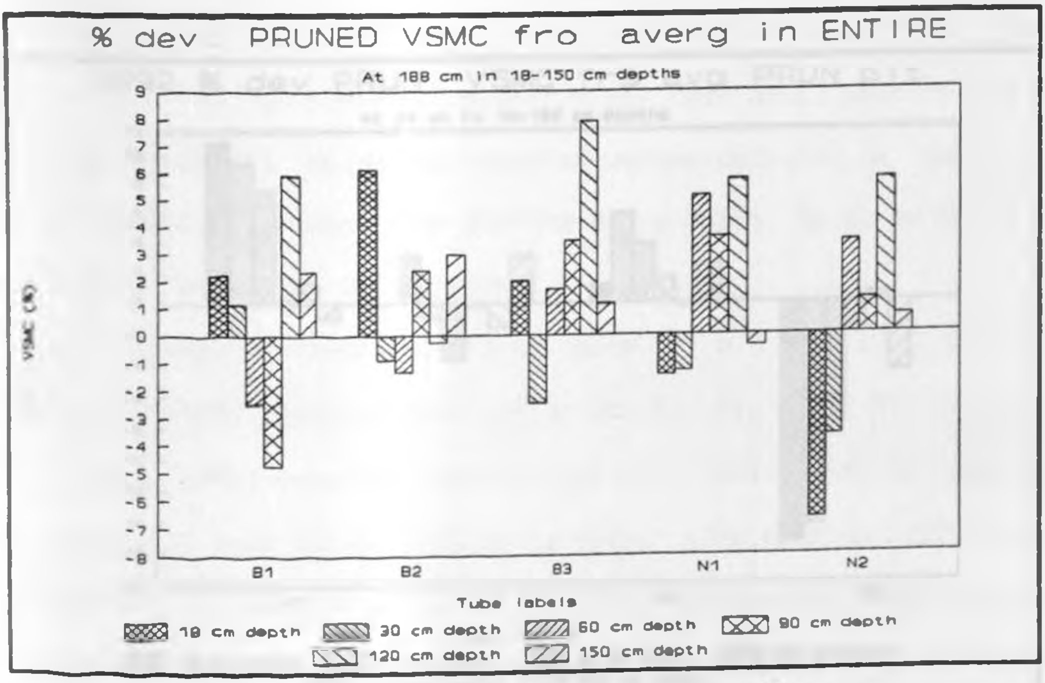

Fig. 163. LR92 per cent deviation of pruned in Entire at 188 cm.

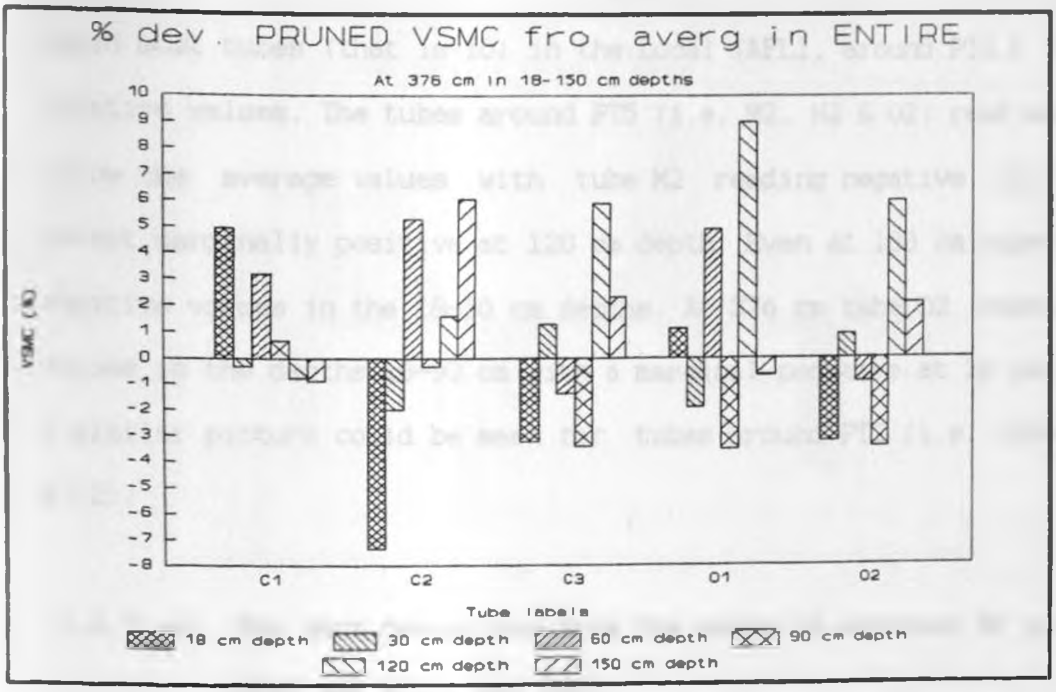

Fig. 164. LR92 per cent deviations of pruned in Entire at 376 cm

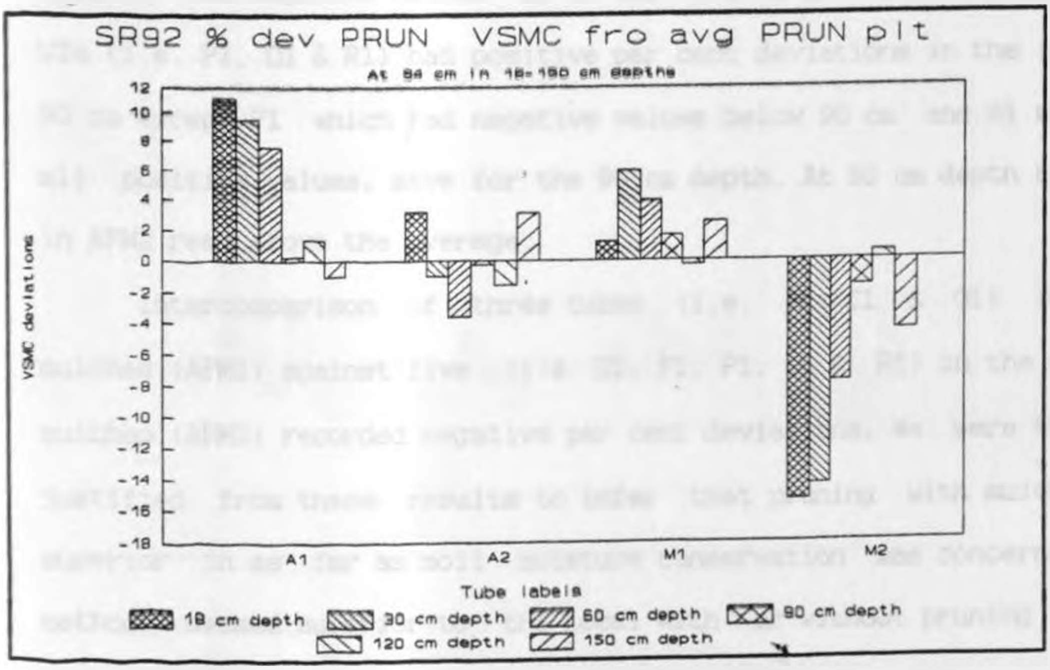

Fig. 165. SR92 per cent deviations of pruned means of pruned at 94 cm from Grevillea robusta trees.

Again most tubes (that is 10) in the Local (AFL1, around PT2 & PT5) had negative values. The tubes around PT5 (i.e. M2, N2 & O2) read mostly below the average values with tube M2 reading negative all through except marginally positive at 120 cm depth. Even at 188 cm tube N2 read negative values in the 18-30 cm depths. At 376 cm tube O2 read negative values in the depths 18-90 cm with a marginal positive at 30 cm depth. A similar picture could be seen for tubes around PT2 (i.e. tubes A2, B2 & C2).

4.2.5 (e) Per cent deviations from the means in unpruned AF plot (AFM2 and AFL2) for SR92

From Fig. 168-170 we see that: of the tubes in unpruned mulching plot (AFM2) tube D1 had negative deviations at 18 and 30 cm depths while tube F1 had negative values at 18 and 150 cm depths. The tubes around UT4 (i.e. P1, Q1 & R1) had positive per cent deviations in the layer 18-90 cm except P1 which had negative values below 90 cm and R1 which had all positive values, save for the 90 cm depth. At 60 cm depth all tubes in AFM2 read above the average.

Intercomparison of three tubes (i.e. B1, C1 & O1) in pruned mulched (AFM1) against five (i.e. D1, F1, P1, Q1 & R1) in the unpruned mulched (AFM2) recorded negative per cent deviations. We were therefore justified from these results to infer that pruning with mulching was superior in as far as soil moisture conservation was concerned. Both methods seemed superior to the Local with or without pruning as most tubes in the Local read below the average values.

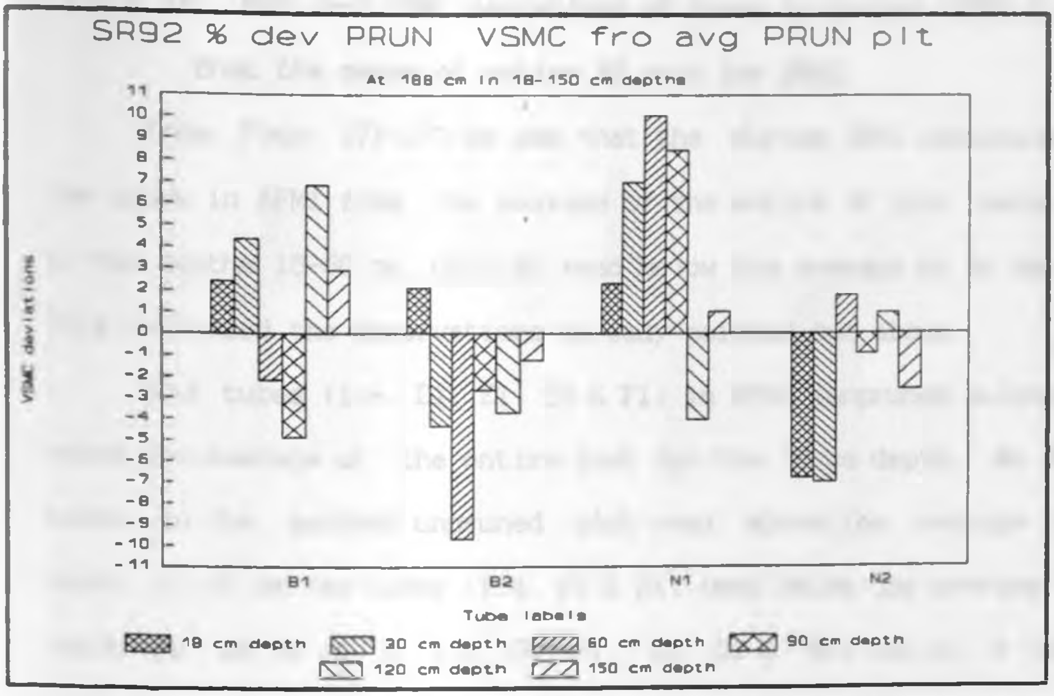

Fig. 166. SR92 per cent deviations of VSMC in pruned plots from the average of the pruning treatment at 188 cm from Grevillea robusta trees.

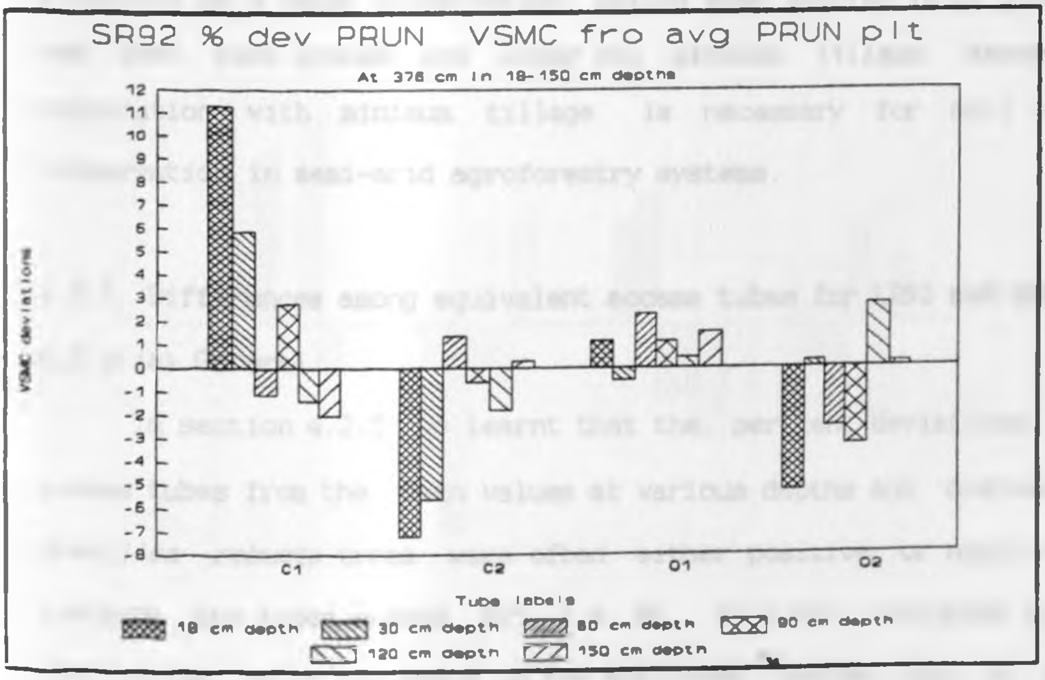

Fig. 167. SR92 per cent deviations of VSMC in pruned plots from the average of the pruning treatment at 376 cm from Grevillea robusta trees.

4.2.5 (f) Per cent VSMC deviations of tubes in pruned (AFM1 & AFL1) from the means of entire AF plot for SR92

From Figs. 171-173 we see that the during SR92 deviations of all the tubes in AFM1 from the average of the entire AF plot were positive in the depths 18-60 cm. Only B1 read below the average at 90 cm depth. This confirmed the observations already pointed out above.

Four tubes (i.e. D1, E1, Q1 & F1) in AFM2 (unpruned mulched) read below the average of the entire plot for the 18 cm depth. At 30 cm all tubes in the mulched unpruned plot read above the average for that depth. At 60 cm two tubes (i.e. F1 & R1) read below the average for that depth and at 90 cm 5 (i.e. D1, P1, E1, Q1 & R1) out of 6 tubes read below the average for the depth. Only F1 read above the average for this depth.

From the foregoing we conclude that crop residue mulching was more effective as a water conservation method when applied in AF plots that had been root pruned and under the minimum tillage. Apparently in combination with minimum tillage is necessary for soil moisture conservation in semi-arid agroforestry systems.

4.2.6 Differences among equivalent access tubes for LR92 and SR92

4.2.6 (a) General

In section 4.2.5 we learnt that the per cent deviations of some access tubes from the mean values at various depths and distances from *Grevillea robusta* trees were often either positive or negative. For instance the tubes around PT5 (i.e. M2, N2 & O2) recorded generally VSMC values below the means in the shallower depths, that is, at 90 cm and above. Those tubes around PT1 (i.e. A1, B1 & C1) and UT1 (i.e. D1,

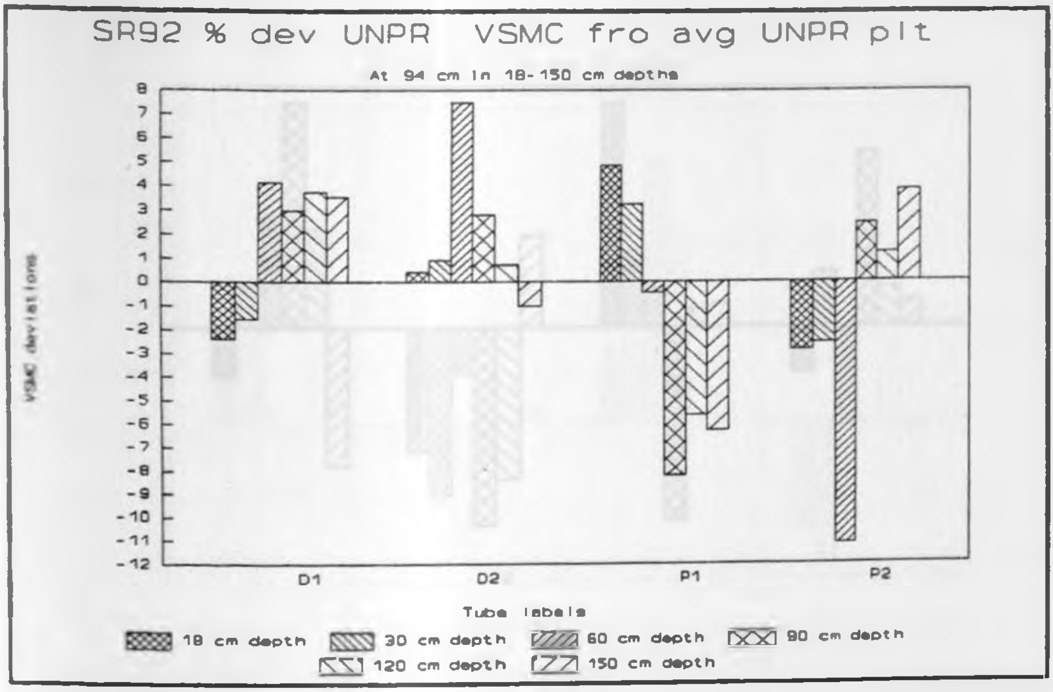

Fig. 168. SR92 per cent deviations of VSMC in unpruned plots from the average of the unpruned treatment at 94 cm from Grevillea robusta trees.

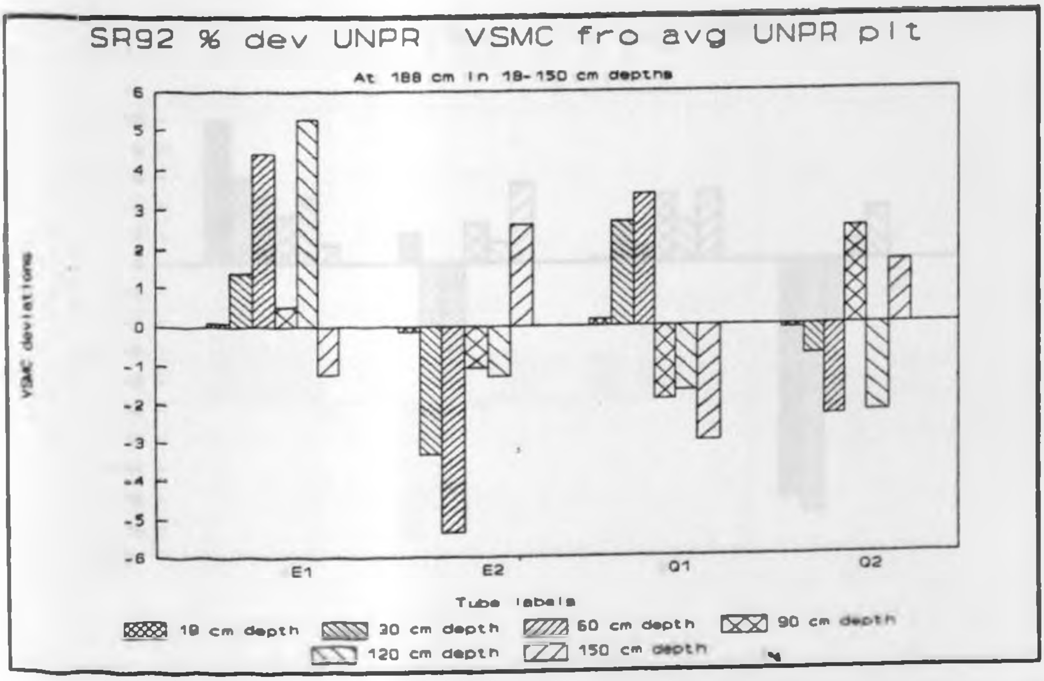

Fig. 169. SR92 per cent deviations of VSMC in unpruned plots from the average of the unpruned treatment at 188 cm from Grevillea robusta trees.

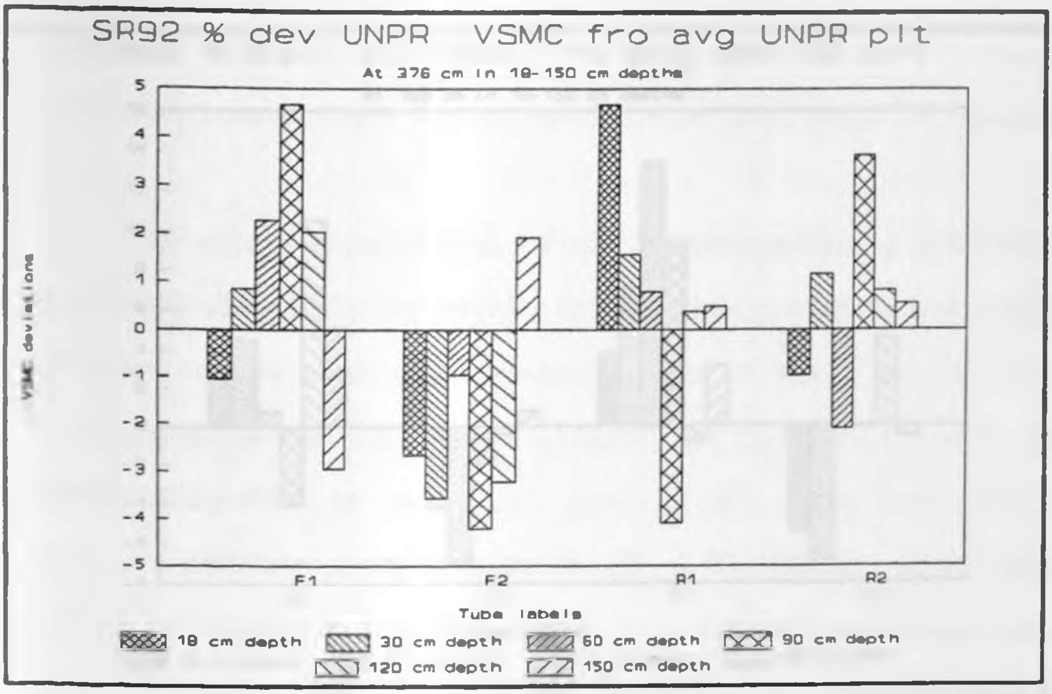

Fig. 170. SR92 per cent deviations of VSMC in unpruned plots from the average of the unpruned treatment at 376 cm from Grevillea robusta trees.

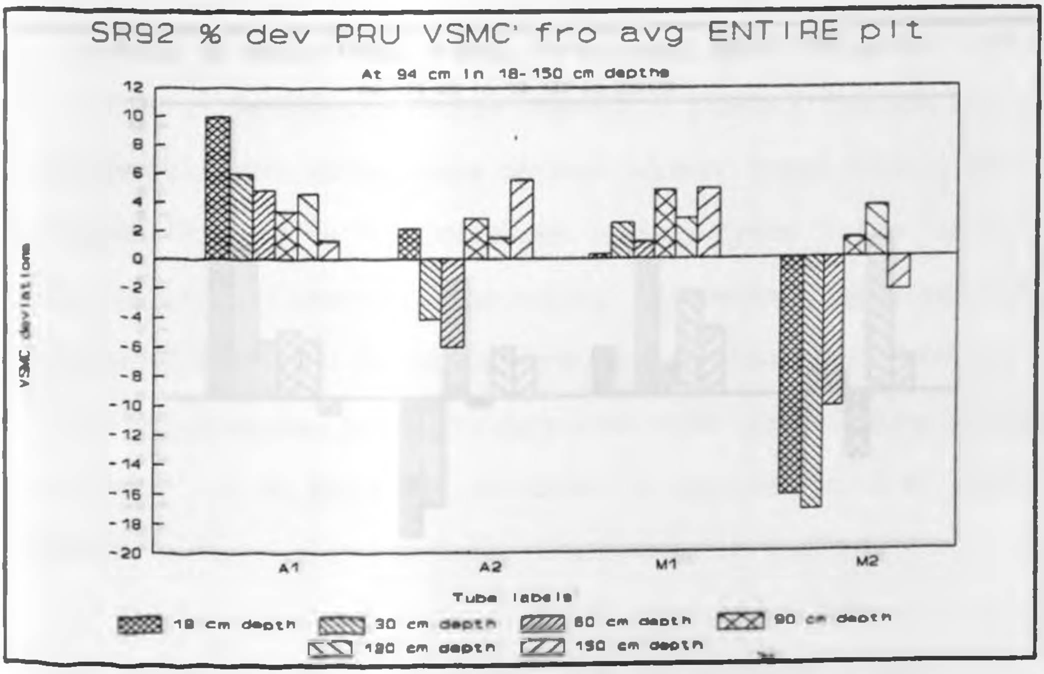

Fig. 171. SR92 per cent deviations of VSMC in pruned plots from the average of Entire AF at 94 cm from Grevillea robusta trees.

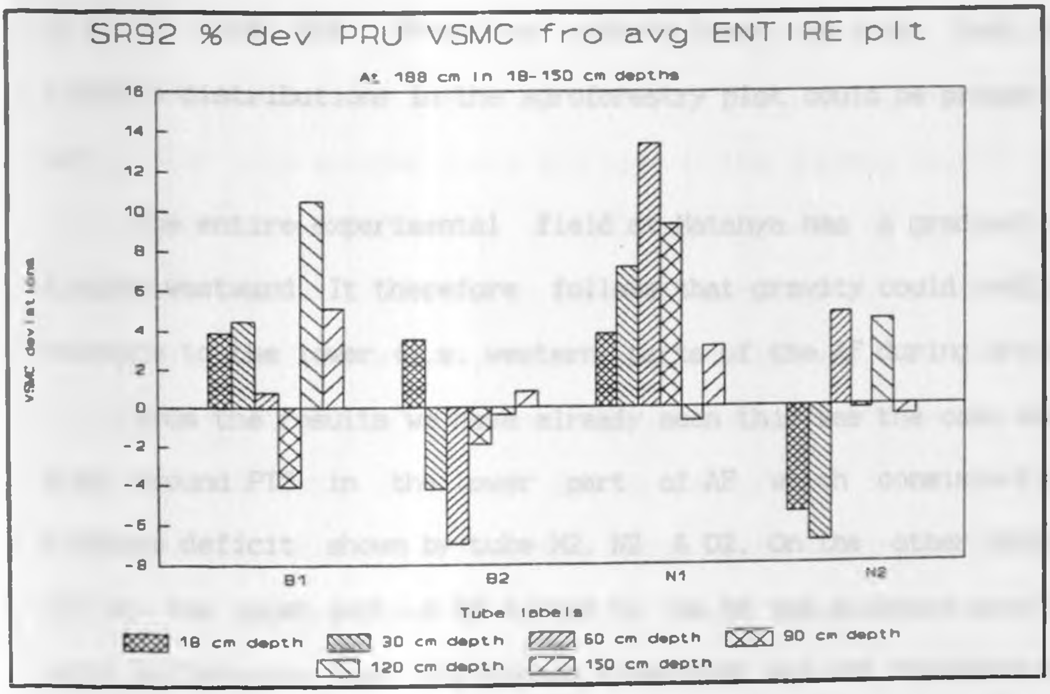

Fig. 172. SR92 per cent deviations of VSMC in pruned plots from the average of Entire AF at 188 cm from Grevillea robusta trees.

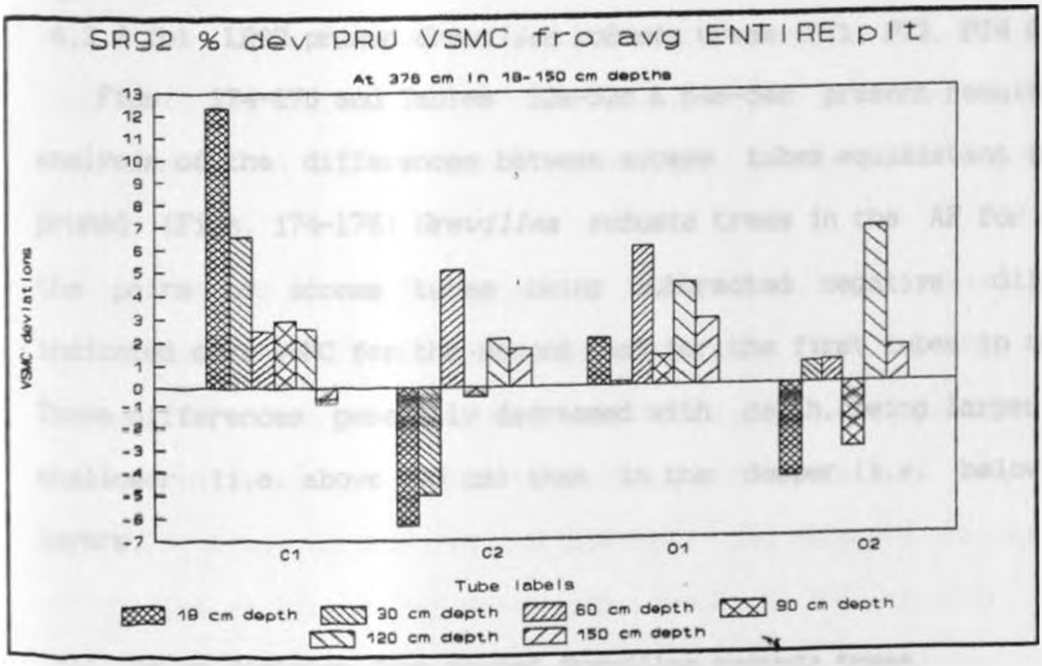

Fig. 173. SR92 per cent deviations of VSMC in pruned plots from the average of Entire AF at 376 cm from Grevillea robusta trees.

E1 & F1) from the *Grevillea robusta* trees in order that the soil moisture distributions in the agroforestry plot could be properly mapped out.

The entire experimental field at Matanya has a gradient of 4-5% sloping westward. It therefore follows that gravity could confine soil moisture to the lower (i.e. western) parts of the AF during dry season.

From the results we have already seen this was the case except the area around PT5 in the lower part of AF which consistently had a moisture deficit shown by tube M2, N2 & O2. On the other hand PT1 and UT1 on the upper part of AF tended to be in the moisture surplus area. Local differences near the access tubes that are not representative for that part of plots in which they were mounted may be a reason but in this case yields show that this moisture distribution may be very real.

4.2.6 (b) LR92 pruned *Grevillea robusta* trees (PT1, PT2, PT4 & PT5)

Figs. 174-176 and Tables 52a-52c & 54a-54c present results of the analysis of the differences between access tubes equidistant from the pruned (Figs. 174-176) *Grevillea robusta* trees in the AF for LR92. Of the pairs of access tubes being subtracted negative differences indicated more VSMC for the second than for the first tubes in the pair. These differences generally decreased with depth, being larger in the shallower (i.e. above 90 cm) than in the deeper (i.e. below 120 cm) layers.

(i) 94 cm distance from pruned *Grevillea robusta* trees

We notice from Fig. 174 and Table 52a that during LR92 at 94 cm the largest positive difference was that of A1 and M2 which gave tube difference of VSMC of +7.25 at 18 cm, indicating more moisture in A1 located in the mulched area than in M2, in the Local plots. All these differences with mulched plots are high in the surface layers. The largest negative difference of -3.55 was between M1 and M2. Here tube M2 in Local had at 170 cm depth more moisture than M1 in the mulched plots. This will have little agronomic consequences. The average of the differences of pair of tubes for the whole soil profile between A1 and M2 was +2.18, which is mainly due to the surface layer, so remarkable agronomically. This value is almost three times the grand average (i.e. average of differences of tubes in pruned and unpruned AF at that distance from the trees) difference in VSMC of 0.82. These differences were mainly positive in all soil depths except 90, 120 and 170 cm where negative values dominated. The differences mainly decreased with depth for the two distances, that is, 94 and 188 cm. At 376 cm (Fig. 176) this trend broke down as mixed higher and lower values could be found even for lower depths. Fig. 174 results in higher moisture up slope and also towards the mulched plots, particularly in the surface layers.

(ii) 188 and 376 cm distance from pruned *Grevillea robusta*

Figs. 175 & 176 and Tables 52b & 52c show that, for LR92 the tubes were on the average at the same soil moisture levels, because as the average differences for all the pairs at 188 cm was 0.03 and at 376 cm was 0.19. Like for the 94 cm distance, the absolute values of the differences at 188 cm decreased with depth. At 188 cm (Fig. 175) the largest positive difference of 3.85 was between B2 and N2 in the surface layer. The largest negative difference of -2.42 was between B1 and N1 in the 90 cm layer: both tubes were in mulched plot (AFM1) near PT1 and

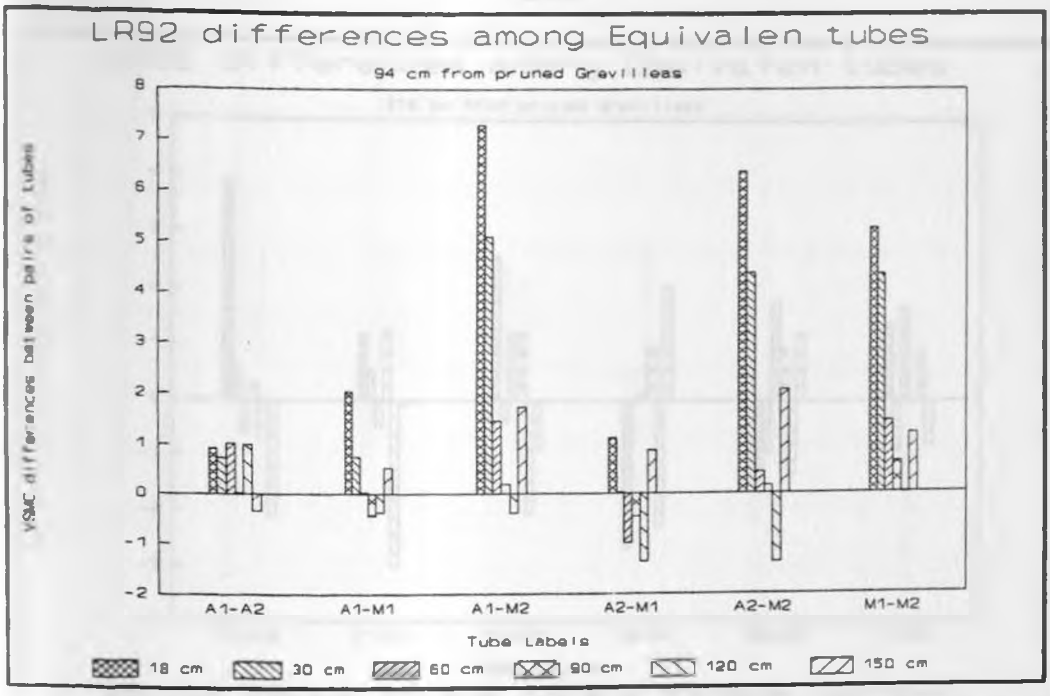

Fig. 174. LR92 differences in VSMC among equivalent access tubes at 94 cm from *Grevillea robusta* trees in pruned plots.

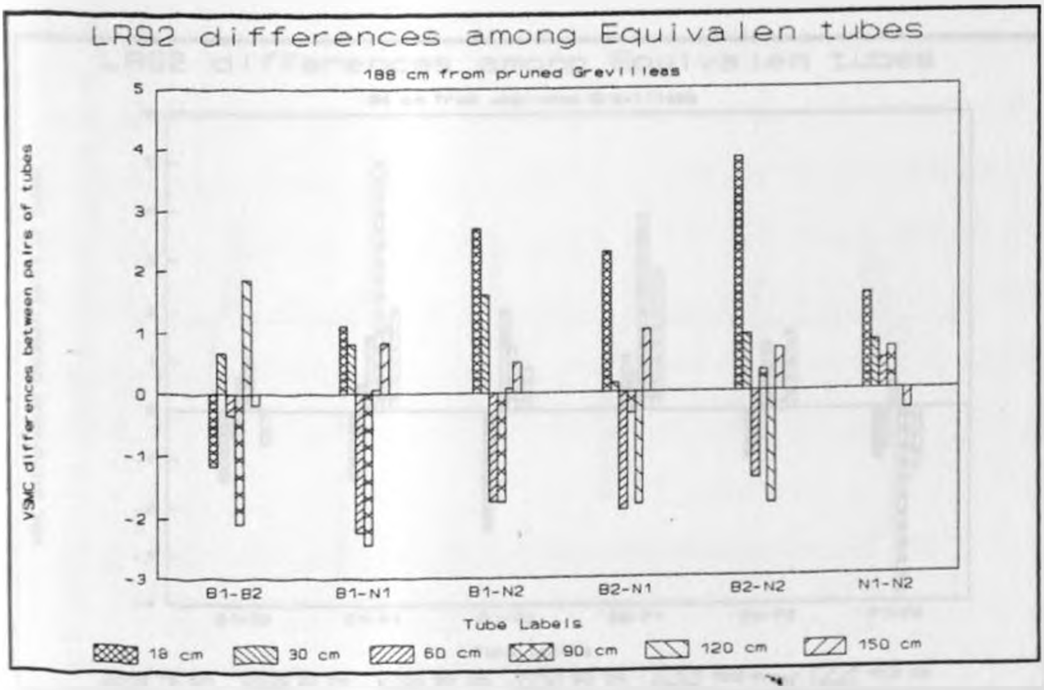

Fig. 175. LR92 differences in VSMC among equivalent access tubes at 188 cm from *Grevillea robusta* trees in pruned plots.

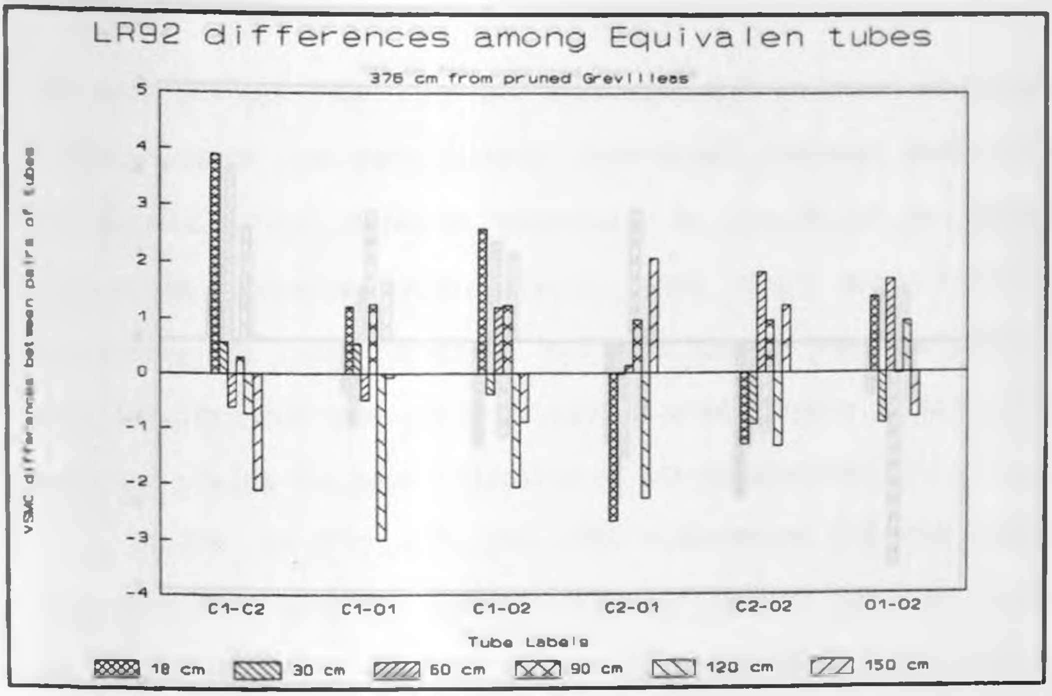

Fig. 176. LR92 differences in VSMC among equivalent access tubes at 376 cm from *Grevillea robusta* trees in pruned plots.

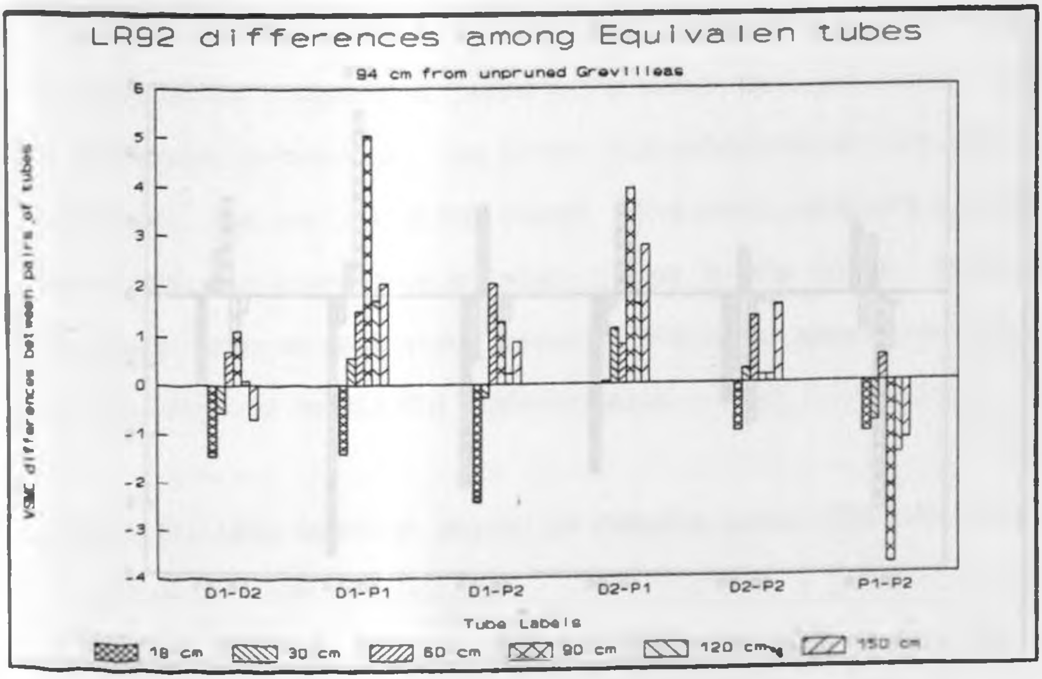

Fig. 177. LR92 differences in VSMC among equivalent access tubes at 94 cm from *Grevillea robusta* trees in unpruned plots.

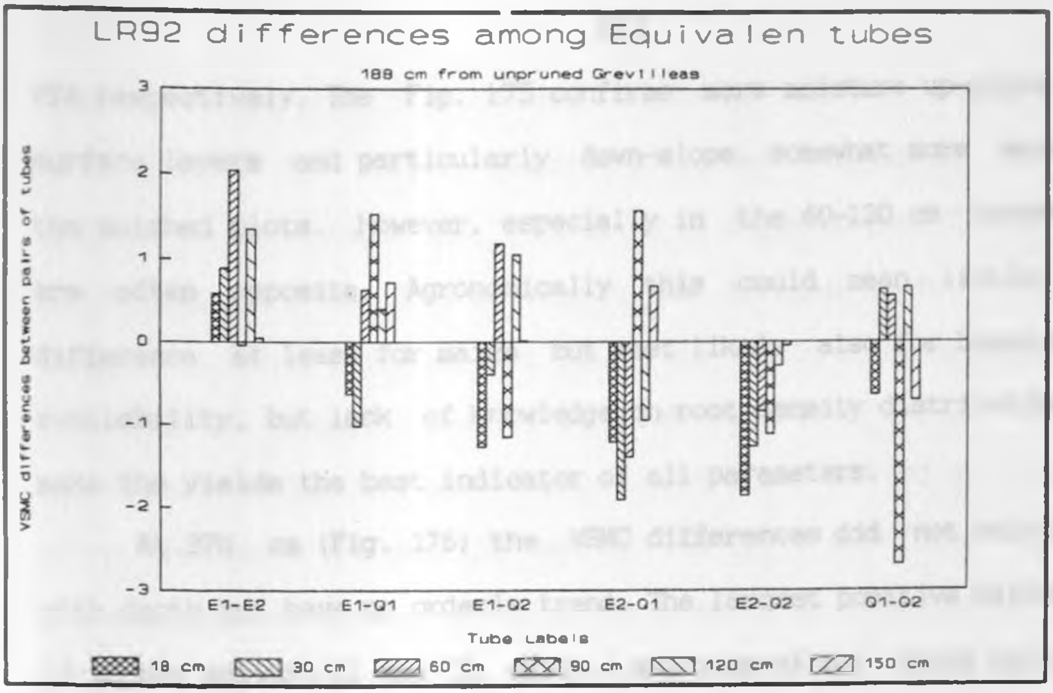

Fig. 178. **LR92 differences in VSMC among equivalent access tubes at 188 cm from *Grevillea robusta* trees in unpruned plots.**

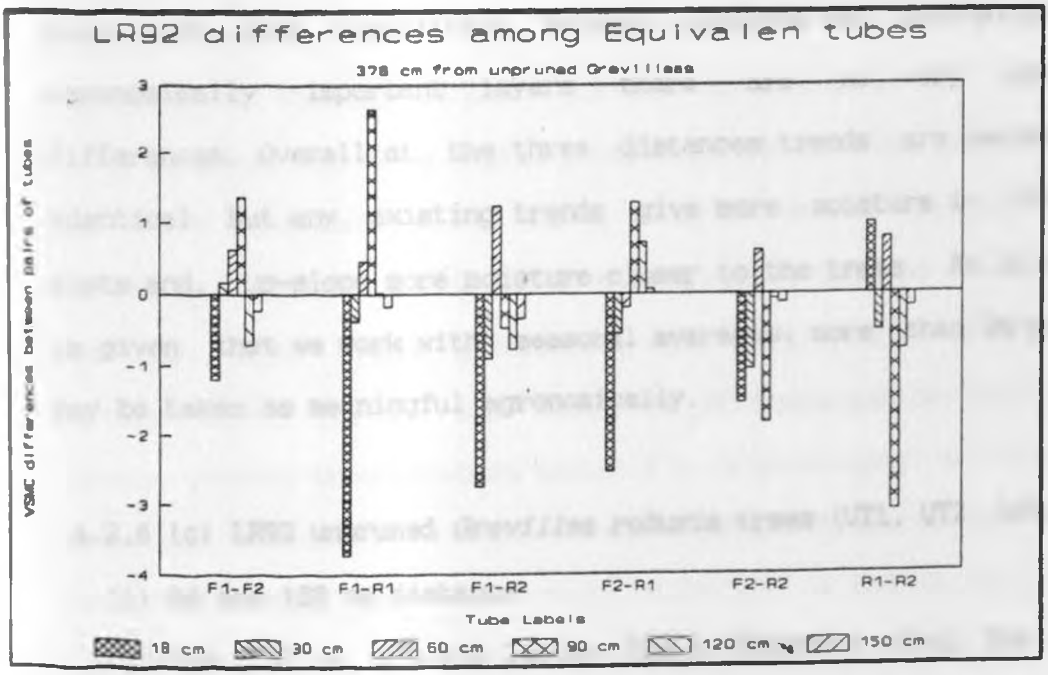

Fig. 179. **LR92 differences in VSMC among equivalent access tubes at 376 cm from *Grevillea robusta* trees in unpruned plots.**

PT4 respectively. The Fig. 175 confirms more moisture up-slope in the surface layers and particularly down-slope, somewhat more moisture in the mulched plots. However, especially in the 60-120 cm layers trends are often opposite. Agronomically this could mean little overall difference at least for maize but most likely also for beans moisture availability, but lack of knowledge on root density distribution should make the yields the best indicator of all parameters.

At 376 cm (Fig. 176) the VSMC differences did not only decrease with depth but have no orderly trend. The largest positive difference of +3.90 was between C1 and C2, again a mulching effect being noticed. The largest negative difference of -3.01 was between C1 and O1 but at 120 cm, which is agronomically not really important. At 376 cm in the surface layers the mulched plots have more moisture, but this is up-slope much more significant. Between up-slope and down-slope in the agronomically important layers there are no very significant differences. Overall at the three distances trends are certainly not identical but any existing trends give more moisture in the mulched plots and, up-slope more moisture closer to the trees. At 30 cm and 60 cm given that we work with seasonal averages, more than 2% difference may be taken as meaningful agronomically.

4.2.6 (c) LR92 unpruned *Grevillea robusta* trees (UT1, UT2, UT4 & UT5)

(i) 94 and 188 cm distance

Figs. 177 & 178 and Tables 53a & 53b show that, for LR92 the overall profile differences between any pair of tubes at 94 and 188 cm were generally low and lay between -0.77 and +1.37 for the former and -0.84 and +0.90 for the latter distances from *Grevillea robusta* trees.

There were no orderly decreasing trends as for the pruned *Grevillea robusta* plots. The largest positive difference between any two pair of tubes at 94 cm distance was 5.05 at 90 cm depth between D1 and P1. The largest negative was -3.79 between P1 and P2 again at 90 cm depth. The largest positive difference at 188 cm was +2.04 at 60 cm depth between E1 and E2 and largest negative was -2.69 between Q1 and Q2, again at 90 cm. There was therefore more moisture around UT1 (at 188 cm) and UT5 (at 94 cm particularly) than the rest of the trees (see Figs. 185 & 186). However, outside these exceptions the moisture in different layers shows opposite differences, making them agronomically most likely unimportant.

(ii) 376 cm distance

Fig. 179 and Table 53c show the differences between pairs of access tubes at 376 cm from *Grevillea robusta* trees for LR92. The results show that the largest positive difference at 376 cm was +2.63 which occurred at 90 cm depth between F1 and R1. The largest negative was -3.73 again between F1 and R1 at 18 cm depth. There was therefore more moisture around UT4 & UT5 at this distance than for the other trees (see Fig. 179). These differences were particularly strong in the surface layer (18 cm) and little or no compensation in the deeper layers. Overall thee moisture around UT4 is surprising, and the position down-slope could be the main reason. Also particularly surprising are such consistently high values at 90 cm for P2, O2 and R2. This can be no incidental picture, but the reason would be more a soil physical one than an agronomic one or have to do with tree root density in such a layer, in combination with less crop roots.

4.2.6 (d) SR92 pruned *Grevillea robusta* trees (PT1, PT2, PT4 & PT5)

Figs. 180-182 & 183-185 and Tables 54a-54c & 55a-55c present results of the analysis of the differences between access tubes equidistant from the pruned (Figs. 180-182 and unpruned (Figs. 183-185 *Grevillea robusta* trees in the AF during SR92. We want to note that generally, when comparing Figs. 174-176 and 177-179 as well as the Tables 52 and 54, there is much striking similarity between general trends. Crops have changed but trees and soil much less. It appears as if we can see the crop water availability as a function of depth and distance being in first instance determined by pre-sowing tree root and soil water conditions and the presence of mulch. As a final decisive factor rainfall distribution is subsequently determining crop development and yields.

(i) **94 cm distance**

We notice from Fig. 180 and Table 54a that for SR92 at the distance of 94 cm the largest positive difference was between A1 and M2 which was +9.38 at 18 cm depth, exactly the same position as in LR92. The largest negative difference of -2.54 was between A2 and M1 at 30 cm depth, as the tube A1 in the mulched plot had more moisture. The largest average of the differences of pair of tubes for the whole soil profile was +3.63 which was between A1 and M2, again the same was true in LR92. These differences were mainly positive when the first tubes of the pair of addends were in mulched plots, indicating more soil moisture in mulched than in the Local plots. The differences mainly decreased with depth for the two distances, that is, 94 and 188 cm. This trend again did not extend to 376 cm from the trees, where only differences in the surface layer were really important. The same conclusions on moisture distribution hold here as found for 94 cm in LR92. the latter being somewhat smaller in range.

(ii) 188 and 376 cm distance

Figs. 181 & 182 and Tables 54b & 54c show that for SR92 positive differences between pairs of tubes almost equalled the negative ones as the average of +0.20 was close to zero, comparable to LR92. The largest positive difference of +5.41 was between N1 and N2 at 30 cm in mulching and Local plots respectively. The minimum of -6.68 was between B2 and N1 at 60 cm depth. Here again we find that tube N1 in mulched plot had a higher VSMC value. The absolute values of the differences at 188 cm for SR92 actually increased somewhat with depth with 60 cm having generally larger differences between pairs of tubes than other depths. Compared to Fig. 172 the differences in Fig. 178 are larger, for which a higher moisture range over that wet season must be responsible. Up-slope the situation in the Local plots is again wetter in the surface layers but this is no longer true in the mulched plots, where of course the surface layer must be different from the previous season. There is less compensation between moisture in different layers as in LR92. Particularly N1 has a lot more moisture relatively than N2 and the soil around B2 is relatively much drier at agronomically important depths.

At 376 cm (Fig. 190) the largest positive difference of +6.76 was between mulched C1 and Local C2, as in the case of LR92. Both tubes were on the upper part of pruned AF. The largest negative difference at 376 cm was -3.05 between Local C2 and Mulched O1 but here at 18 cm depth, where also a large difference occurred in LR92. Differences are again generally larger in SR92.

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At 376 cm (Fig. 190) the largest positive difference of +6.76 was between mulched C1 and Local C2, as in the case of LR92. Both tubes were on the upper part of pruned AF. The largest negative difference at 376 cm was -3.05 between Local C2 and Mulched O1 but here at 18 cm depth, where also a large difference occurred in LR92. Differences are again generally larger in SR92.

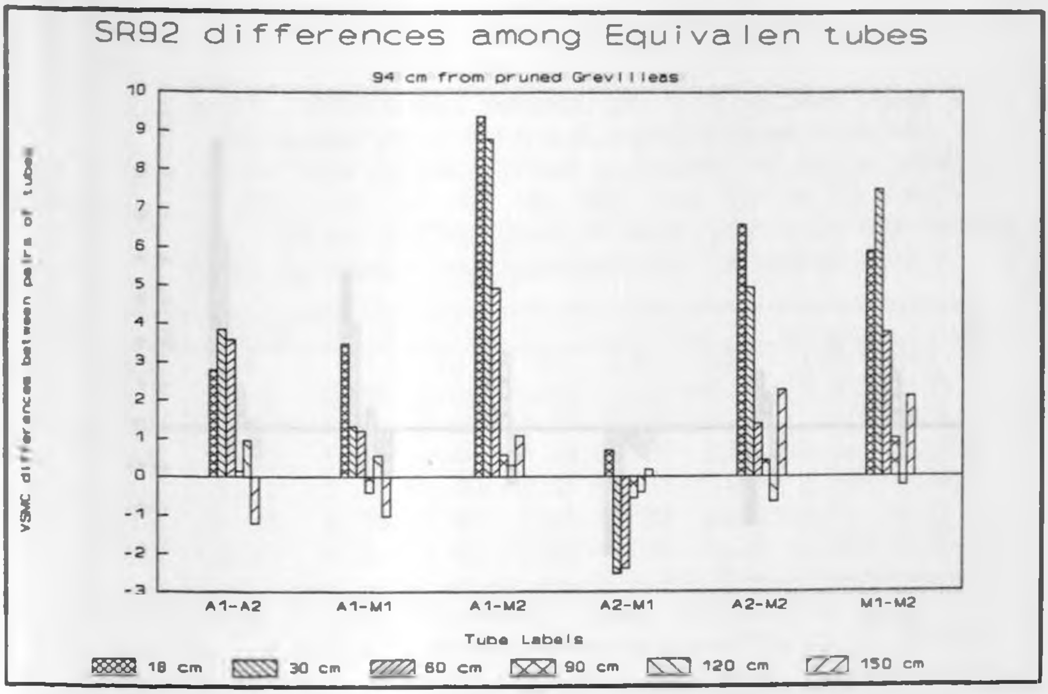


Fig. 180. SR92 differences in VSMC among equivalent access tubes at 94 cm from *Grevillea robusta* trees in pruned plots.

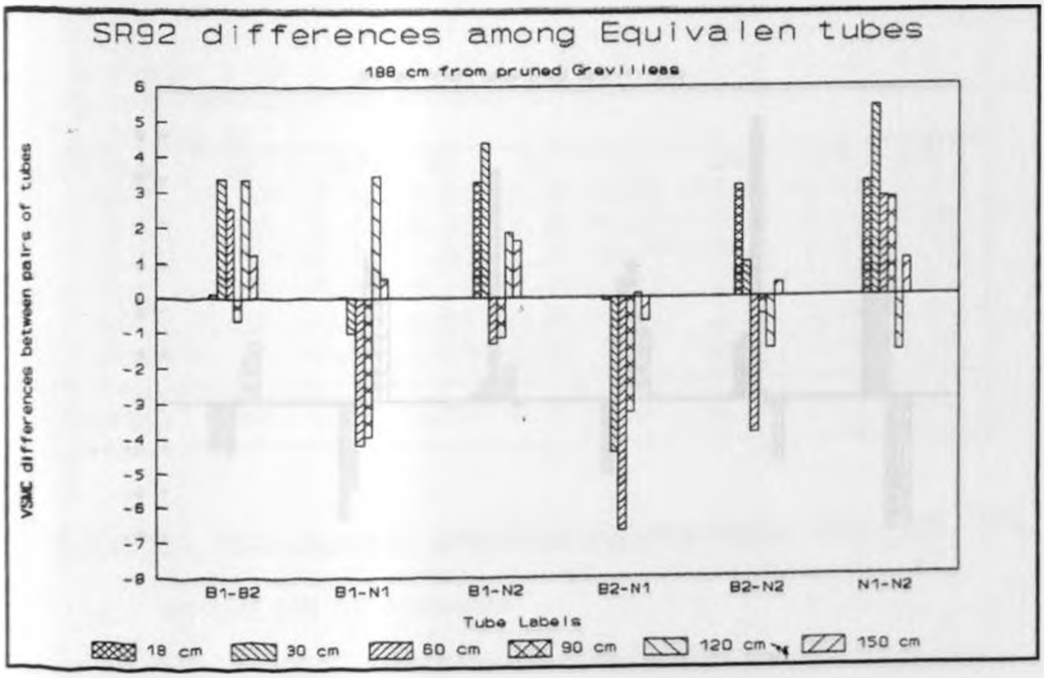


Fig. 181. SR92 differences in VSMC among equivalent access tubes at 188 cm from *Grevillea robusta* trees in pruned plots.

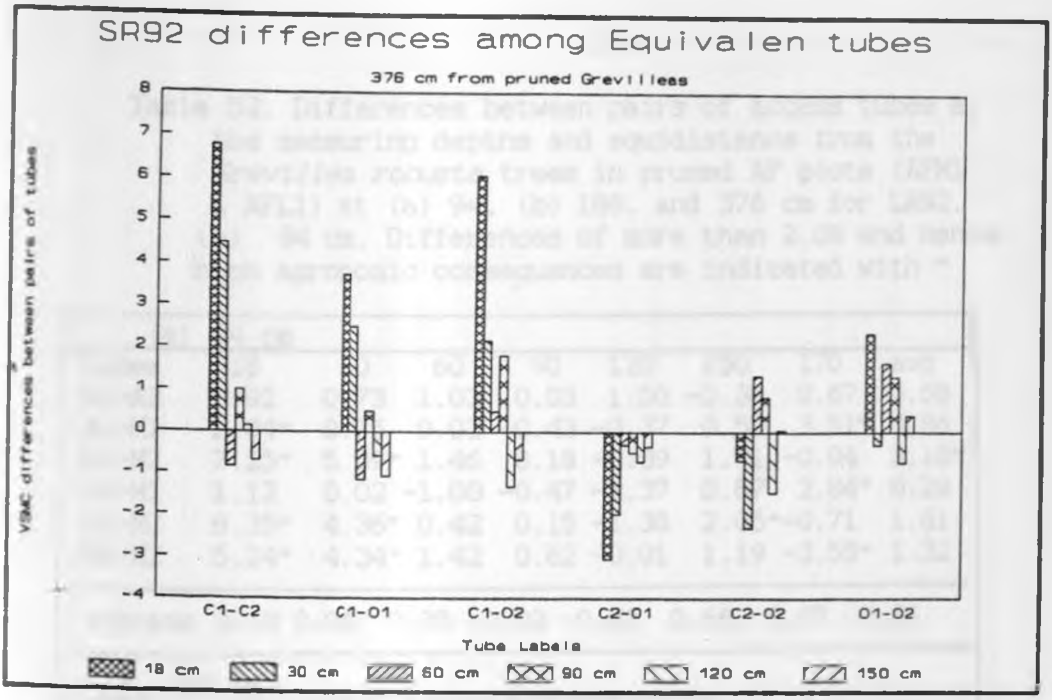


Fig. 182. SR92 differences in VSMC among equivalent access tubes at 376 cm from *Grevillea robusta* trees in pruned plots.

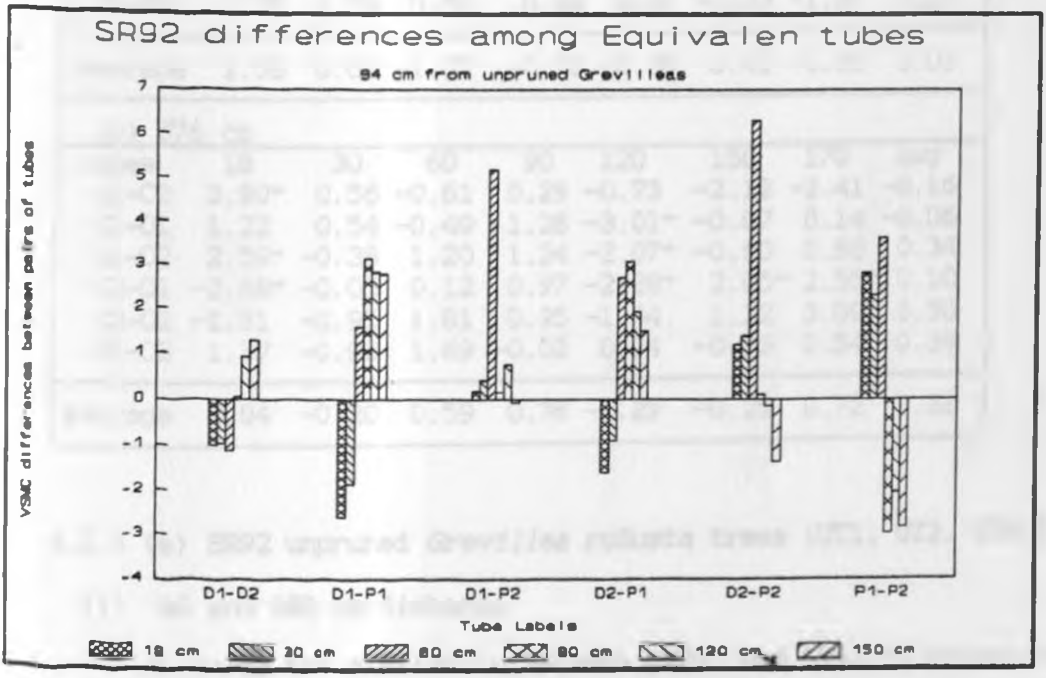


Fig. 183. SR92 differences in VSMC among equivalent access tubes at 94 cm from *Grevillea robusta* trees in unpruned plots.

Table 52. Differences between pairs of access tubes at the measuring depths and equidistance from the *Grevillea robusta* trees in pruned AF plots (AFM1 & AFL1) at (a) 94, (b) 188, and 376 cm for LR92. (a) 94 cm. Differences of more than 2.0% and hence high agronomic consequences are indicated with $^+$

(a) 94 cm

tubes	18	30	60	90	120	150	170	avg
A1-A2	0.92	0.73	1.03	0.03	1.00	-0.34	0.67	0.58
A1-M1	2.04$^+$	0.75	0.03	-0.43	-0.37	0.53	3.51$^+$	0.86
A1-M2	7.25$^+$	5.09$^+$	1.46	0.18	-0.39	1.71	-0.04	2.18$^+$
A2-M1	1.12	0.02	-1.00	-0.47	-1.37	0.87	2.84$^+$	0.29
A2-M2	6.35$^+$	4.36$^+$	0.42	0.15	-1.38	2.05$^+$	-0.71	1.61
M1-M2	5.24$^+$	4.34$^+$	1.42	0.62	-0.01	1.19	-3.55$^+$	1.32
average	3.13	2.04	0.38	-0.02	-0.43	0.66	0.07	0.86

(b) 188 cm

tubes	18	30	60	90	120	150	170	avg
B1-B2	-1.17	0.66	-0.35	-2.08$^+$	1.86	-0.19	1.01	-0.03
B1-N1	1.11	0.80	-2.24$^+$	-2.42$^+$	0.06	0.84	0.62	-0.17
B1-N2	2.68$^+$	1.59	-1.74	-1.74	0.06	0.51	-0.68	0.10
B2-N1	2.28$^+$	0.14	-1.89	-0.34	-1.80	1.02	-0.39	-0.14
B2-N2	3.85$^+$	0.93	-1.39	0.34	-1.80	0.70	-1.69	0.15
N1-N2	1.57	0.79	0.50	0.68	0.00	-0.33	-1.30	0.27
average	1.58	0.66	-1.07	-0.76	-0.38	0.41	-0.35	0.01

(c) 376 cm

tubes	18	30	60	90	120	150	170	avg
C1-C2	3.90$^+$	0.56	-0.61	0.29	-0.73	-2.12	-2.41	-0.16
C1-01	1.22	0.54	-0.49	1.26	-3.01$^+$	-0.07	0.14	-0.06
C1-02	2.59$^+$	-0.38	1.20	1.24	-2.07$^+$	-0.90	0.68	0.34
C2-01	-2.68$^+$	-0.03	0.12	0.97	-2.28$^+$	2.05$^+$	2.55$^+$	0.10
C2-02	-1.31	-0.95	1.81	0.95	-1.34	1.22	3.09$^+$	0.50
01-02	1.37	-0.92	1.69	-0.02	0.94	-0.83	0.54	0.39
average	0.84	-0.20	0.59	0.78	-1.29	-0.25	0.72	0.31

4.2.6 (e) SR92 unpruned *Grevillea robusta* trees (UT1, UT2, UT4 & UT5)

(i) 94 and 188 cm distance

At 94 cm the similarity between SR92 and LR92 is appreciably less striking though not completely absent. It is again better at 188 cm, and somewhat in between at 376 cm. It appears as if pruning of the trees makes similarity between moisture patterns for contrasting seasons

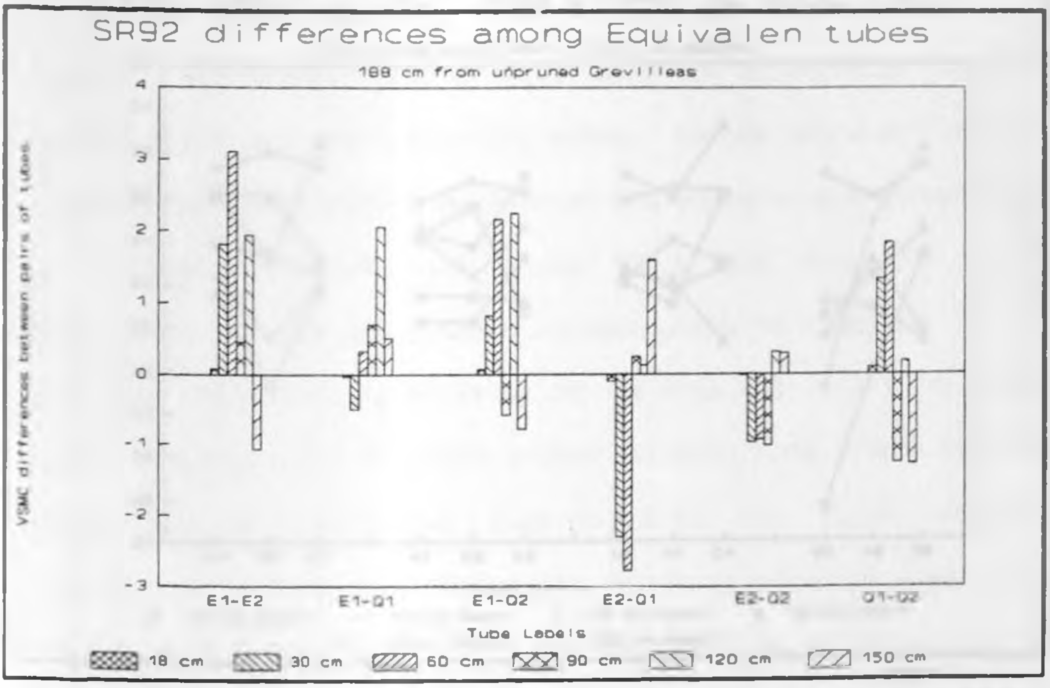


Fig. 184. SR92 differences in VSMC among equivalent access tubes at 188 cm from *Grevillea robusta* trees in unpruned plots.

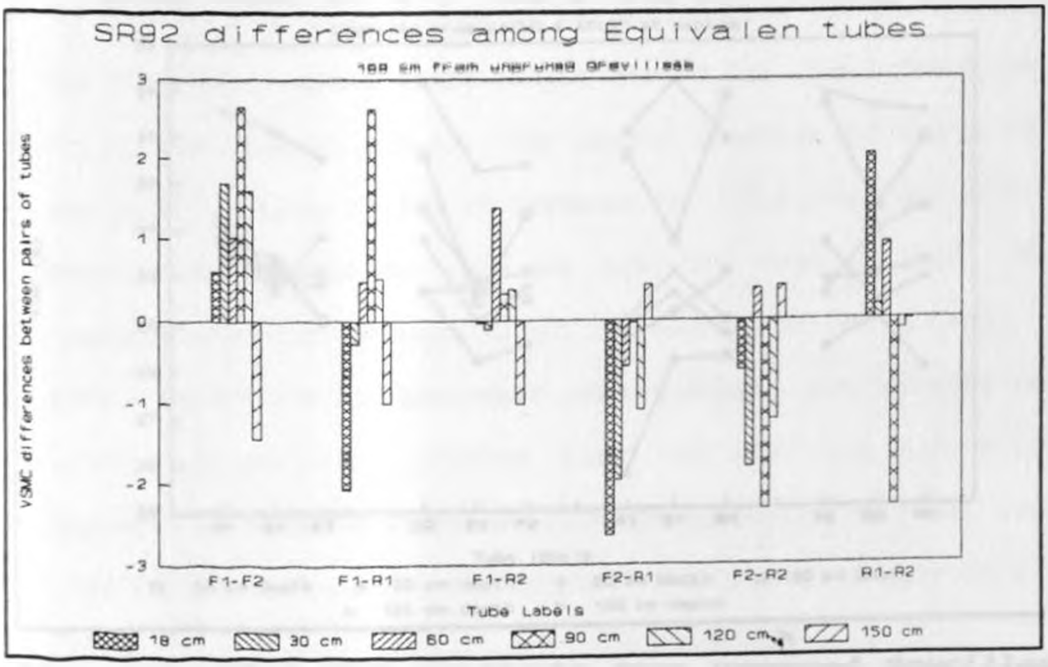


Fig. 185. SR92 differences in VSMC among equivalent access tubes at 376 cm from *Grevillea robusta* trees in unpruned plots.

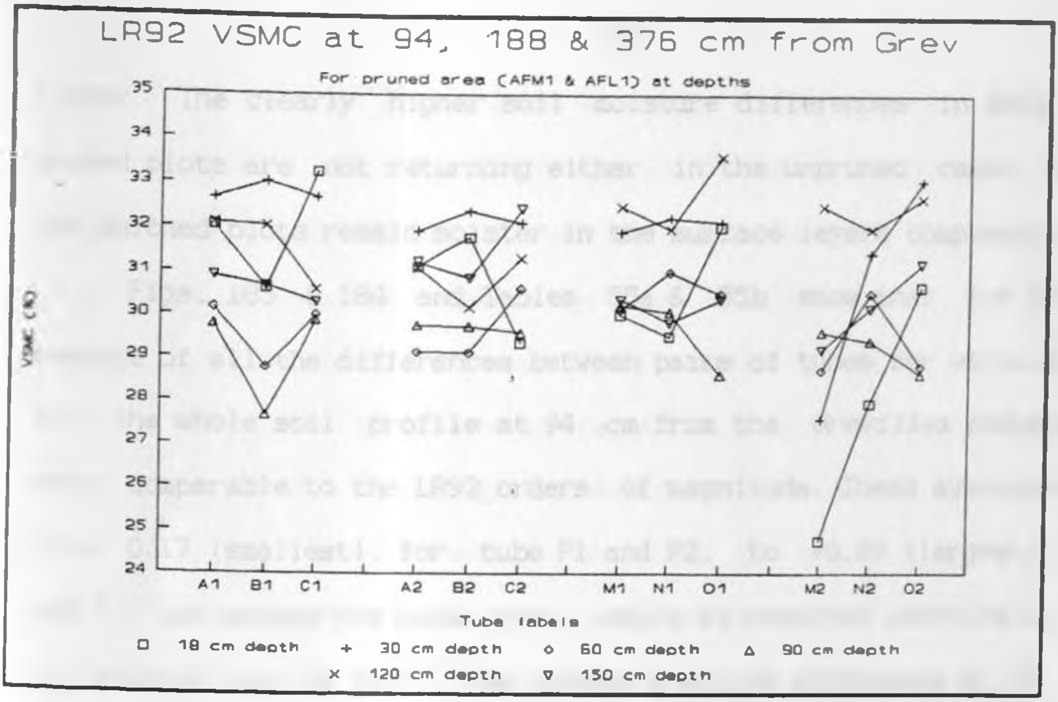


Fig. 186. LR92 VSMC gradients from pruned *Grevillea robusta* trees.

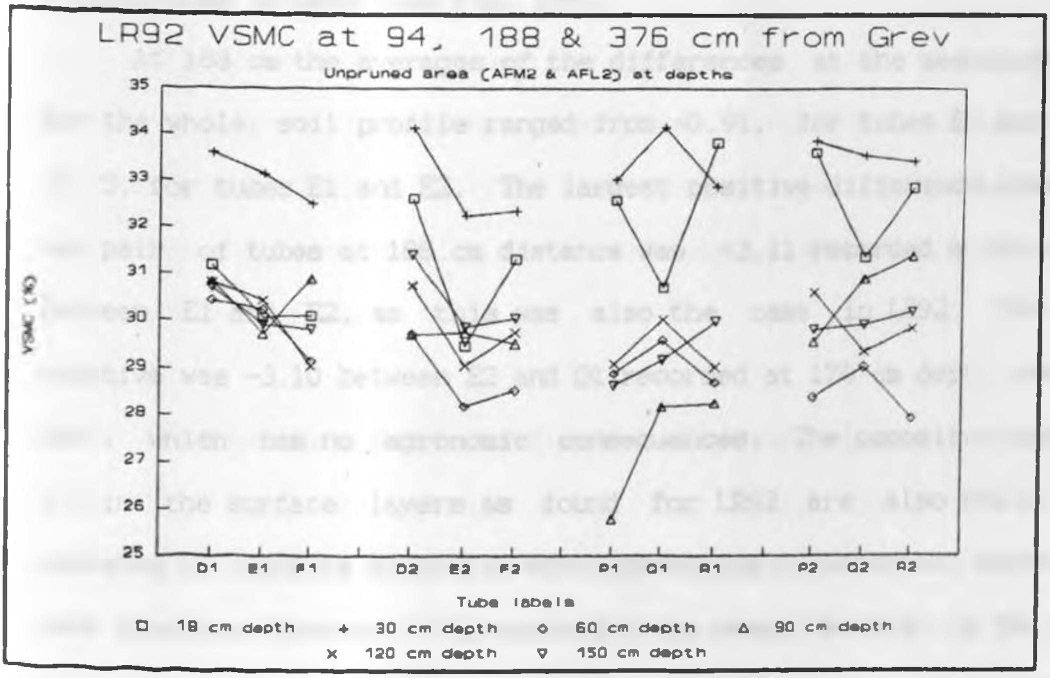


Fig. 187. LR92 VSMC gradients from unpruned *Grevillea robusta* trees.

higher. The clearly higher soil moisture differences in SR92 in the pruned plots are not returning either in the unpruned cases. However, the mulched plots remain moister in the surface layers compared to LR92.

Figs. 183 & 184 and Tables 55a & 55b show that for SR92 the average of all the differences between pairs of tubes for various depths for the whole soil profile at 94 cm from the *Grevillea robusta* trees were comparable to the LR92 orders of magnitude. These averages ranged from +0.17 (smallest), for tube P1 and P2, to +0.99 (largest), for D1 and P2, so across the Local plot, while it occurred identically across the mulched plot in LR92. The largest positive difference at 94 cm was +6.30 recorded at 60 cm depth between D2 and P2 and the largest negative one was -2.98 between P1 and P2 recorded at 90 cm, exactly the same situation as in LR92 (see Fig. 175).

At 188 cm the averages of the differences at the measuring depths for the whole soil profile ranged from -0.91, for tubes E2 and Q1, to +1.25, for tubes E1 and E2. The largest positive difference between any two pair of tubes at 188 cm distance was +3.11 recorded at 60 cm depth between E1 and E2, as this was also the case in LR92. The largest negative was -3.10 between E2 and Q1 recorded at 170 cm depth (see Fig. 184), which has no agronomic consequences. The opposite directions within the surface layers as found for LR92 are also still there, assisted by opposite direction with agronomically important depth at the same distance. However, the mulched plots remain moister in the surface layers.

(ii) 376 cm distance

Fig. 185 and Table 55c show for SR92 the differences between pairs of access tubes at 376 cm from *Grevillea robusta* trees. The results show the largest positive difference at 376 cm to be +2.64 recorded at 90 cm depth between F1 and F2, but the one between F1 and R1 with +2.61 is also close and that one is the same as the maximum for LR92. The largest negative difference was -2.64 between F2 and R1 recorded at 18 cm depth, which was also strongly negative in LR92. The averages of the differences at the measuring depths for the whole soil profile ranged from -1.00, for tubes F2 and R1, to +0.93, for tubes F1 and F2, showing again moister mulched plots. There was therefore more moisture at 376 cm from UT5 than the other trees (see Fig. 182), again in line with LR92 situation. The same surprising result as in LR92 occurs in SR92 with respect to the moisture around UT5. Exactly the same high values occur here at P2, O2 and R2 at 90 cm depth. These are no coincidences but show the similarities between moisture profiles in these two contrasting seasons. It should, however, remain in mind that seasonal averages obscure consequences of rainfall distribution that agronomically can be disastrous and lead to high yield differences and even yield behaviour (yes grain, no grain).

4.2.7 Soil moisture gradients from the *Grevillea robusta* trees

Figs. 186& 187 and 188 & 189 and, Tables 56a & 56b show the behaviour of soil moisture (VSMC) with the distance (i.e. 94, 188 and 376 cm) from the Grevillea robusta trees in the AF plot for the representative seasons LR92 and SR92. These indicate the gradients of soil moisture from the Grevilleas trees for the access tubes installed at 94, 188 and 376 from these trees (see Fig. 9 & Table 3).

Table 53. Differences between pairs of access tubes at the measuring depths and equidistance from the *Grevillea robusta* trees in unpruned AF plots (AFM2 & AFL2) at (a) 94, (b) 188, and 376 cm for LR92. Differences of more than 2.0% and hence high agronomic consequences are indicated with +

(a) 94 cm

tubes	18	30	60	90	120	150	170	avg
D1-D2	-1.45	-0.56	0.70	1.12	0.08	-0.71	0.32	-0.07
D1-P1	-1.40	0.57	1.52	5.05+	1.71	2.06+	-0.40	1.30
D1-P2	-2.44+	-0.27	2.05+	1.26	0.23	0.87	2.04+	0.53
D2-P1	0.04	1.12	0.81	3.93+	1.63	2.76+	-0.72	1.37
D2-P2	-0.99	0.29	1.34	0.15	0.14	1.58	1.71	0.60
P1-P2	-1.03	-0.84	0.53	-3.79+	-1.49	-1.18	2.44+	-0.77
average	-0.96	0.23	1.11	1.34	0.53	1.07	-0.45	0.41

(b) 188 cm

tubes	18	30	60	90	120	150	170	avg
E1-E2	0.58	0.89	2.04+	-0.03	1.35	0.05	1.40	0.90
E1-Q1	-0.63	-1.02	0.64	1.53	0.40	0.73	0.22	0.27
E1-Q2	-1.28	-0.39	1.19	-1.16	1.06	0.01	0.95	0.05
E2-Q1	-1.22	-1.91	-1.40	1.57	-0.95	0.68	-1.18	-0.63
E2-Q2	-1.86	-1.28	-0.85	-1.12	-0.30	-0.04	-0.45	-0.84
Q1-Q2	-0.64	0.63	0.55	-2.69+	0.66	-0.72	0.73	-0.21
average	-0.76	-0.54	0.20	-0.15	0.23	0.14	0.14	-0.10

(c) 376 cm

tubes	18	30	60	90	120	150	170	avg
F1-F2	-1.20	0.16	0.63	1.36	-0.70	-0.22	1.67	0.24
F1-R1	-3.73+	-0.38	0.45	2.63+	0.02	-0.16	0.04	-0.16
F1-R2	-2.75+	-0.90	1.23	-0.46	-0.77	-0.34	0.34	-0.52
F2-R1	-2.53+	-0.54	-0.18	1.27	0.72	0.06	-1.62	-0.41
F2-R2	-1.54	-1.06	0.60	-1.83	-0.07	-0.12	-1.33	-0.77
R1-R2	0.98	-0.51	0.78	-3.09+	-0.79	-0.18	0.30	-0.36
average	-1.60	-0.47	0.45	0.07	-0.17	-0.13	-0.19	-0.29

Table 54. Differences between pairs of access tubes at the measuring depths and equidistance from the *Grevillea robusta* trees in pruned AF plots (AFM1 & AFL1) at (a) 94, (b) 188, and 376 cm for SR92. (a) 94 cm. Differences of more than 2.0% and hence high agronomic consequences are indicated with $^{+}$

(a) 94 cm

tubes	18	30	60	90	120	150	170	avg
A1–A2	2.80^{+}	3.85^{+}	3.57^{+}	0.15	0.94	−1.20	0.35	1.50
A1–M1	3.49^{+}	1.31	1.19	−0.41	0.54	−1.03	0.93	0.86
A1–M2	9.38^{+}	8.78^{+}	4.94^{+}	0.57	0.29	1.06	0.38	3.63^{+}
A2–M1	0.68	−2.54^{+}	−2.38^{+}	−0.56	−0.40	0.17	0.58	−0.64
A2–M2	6.58^{+}	4.94^{+}	1.37	0.42	−0.66	2.26^{+}	0.03	2.13^{+}
M1–M2	5.90^{+}	7.48^{+}	3.75^{+}	0.98	−0.25	2.09^{+}	−0.55	2.77^{+}

(b) 188 cm

tubes	18	30	60	90	120	150	170	avg
B1–B2	0.11	3.36^{+}	2.54^{+}	−0.64	3.35^{+}	1.24	−0.44	1.36
B1–N1	0.03	−1.02	−4.14^{+}	−3.92^{+}	3.45^{+}	0.56	0.22	−0.69
B1–N2	3.29^{+}	4.39^{+}	−1.33	−1.15	1.87	1.63	−1.07	1.09
B2–N1	−0.09	−4.39^{+}	−6.68^{+}	−3.28^{+}	0.10	−0.68	0.66	−2.05^{+}
B2–N2	3.17^{+}	1.03	−3.87^{+}	−0.51	−1.49	0.40	−0.63	−0.27
N1–N2	3.26^{+}	5.41^{+}	2.81^{+}	2.77^{+}	−1.59	1.08	−1.29	1.78

(c) 376 cm

tubes	18	30	60	90	120	150	170	avg
C1–C2	6.76^{+}	4.48^{+}	−0.84	0.99	0.15	−0.71	−1.70	1.30
C1–O1	3.72^{+}	2.49^{+}	−1.16	0.49	−0.59	−1.07	0.11	0.57
C1–O2	6.07^{+}	2.18^{+}	0.49	1.82	−1.32	−0.67	0.26	1.26
C2–O1	−3.05^{+}	−1.99	−0.31	−0.51	−0.73	−0.37	1.81	−0.73
C2–O2	−0.69	−2.30^{+}	1.34	0.82	−1.47	0.03	1.96	−0.04
O1–O2	2.35^{+}	−0.31	1.65	1.33	−0.74	0.40	0.15	0.69

Table 55. Differences between pairs of access tubes at the measuring depths and equidistance from the *Grevillea robusta* trees in unpruned AF plots (AFM2 & AFL2) at (a) 94, (b) 188, and 376 cm for SR92. Differences of more than 2.0% and hence high agronomic consequences are indicated with ⁺

(a) 94 cm

tubes	18	30	60	90	120	150	170	avg
D1-D2	-1.01	-0.96	-1.12	0.06	0.91	1.29	2.31⁺	0.21
D1-P1	-2.62⁺	-1.87	1.57	3.13⁺	2.82⁺	2.78⁺	-0.07	0.82
D1-P2	0.18	0.41	5.17⁺	0.15	0.76	-0.08	0.35	0.99
D2-P1	-1.61	-0.91	2.70⁺	3.08⁺	1.91	1.48	-2.38⁺	0.61
D2-P2	1.19	1.37	6.30⁺	0.10	-0.15	-1.37	-1.97	0.78
P1-P2	2.80⁺	2.28⁺	3.60⁺	-2.98⁺	-2.06⁺	-2.85⁺	0.41	0.17

(b) 188 cm

tubes	18	30	60	90	120	150	170	avg
E1-E2	0.08	1.81	3.11⁺	0.45	1.94	-1.08	2.42⁺	1.25
E1-Q1	-0.02	-0.50	0.33	0.69	2.06⁺	0.50	-0.68	0.34
E1-Q2	0.07	0.82	2.16⁺	-0.58	2.24⁺	-0.79	0.77	0.67
E2-Q1	-0.11	-2.31⁺	-2.78⁺	0.24	0.12	1.58	-3.10⁺	-0.91
E2-Q2	-0.01	-0.99	-0.94	-1.03	0.31	0.29	-1.65	-0.57
Q1-Q2	0.09	1.32	1.84	-1.27	0.18	-1.29	1.45	0.33

(c) 376 cm

tubes	18	30	60	90	120	150	170	avg
F1-F2	0.58	1.69	1.02	2.64⁺	1.59	-1.42	0.40	0.93
F1-R1	-2.06⁺	-0.27	0.47	2.61⁺	0.50	-1.00	-0.75	-0.07
F1-R2	-0.02	-0.11	1.39	0.32	0.37	-1.02	-0.58	0.05
F2-R1	-2.64⁺	-1.97	-0.55	-0.03	-1.09	0.42	-1.16	-1.00
F2-R2	-0.61	-1.81	0.37	-2.33⁺	-1.22	0.40	-0.96	-0.88
R1-R2	2.03⁺	0.16	0.92	-2.30⁺	-0.13	-0.02	0.18	0.12

4.2.7 (a) Pruned *Grevillea robusta* trees (PT1, PT2, PT4 & PT5) for LR92 and SR92

Figs. 186 & 188 and Table 56a display the VSMC behaviour in pruned plots (AFM1 & AFL1). We consider here general direction of moisture with distance from the trees. The differences between tubes at 94 and 188 and between 188 and 376 cm had to be more than 1.5% for LR92 and 2.0% for SR92 to be considered of agronomic consequences. Again considering the rooting depths of beans and maize the surface layer, 18, 30, 60, 90 and marginally 120 cm become agronomically important. Here again we find general striking similarity between general trends for LR92 and SR92.

(i) PT1 (i.e. tubes A1, B1 & C1)

For LR92, at 18, 60 and 90 cm depths the VSMC decreased somewhat between the distances 94 and 188 cm from PT1 and then increased between 188 and 376 cm to the same level for 90 and 60 cm and to the highest level for 18 cm depths. Only at 90 cm and 18 cm were there trends numerically important (Fig. 186 & Table 56a).

The SR92 trends were the same in the agronomically important layers (Fig. 188 & Table 56a).

(ii) PT2 (i.e.tubes A2, B2 & C2)

For LR92, at 18 cm depth there was decrease of VSMC with distance from the PT2 beyond the 94 cm level while at 60 cm a general increase was observed. The trends at 30 and 90 cm depths were unimportant agronomically as they were smaller than ± 1.5% limit (Fig. 186 & Table 56a).

The SR92 trends for 18 cm and 60 cm were the same as for LR92 above, except that the two depths had large differences at 94 cm and 188 cm but attained the same moisture status at 376 cm (Fig. 188 & Table 56a). Again other trends in agronomically important layers were smaller than +2.0% and therefore not useful agronomically.

(iii) PT4 (i.e.tubes M1, N1 & O1)

For LR92, at 18 and 150 cm depths the VSMC decreased between 94 and 188 cm from PT4 and then increased between 188 and 376 cm for agronomically important depth of 18 cm and marginally important depth of 120 cm. The trend at 30 cm was too small to be of any agronomic consequence while the trend was generally decreasing at 90 cm depth between 188 and 376 cm distances from PT4 (Fig. 186 & Table 56a).

The SR92 VSMC behaved similar to LR92 for the 30, 60 and 120 cm depths. The trend at 18 cm was very small and had no agronomic consequences but increased between 94 and 376 cm. For the 90 cm depth it increased between 94 and 188 cm but decreased at 376 cm to its level at 94 cm (Fig. 188 & Table 56a).

(iv) PT5 (i.e.tubes M2, N2 & O2)

For LR92, at 18 and 30 cm depths the VSMC increased between 94 cm to 376 cm from PT5 with the 30 cm being the most striking increase. At 90 cm depth there was decrease in VSMC between 94 and 376 cm but had little agronomic consequences. At 60 cm depth the VSMC increased between 94 and 188 cm from PT5 and then decreased at 376 cm to its level at 94 cm. Other changes in VSMC trends with distance from PT5 had negligible agronomic consequences (Fig. 186 & Table 56a).

The SR92 VSMC behaved similar to LR92 at all depths except 120 cm depth where it increased between 94 and 376 cm from PT5 as opposed to LR92 trend of a decrease followed an increased (Fig. 180 & Table 56a).

4.2.7 (b) Unpruned *Grevillea robusta* trees (UT1, UT2, UT4 & UT5) for LR92 and SR92

Like in the case of the pruned trees Figs. 186 & 187 and Table 56b display the behaviour of VSMC in unpruned plots (AFM2 & AFL2).

(i) UT1 (i.e.tubes D1, E1 & F1)

Most of the trends for the VSMC around UT1 in LR92 were of little agronomic importance. This condition may have come about as the result of depletion of moisture in the upper layers by the unpruned trees. Nevertheless though of little value agronomically the most trends decreased between 94 and 376 cm from UT1, with 30 cm being clearly the highest (Fig. 187 & Table 56b).

The decreasing trend observed in LR92 could only be repeated at 60 cm depth in SR92. Otherwise the picture for the SR92 was somewhat different from the LR92 one. (Fig. 189 & Table 56b).

(ii) UT2 (i.e.tubes D2, E2 & F2)

In LR92, at UT2 except for the 90 cm depth, VSMC generally decreased between 94 and 188 cm and then increased from 188 to 376 cm at all agronomically important depths. At 90 cm depth it took the opposite trend by increasing from 94 to 188 cm and then decreasing thereafter to 376 cm from UT2 (Fig. 187 & Table 56b).

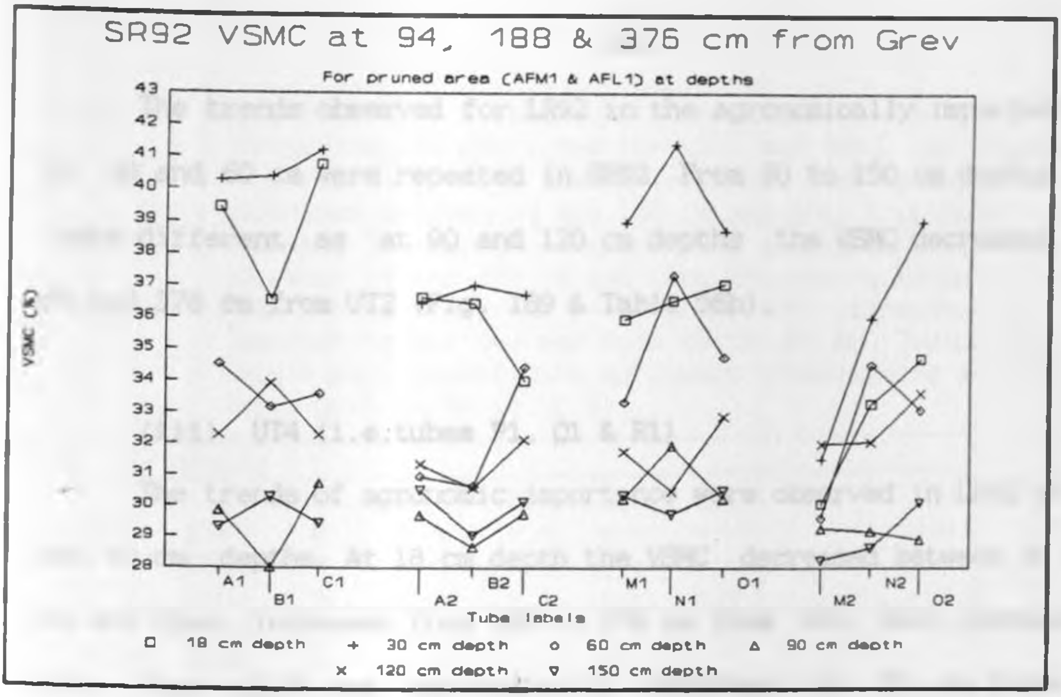


Fig. 188. SR92 VSMC gradients from pruned *Grevillea robusta* trees.

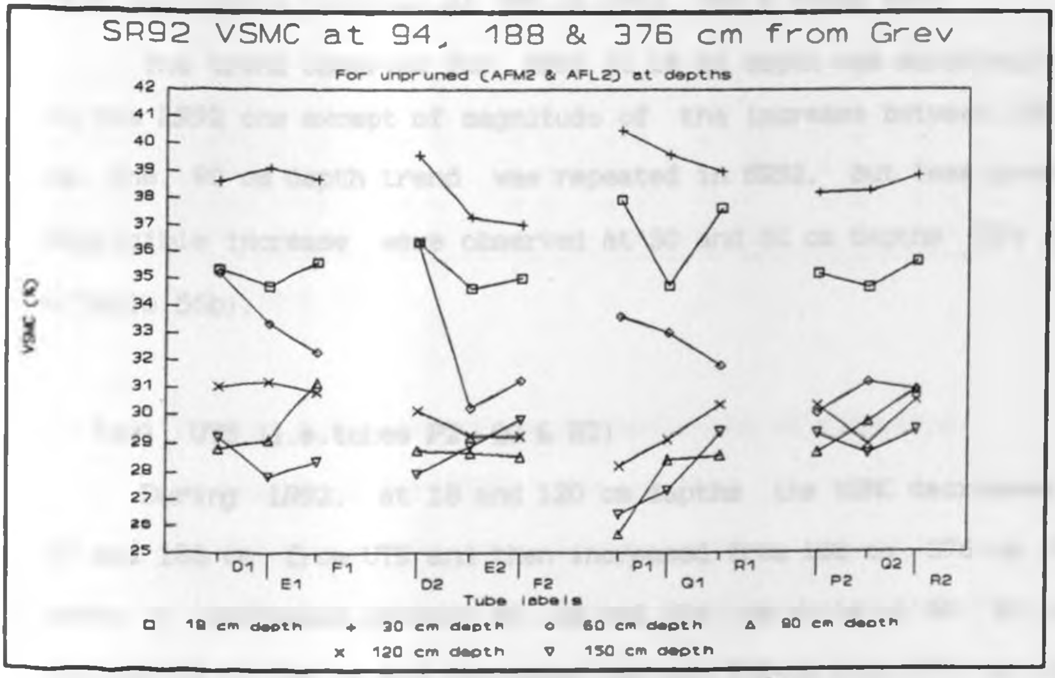


Fig. 189. SR92 VSMC gradients from unpruned *Grevillea robusta* trees.

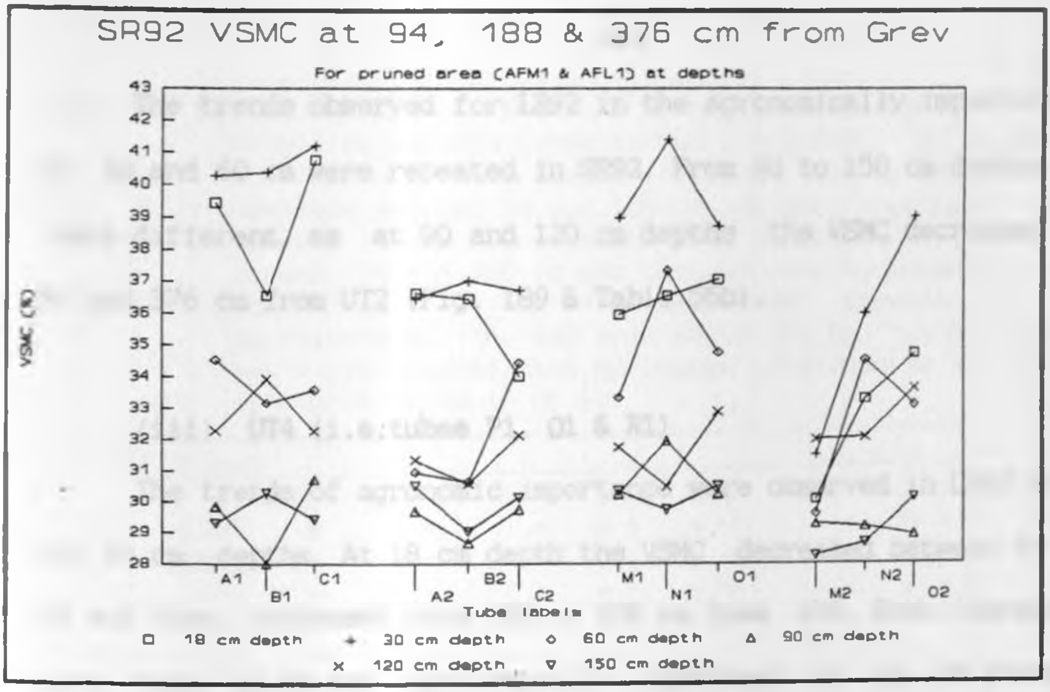


Fig. 188. SR92 VSMC gradients from pruned *Grevillea robusta* trees.

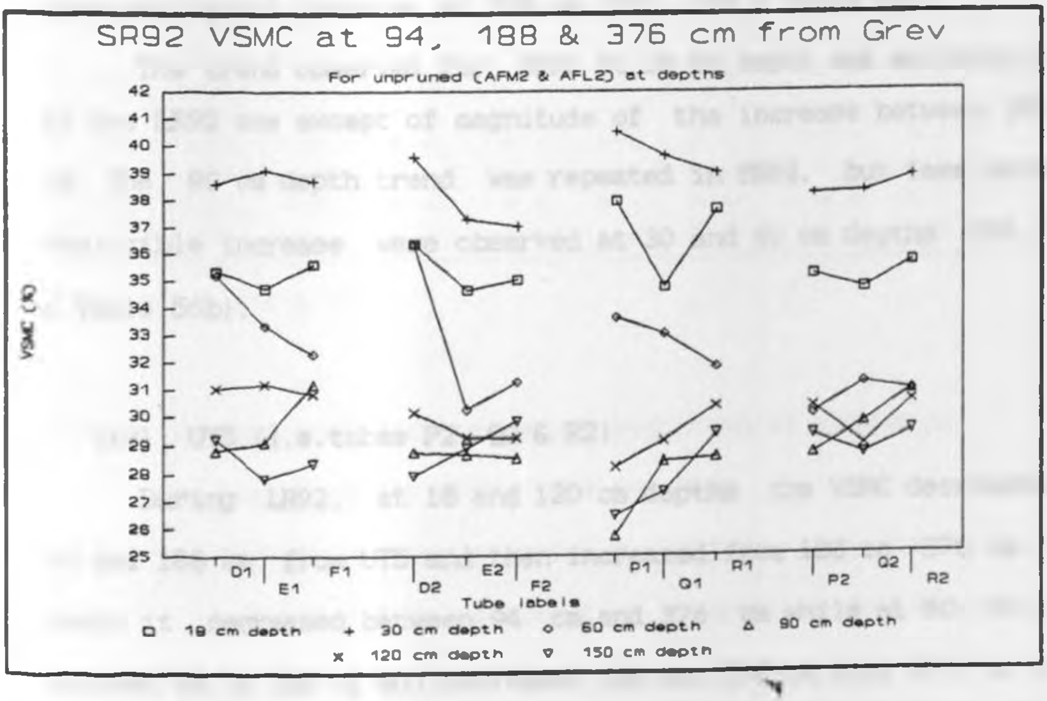


Fig. 189. SR92 VSMC gradients from unpruned *Grevillea robusta* trees.

The trends observed for LR92 in the agronomically important depths 18. 30 and 60 cm were repeated in SR92. From 90 to 150 cm depths things were different. as at 90 and 120 cm depths the VSMC decreased between 94 and 376 cm from UT2 (Fig. 189 & Table 56b).

(iii) UT4 (i.e.tubes P1, Q1 & R1)

The trends of agronomic importance were observed in LR92 at 18, 30 and 90 cm depths. At 18 cm depth the VSMC decreased between 94 and 188 cm and then increased from 188 to 376 cm from UT4. Both increases were more than ±2.0% and agronomically important. At 30 cm there was a positive trend and a decrease to almost its initial level at 376 cm from UT4. At 90 cm the VSMC had a steep increase between 94 and 188 cm and then negligible increase at 376 cm (Fig. 189 & Table 56b).

The trend observed for SR92 at 18 cm depth was strikingly similar to the LR92 one except of magnitude of the increase between 188 and 376 cm. The 90 cm depth trend was repeated in SR92. but less prominently. Negligible increase were observed at 30 and 60 cm depths UT4 (Fig. 189 & Table 56b).

(iv) UT5 (i.e.tubes P2, Q2 & R2)

During LR92. at 18 and 120 cm depths the VSMC decreased between 94 and 188 cm from UT5 and then increased from 188 to 376 cm. At 30 cm depth it decreased between 94 cm and 376 cm while at 60 it increased between 94 to 188 cm and decreased 188 and 376 cm from UT5. At 90 cm it increased all the way outward from the tree (Fig. 187 & Table 56b).

There were little similarities in the trends between SR92 and LR92. as the VSMC increased all the way from 94 to 376 cm from 18 to 90 cm depths. The trend of LR92 was repeated for 90 and 120 cm depths only

Table 56. Directions of soil moisture with distance from the *Grevillea robusta* trees for LR92 and SR92. (a) pruned (b) unpruned. Note that (− +) means VSMC decreasing with distance between 94 and 188 cm and then increasing between 188 and 376 cm. (+ −) means VSMC increasing with distance between 94 and 188 cm and then decreasing between 188 and 376 cm. (+ +) or (− −) means VSMC increasing or decreasing all the way from 94 to 376 cm. Trends that would give significant agronomic consequences are shown with bold signs (**−** or **+**).

(a) Pruned								
		18	30	60	90	120	150	170
PT1:	LR92	− +	+ −	− +	**− +**	+ −	− −	− −
	SR92	− +	+ +	− +	**− +**	**+ −**	+ −	− +
PT2:	LR92	+ −	+ −	+ +	+ −	− +	− +	− +
	SR92	+ −	+ −	+ −	+ −	− +	− +	+ +
PT4:	LR92	− +	+ −	+ −	− −	− +	− +	+ +
	SR92	+ +	+ −	+ −	+ −	− +	+ −	+ +
PT5	LR92	+ +	+ +	+ −	− −	− +	+ +	+ −
	SR92	+ +	+ +	+ −	− −	+ +	+ +	+ −

(b) Unpruned								
		18	30	60	90	120	150	170
UT1:	LR92	− −	− −	− −	− +	− −	− −	+ +
	SR92	− +	+ −	− −	+ +	+ −	− +	+ +
UT2:	LR92	− +	− +	**−** +	+ −	**−** +	− +	− +
	SR92	− +	− +	**− +**	− −	− −	+ +	+ +
UT4:	LR92	− +	+ −	+ −	+ +	+ −	+ +	+ +
	SR92	− +	− −	− −	+ +	+ +	+ +	+ +
UT5	LR92	− +	− −	+ −	+ +	− +	+ +	+ +
	SR92	+ +	+ +	+ +	+ +	− +	+ −	− +

(Fig. 189 & Table 56b).

4.2.8 On-farm soil moisture experimentation at Kiahuko-A and Kiahuko-B for SR93, LR94 and SR94

4.2.8 (a) Effects of *Coleus barbatus* livefence root pruning on Soil moisture distribution in cropland at Kiahuko-A

Figs. 190 & 191 present results of analysis of soil moisture variations with distances from (a) pruned (b) unpruned *Coleus barbatus* livefence at Kiahuko-A during the three seasons (i.e. SR93, LR94 & SR94) of the on-farm experimentation.

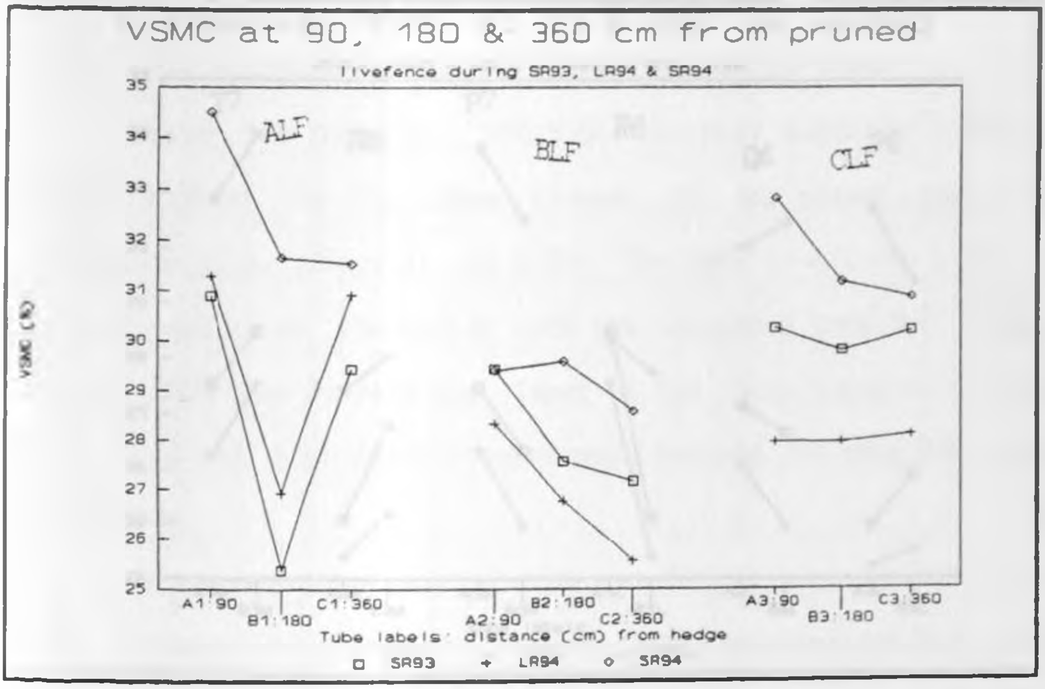


Fig. 190. VSMC gradients from pruned livefence at Kiahuko-A on-farm in SR93, LR94 & SR94

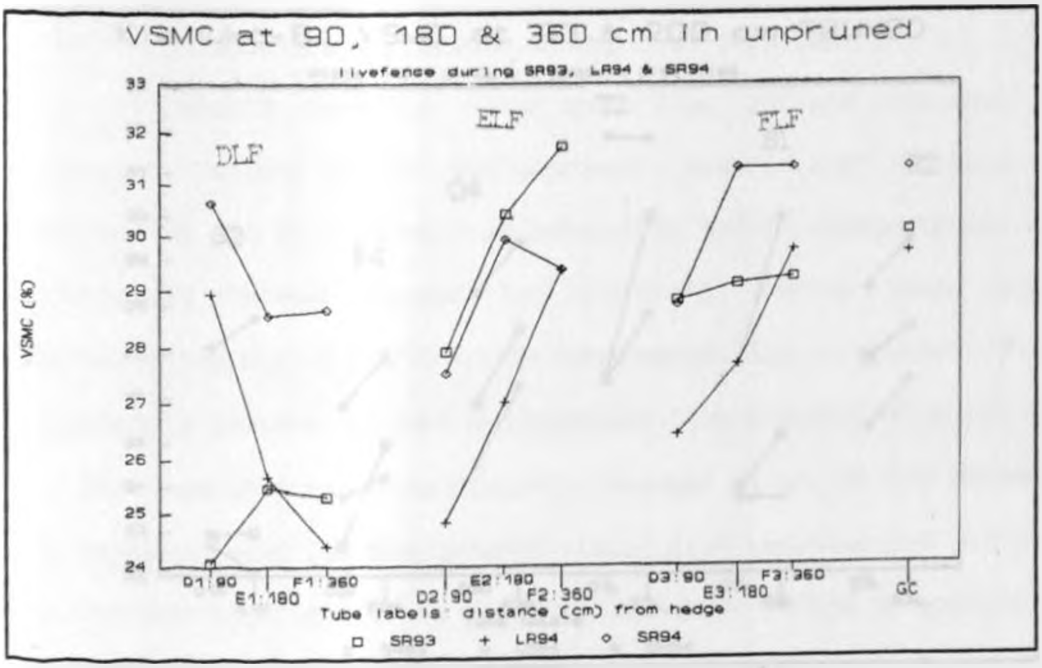


Fig. 191. VSMC gradients from unpruned livefence at Kiahuko-A on-farm in SR93, LR94 & SR94.

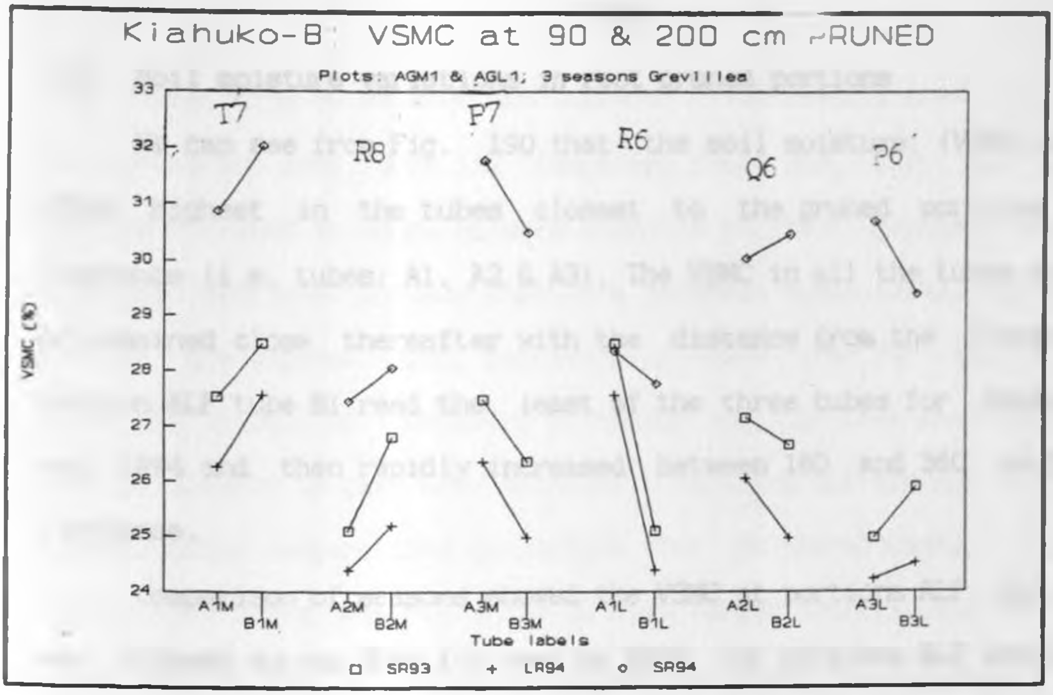


Fig. 192. VSMC gradients from pruned Grevillea trees (AGM1 & AGL1) at Kiahuko-B on-farm in SR93, LR93 & SR94

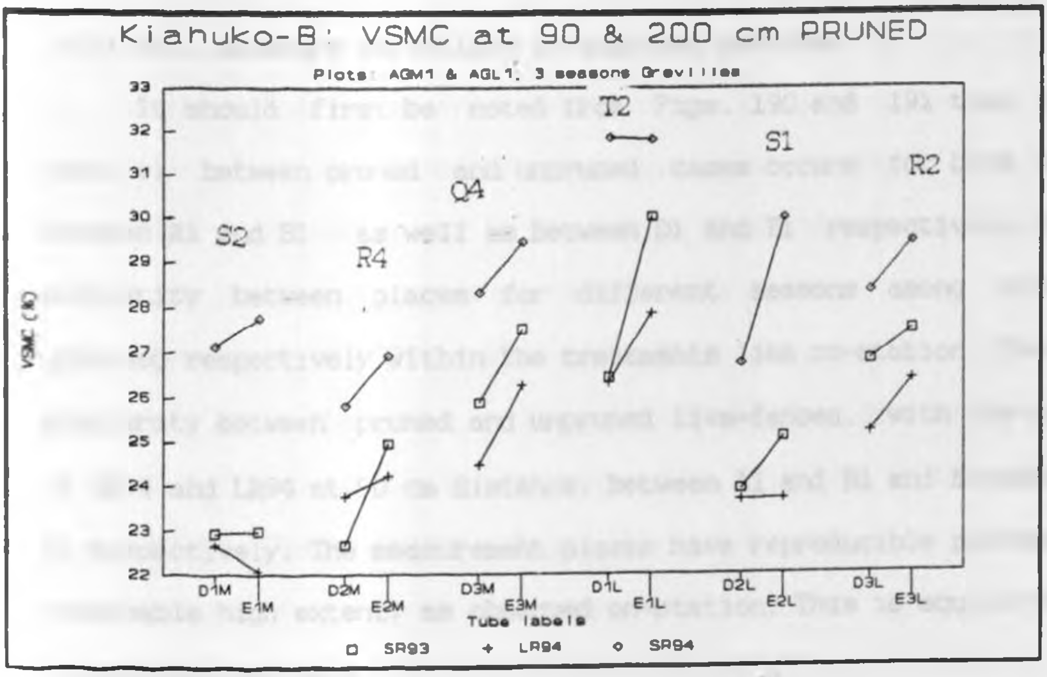


Fig. 193. VSMC gradients in unpruned *Grevillea robusta* trees at Kiahuko-B on-farm in SR93, LR94 & SR94.

(i) Soil moisture variations in root pruned portions

We can see from Fig. 190 that the soil moisture (VSMC) was most often highest in the tubes closest to the pruned portions of the livefence (i.e. tubes: A1, A2 & A3). The VSMC in all the tubes decreased or remained close thereafter with the distance from the livefence. In portion ALF tube B1 read the least of the three tubes for seasons SR93 and LR94 and then rapidly increased between 180 and 360 cm from the livefence.

Comparison of seasons showed the VSMC at portions ALF, BLF and CLF was highest during SR94 followed by SR93 for portions BLF and CLF. The three tubes of portion ALF (i.e. A1, B1 & C1) read lowest VSMC during SR93 only.

(ii) Soil moisture variations in unpruned portions

It should first be noted from Figs. 190 and 191 that the only parallel between pruned and unpruned cases occurs for LR94 and SR94 between A1 and B1 as well as between D1 and E1 respectively. There is similarity between places for different seasons among pruned and unpruned respectively within the treatments like on-station. There is no similarity between pruned and unpruned live-fences, with the exception of SR94 and LR94 at 90 cm distance, between A1 and B1 and between D1 and E1 respectively. The measurement places have reproducible patterns (to a reasonable high extent) as observed on-station. This is equally true for pruned/unpruned data.

From Fig. 191 we see that the soil moisture situation in the unpruned portions of the livefence was indeed different. All tubes closest to the livefence (i.e. tube D1, in position DLF, tube D2 in portion ELF and tube D3 in portion FLF) showed that there was the least soil moisture at 90 cm from the unpruned livefence compared to the other two distances away from it. Comparing BLF, ELF, CLF, and FLF, any important trends in unpruned were opposite to their pruned equivalents. In these portions (ELF and FLF) the farthest tubes (i.e. tubes F2 and F3) had the highest VSMC, particularly SR93 (for F2) and LR94 (for both). It is only in comparing plots ALF and DLF that the pruned plot appears clearly to have more moisture. Comparing BLF and ELF only A2 was significantly larger than D2 in LR94, but F2 significantly larger than C2 for the three seasons while E2 was larger than B2 for SR93 only. Comparing CLF and FLF A3 was significantly larger than D3 only for SR94, no where was B3 larger than E3 with any significance, and even F3 was larger than C3 for LR94 only with some significance.

It should be noted that for DLF, for LR94 and SR94, the VSMC was highest closest to the livefence, because the farmer had heaped dead vegetation he had weeded from the field on this part of the livefence to compost it. This interfered with the soil moisture status of the soil by increasing moisture closer to the hedge. This strengthens the influence of pruning on the soil moisture close to the hedge.

Comparison of VSMC in the unpruned plots during the three seasons show that again there was most soil moisture for SR94 at DLF and FLF portions and also at the control tube (GC), which was in the open centre of the plot. These seasons (Figs. 190 & 191) show that LR94 was the driest season of the three with respect to moisture status in the soil in on-farm plot. However, as for ALF, also in DLF that season was higher in moisture than SR93, be it not at 360 cm. Of course again, the averaging of seasons gives only a limited picture. For the full picture the influence of rainfall distribution only follows from data broken down over the season.

4.2.8 (b) Effects of *Grevillea robusta tree* root pruning on Soil moisture distribution in cropland at Kiahuko-B

Figs. 192 & 193 present results of soil moisture variations with the distance from the *Grevillea robusta* trees under the on-farm conditions at Kiahuko-B for the three seasons (i.e. SR93, LR94 & SR94).

The two distances (i.e. 90 and 200 cm) from the *Grevillea robusta* trees at which access tubes were installed gave us the two data points per line that appear in Figs. 192 & 193. The first point from the left was the tube closer to the tree at 90 cm while the second point was the tube farther from the tree at 200 cm.

(i) Soil moisture variations in root pruned *Grevilleas*

We can see from Fig. 192 in the root pruned *Grevillea robusta* trees that VSMC was higher in same tubes nearer to the trees (i.e. tube A3M at tree P7, tube A1L at R6 and (unimportant) A2L at Q6) than those farther away (i.e. tube B3M at tree P7, tube B1L at R6 and B2L at Q6). However, pruning did not seem to work for some other trees: (very unimportant) T7 (i.e. A1M & B1M) and (with only one significant season) R8 (i.e. A2M & B2M) as the VSMC was lower closer to the tree than farther away for all the three seasons, while at P6 (i.e. A3L and B3L) pruning was marginally effective during SR94 only. It must be appreciated that only in three cases an appreciable difference (larger than 1.5%) occurred because of pruning and marginal differences in two cases. Opposite to expectation was one case, with one marginal case as well.

Comparing soil moisture in the three seasons we see VSMC was for all cases highest for SR94 and lowest for LR94 (see Fig. 192). The highest effect of pruning on soil moisture (between 3 and 3.5%) was however realized in SR93 and LR94 near one tree only. as it was very high only next to the pruned tree (R6) at 90 cm (tube A1L) and was lower farther away at 200 cm (tube B1L). The all over assessment must be that there is on the average a small effect.

We see in Figs. 192 and also Fig. 193 that there is reasonable symmetry between seasons. In most cases where either moisture is higher or lower near the trees. this is true for all seasons. Only where all distances are small or marginal this is not true in all cases.

(ii) Soil moisture variations in unpruned *Grevilleas*

From Fig. 193 we notice that all unpruned *Grevillea robusta* trees had the same effect on soil moisture with the distances from them. as the tubes closer to the trees (at 90 cm) read lower VSMC than those further away (at 200 cm). This is larger than 1.5% in more cases. The highest effect (of 3.5%) was realized for tubes D1L and E1L at tree S2. It should be observed that pruning appears more successful when comparing it with the opposite trend in moisture with distance to the trees in unpruned plots.

Comparison of VSMC for different seasons shows that overall SR94 had the highest soil moisture status while LR94 had the lowest.

From these results we were not able to discern the effect of mulching on soil moisture status of the soil. Finally the spacing between adjacent *Grevillea* rows enabled the canopies to close up and almost completely shade the ground. thereby reducing direct evaporation from the ground. reduce soil temperatures considerably and decreasing this way the effect of mulching. Secondly the *Grevillea robusta* trees themselves shed their leaves and therefore added substantial leaf mulch to the unmulched (Local) plots and to the mulched ones too, again decreasing any existing differences. This can be seen in Fig. 194 which compares pruned and unpruned mulching (AGM1 & AGM2) with pruned and unpruned Local (AGL1 & AGL2). The pruning effect was only pronounced in the mulched plots as AGM2 had the least VSMC.

However, one finding we observed here as well as at Matanya AF was that unpruned mulching with minimum tillage had less soil moisture than unpruned (as well as pruned) Local with deep tillage. This finding came up repeatedly for most of the Matanya data. The seasonal averaging does not show this clearly as it does not indicate whether this was mainly the case towards the end of the season (where it could be a consequence of both vegetative growth earlier in the season or throughout the season). Termites could be involved also.

The VSMC in the agroforestry plots was appreciably less than that in the control plots (CTRL-MUL and CTRL-LOC). The Mulched plot in the control had negligibly higher VSMC than the Local plot. In line with the other plots, SR94 had again the highest VSMC in the control plots. AGM2 appears to be less than marginally different from all others, apart from three cases with respect AGL1. So this indeed means no mulch effects in agroforestry treatments nor in control. It looks as if pruned mulched is most successful with respect to unpruned mulched, but the Local pruned and unpruned differ little among each other and little with pruned mulched.

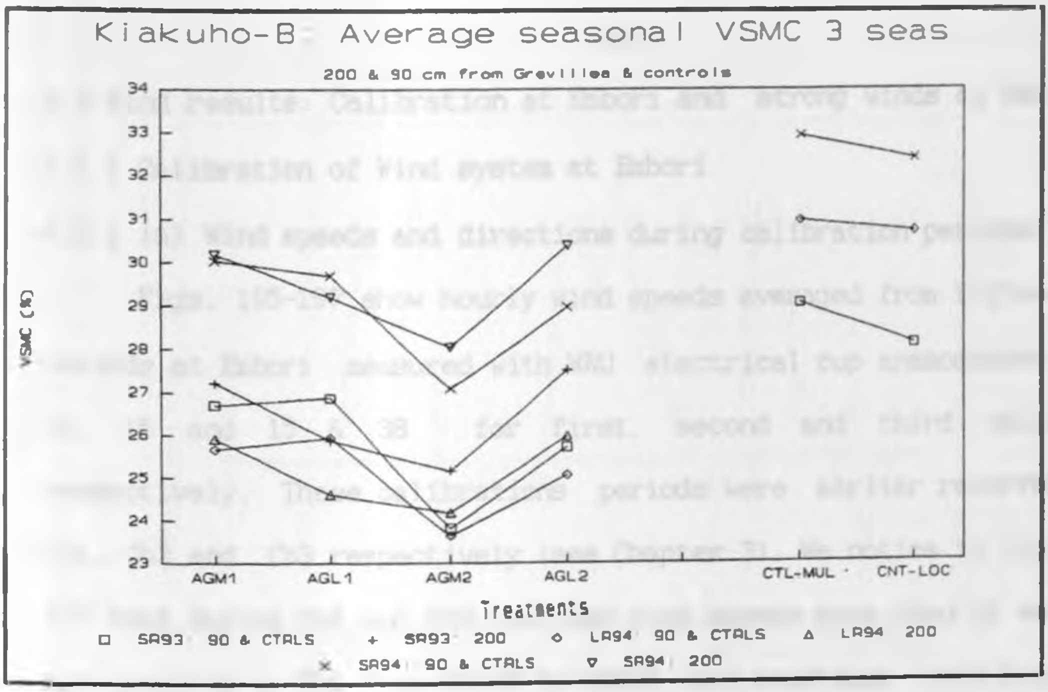


Fig. 194. Average VSMC for three seasons at Kiahuko-B on-farm for 90 and 200 cm from Grevillea trees and Control plots

4.3 Wind results: Calibration at Embori and strong winds at Matanya

4.3.1 Calibration of Wind system at Embori

4.3.1 (a) Wind speeds and directions during calibration periods

Figs. 195-197 show hourly wind speeds averaged from fifteen minute records at Embori measured with WAU electrical cup anemometers Sr Nrs 10, 15 and 15 & 38 for first, second and third calibrations respectively. These calibrations periods were earlier referred to as Cb1, Cb2 and Cb3 respectively (see Chapter 3). We notice in Figs. 195 & 197 that during Cb1 and Cb3 the high wind speeds more than or equal to 4 m/s occurred in Cb1 from 08h00 to 20h00 (and sometimes even beyond) and in Cb3, with some exception, between the same times. We further notice that highest winds ranged from between 7 m/s and more than 8 m/s during Cb1 and Cb3. All the WAU electrical cup anemometers displayed similar trends.

During Cb2 the winds at Embori were generally light, below 4 m/s (see Fig. 196). These light winds were mainly influenced by local topography, especially the nearby Mt. Kenya slopes and also valleys around the calibration site. The relatively high winds more than or equal to 2 m/s occurred between 10h00 and 16h00 during daytime and from 20h00 to 06h00 during nighttime (Fig. 196). The nighttime high winds were as a result of increased katabatic flow down the cold Mt. Kenya slope on the south east (S.E.) of the calibration site.

Figs. 198-207 present the relative per cent frequency wind direction roses for Embori worked out from hourly wind directions recorded with the Woelfle anemograph Sr. Nr. 31587, hereafter referred to as WB, during the calibration periods. These wind direction roses showed that the wind at Embori for the Cb1 (Figs. 198-201 and Cb3

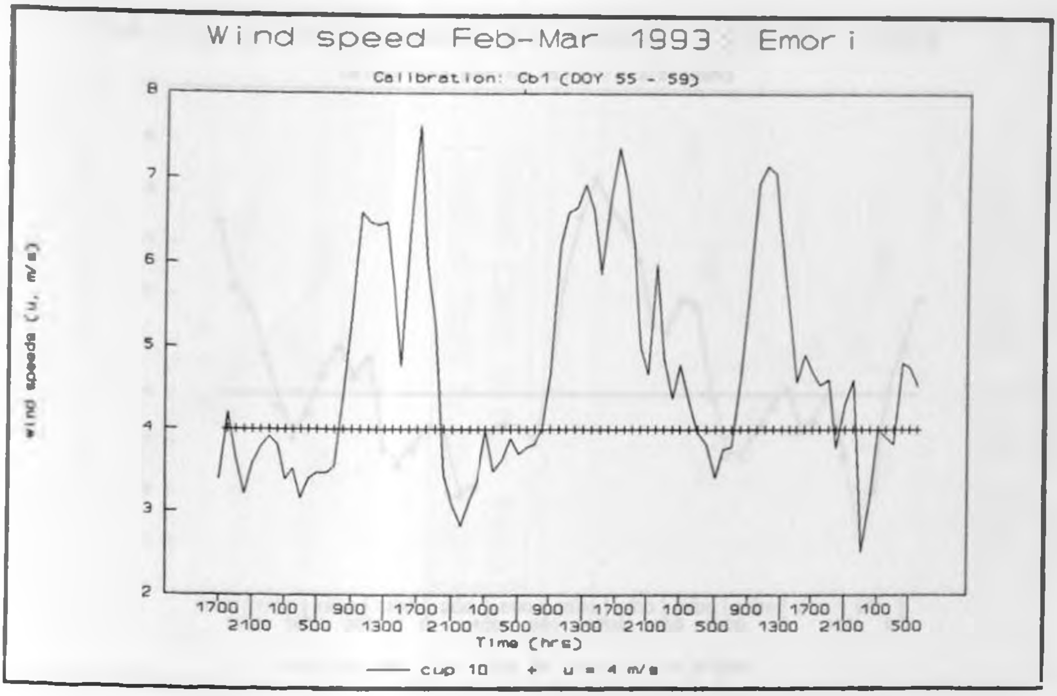


Fig. 195. Hourly wind speeds for Embori for DOY 55-59 of 1993 as read with cup anemometer 10.

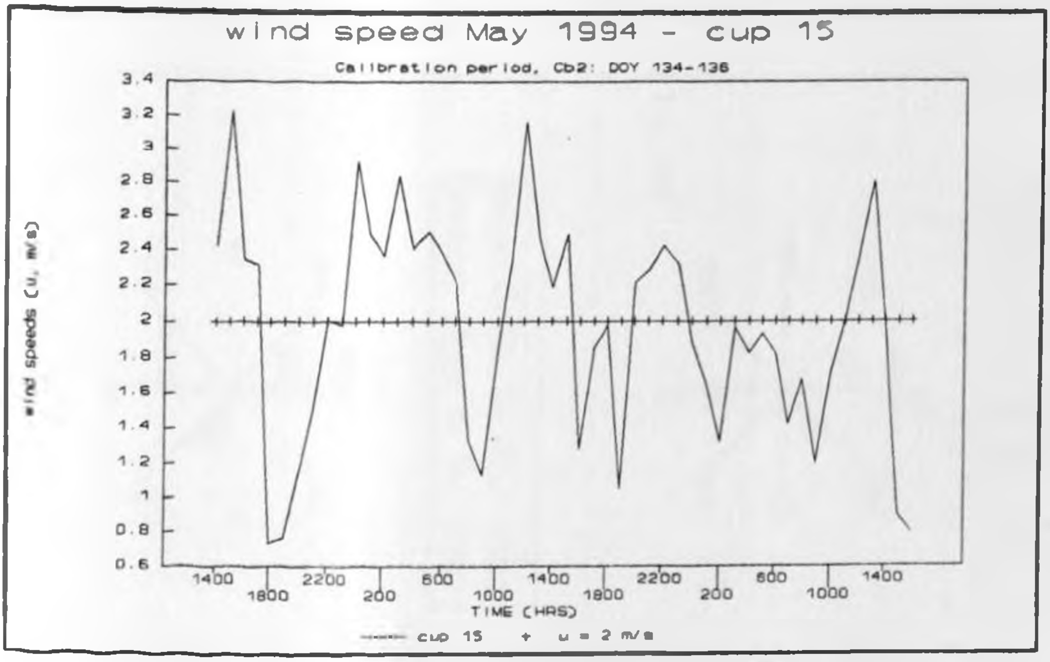


Fig. 196. Hourly wind speeds for Embori for DOY 134-146 of 1994 as read with cup anemometer 15.

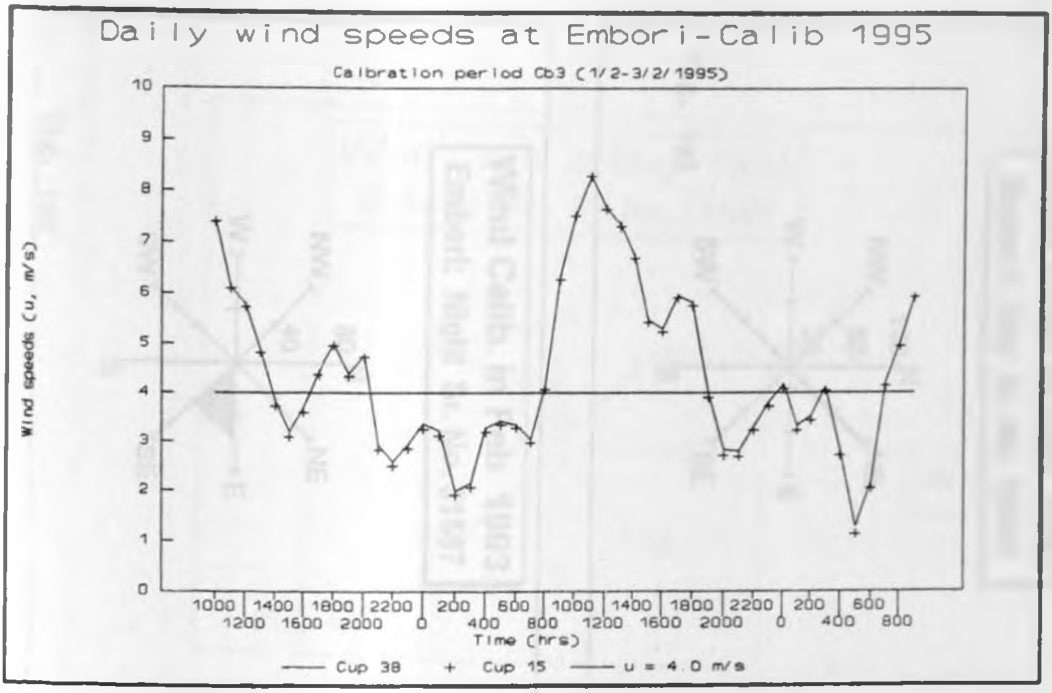


Fig. 197. Hourly wind speeds at Embori for DOY 32-34 of 1995 as read with cup anemometers 15 and 38.

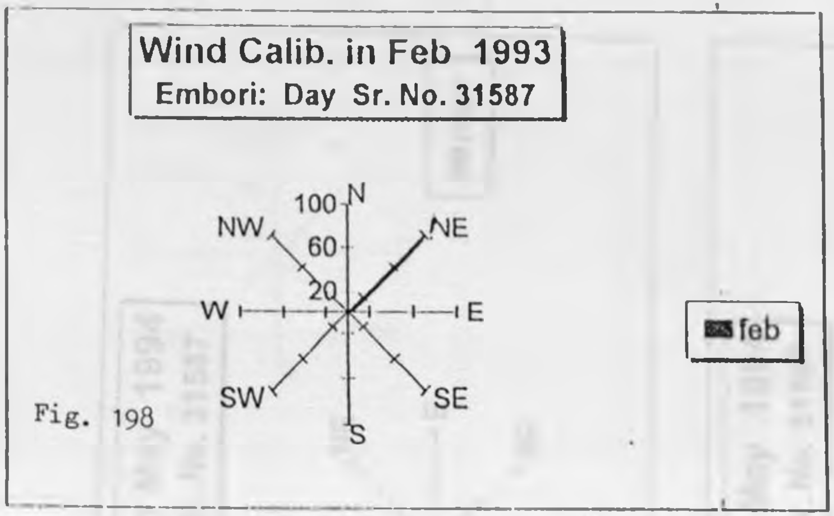


Fig. 198

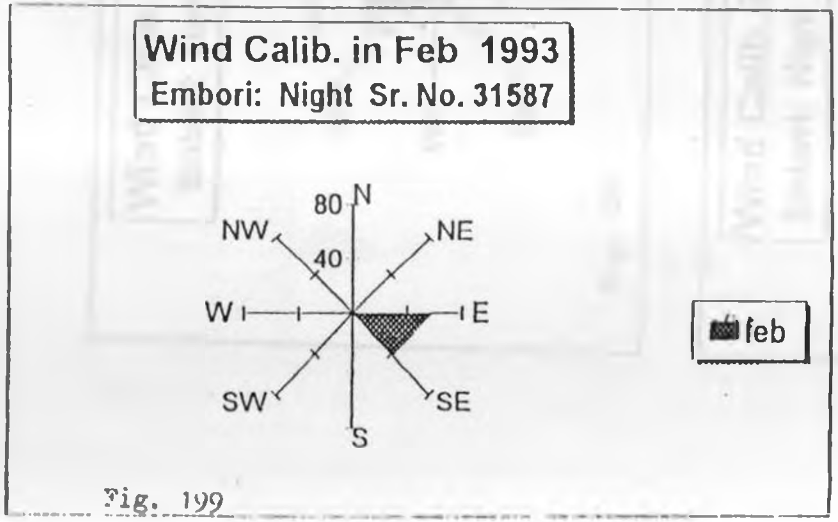


Fig. 199

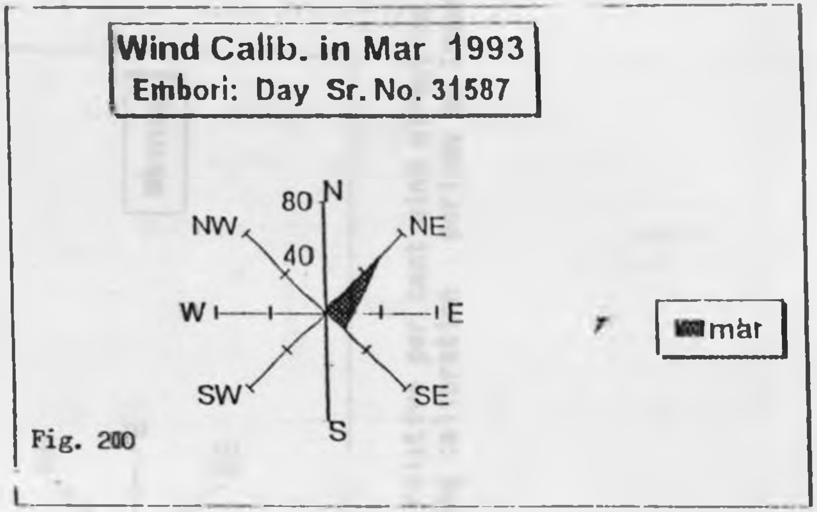


Fig. 200

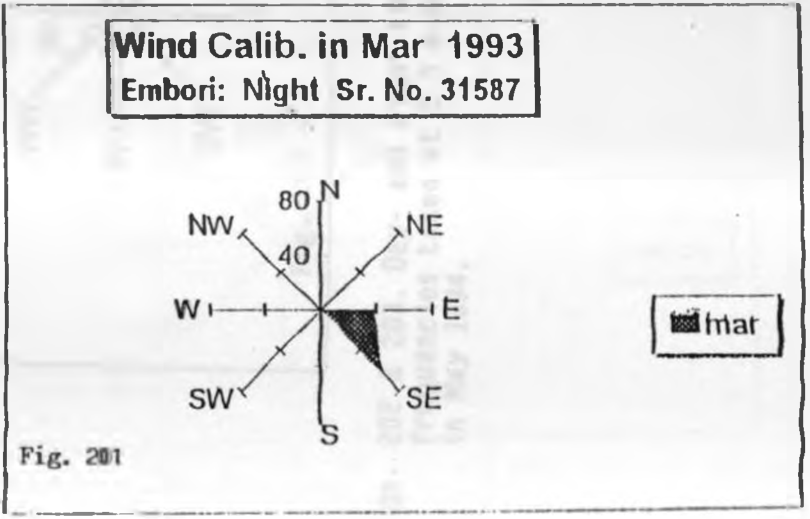


Fig. 201

Figs. 198-201 Day- and night-time relative per cent wind direction frequencies taken at 2.0 m during calibration periods at Embori in February-March 1993.

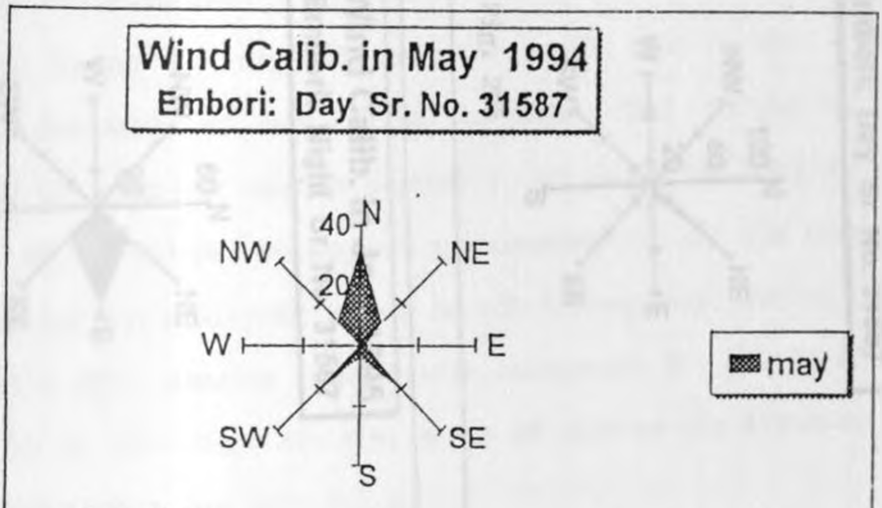


Fig. 202

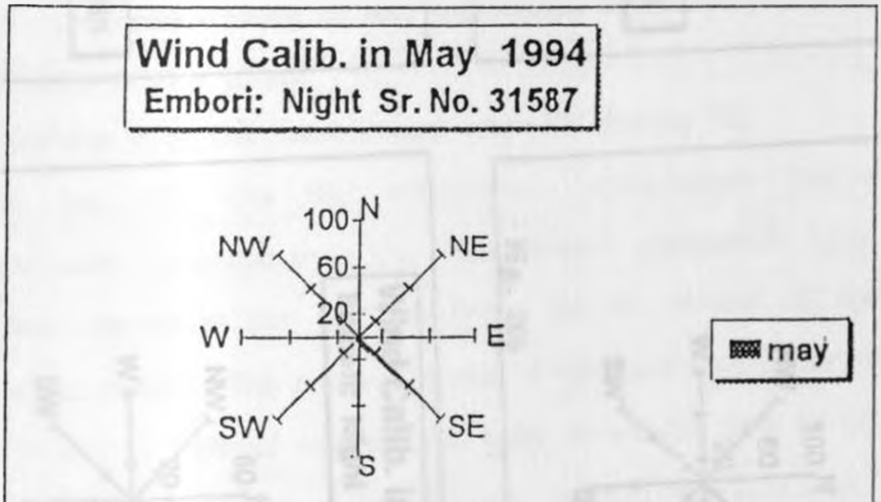


Fig. 203

Figs. 202 & 203. Day- and night-time relative per cent wind direction frequencies taken at 2.0 m during calibration periods at Embori in May 1994.

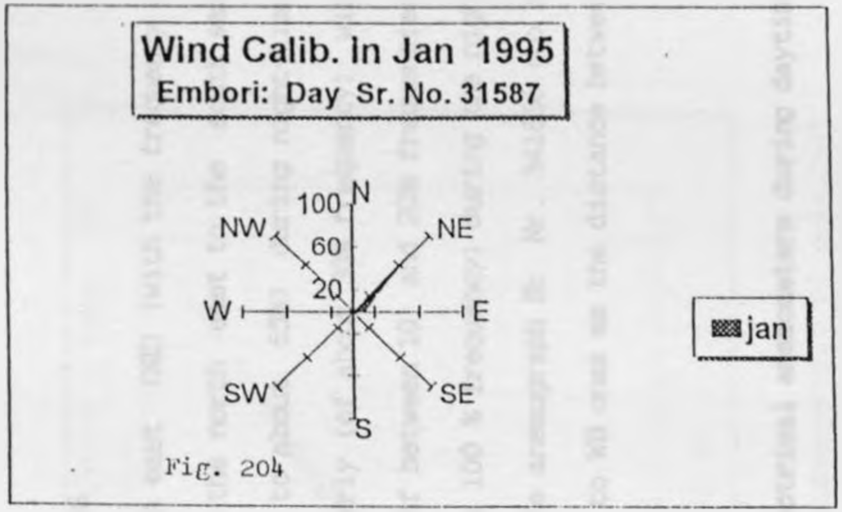


Fig. 204

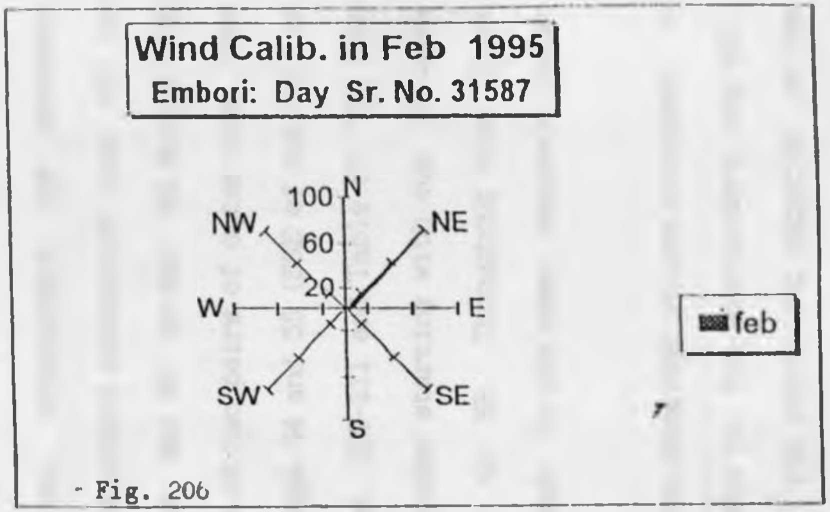


Fig. 206

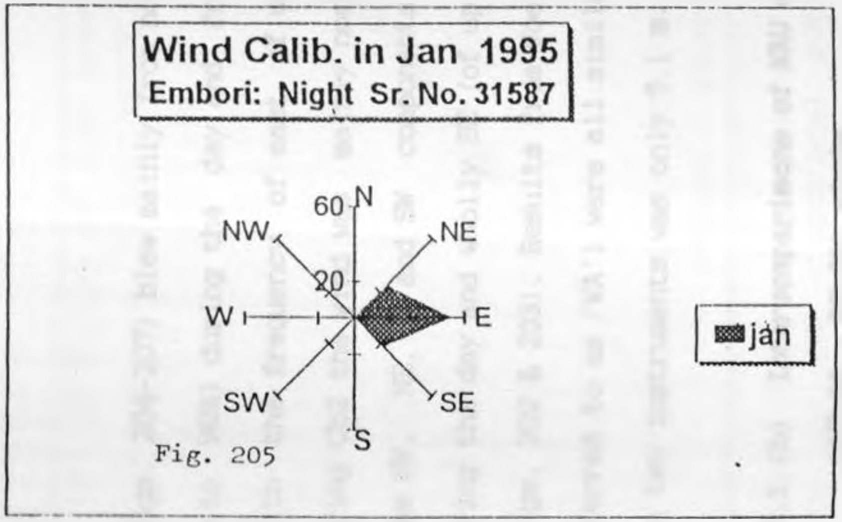


Fig. 205

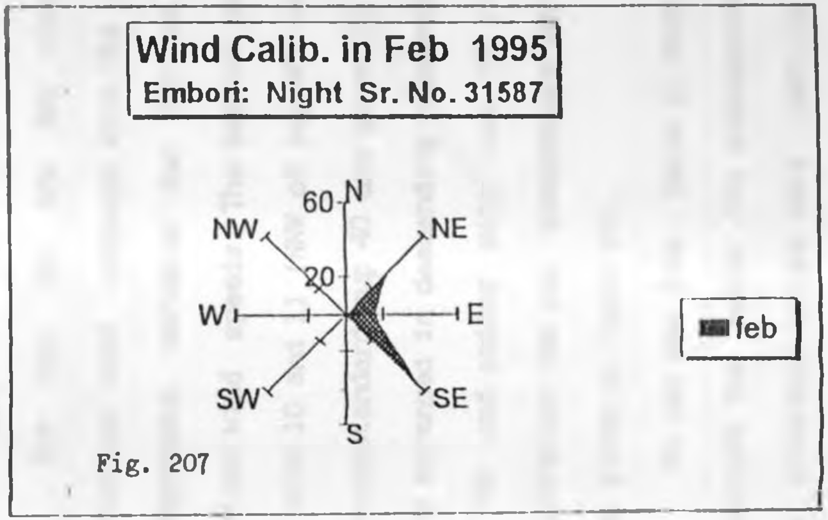


Fig. 207

Figs. 204-207. Day- and night-time relative per cent wind direction frequencies during calibration periods at Embori in January-February 1995.

(Figs. 204-207) blew mainly from north east (NE) (with the frequency of up to 90%) during the day and from the north east to the south east (with the frequency of east of up to about 65%) during night-time. During Cb2 the wind was mainly northerly (of about 30% frequency) with some NW, NE, SE and SW components (of between 10 and 20% frequencies) during the day and wholly SE (of up to 100 % frequency) during the night (Figs. 202 & 203). Results from Woelfle anemograph Sr. Nr. 341836 (to be referred to as 'WA') were all similar to WB ones as the distance between the two instruments was only 5.1 m.

4.3.1 (b) Intercomparisons of WAU electrical anemometers during daytime (07h00 - 20h00) winds

(i) Comparison with the substandard (cup 40) during Cb1

For the Cb1 the WAU electrical anemometers (as dependent variables) were compared with the substandard anemometer (cup 40) (as independent variable) for 100 hrs from day 55 to day 62 during high daytime wind speeds. The scatter plots of two pairs of outer cups, that is cups 10 and 11 (NNW of cup 40) and cups 44 and 55 (SSE of cup 40), on the substandard cup 40 are given in Figs. 208-211 and Table 57. The cups were arranged in descending /ascending order starting with cup 10 close to WA and ending with cup 55 close to WB. Throughout this first calibration the cup anemometers were kept in the same sequence (order also given in Table 57).

We can see from Table 57 that the intercept values decreased in magnitude the nearer the anemometers were to the substandard (cup 40). The intercept values were positive on the north and negative on the south of cup 40. These two observations suggest that the nearby valley influenced the behaviour of the wind field. The values ranged from -0.06

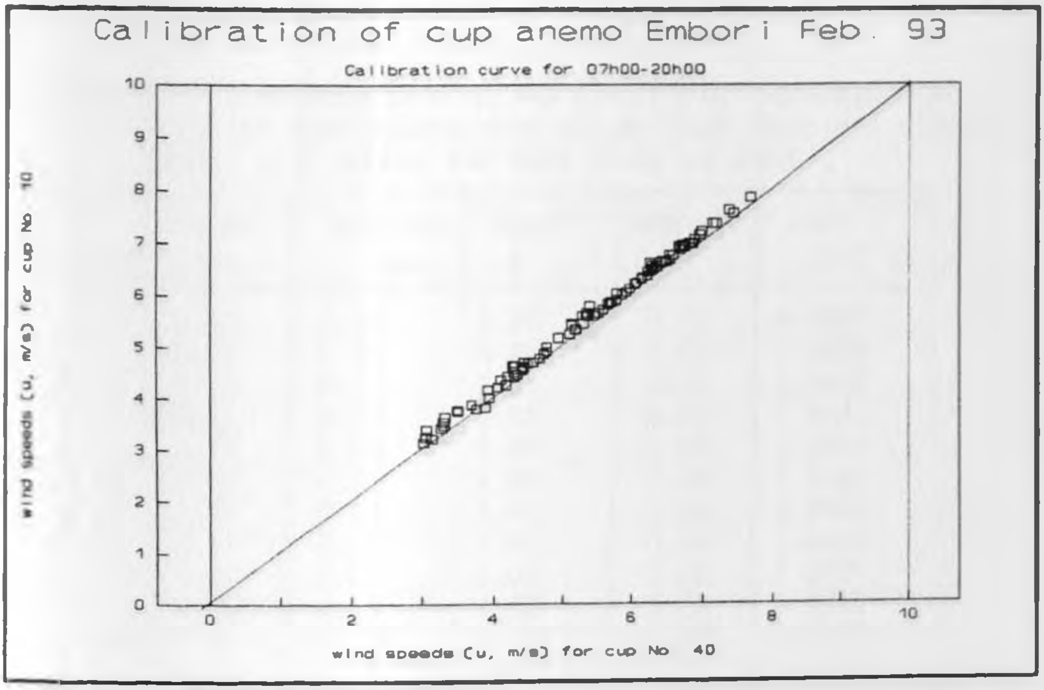


Fig. 208. The scatter plot and 1:1 line of hourly wind speeds for WAU electrical cup anemometer 10 against substandard 40 for the day-time period (07h00-20h00) at Embori for 55-62 of 1993.

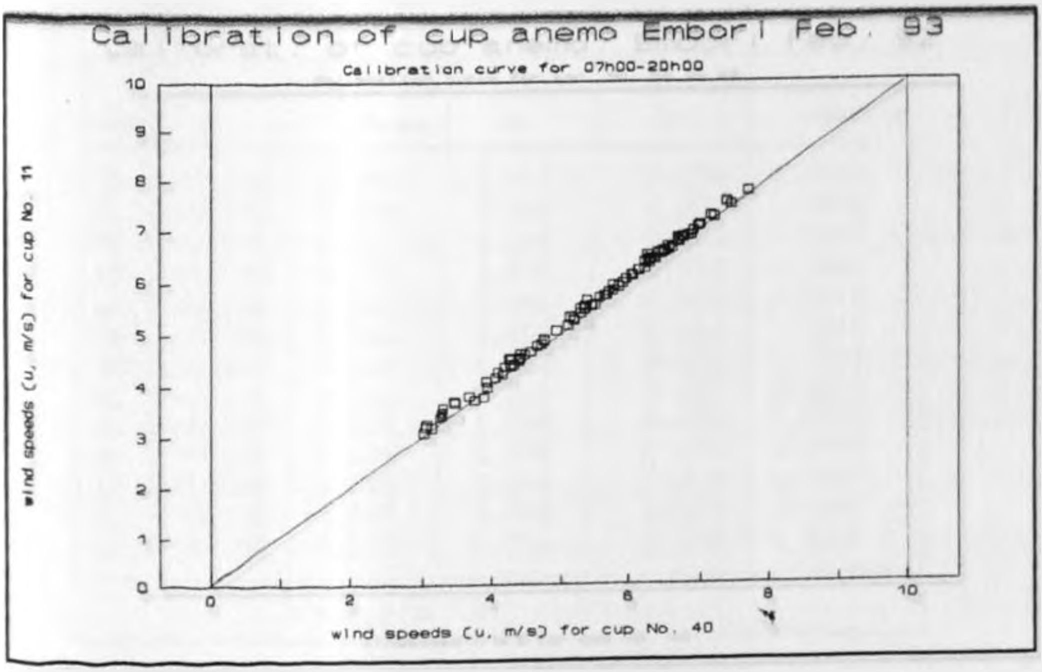


Fig. 209. The scatter plot and 1:1 line of hourly wind speeds for cup anemometer 11 against substandard 40 for the day-time period (07h00-20h00) at Embori for 55-62 of 1993.

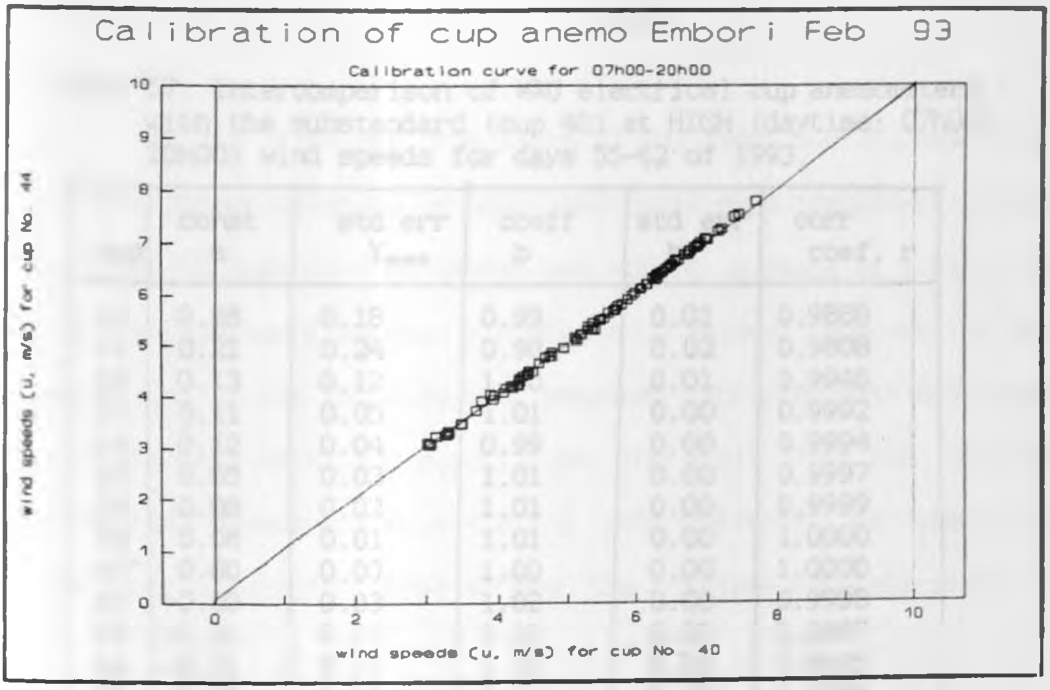


Fig. 210. The scatter plot and 1:1 WAU electrical cup anemometer 44 against substandard 40 for the day-time period (07h00-20h00) at Embori for 55-62 of 1993.

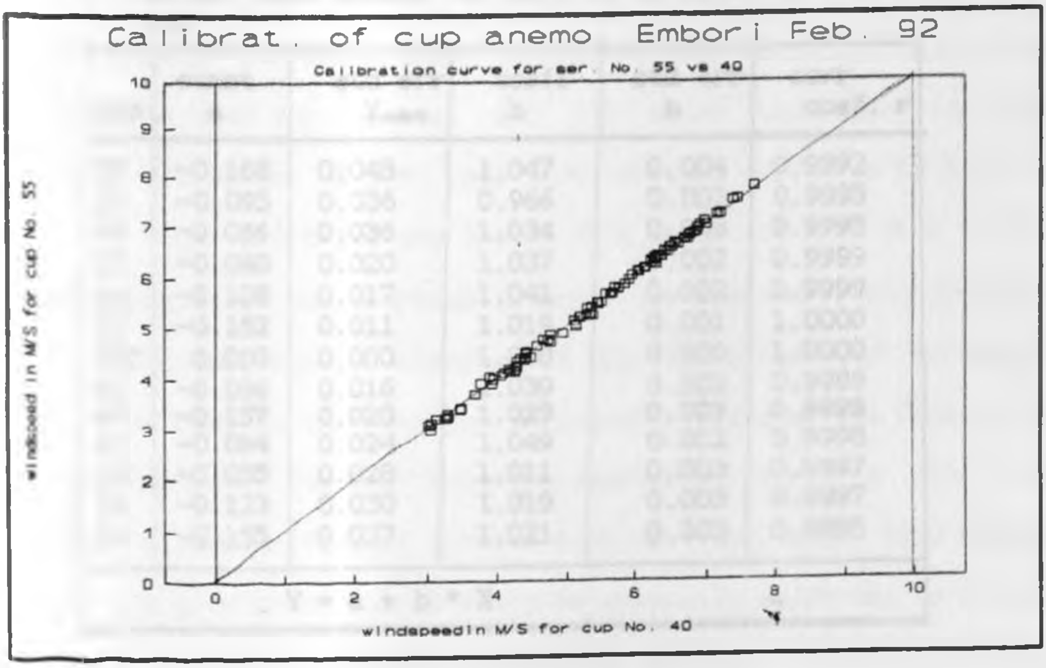


Fig. 211. The scatter plot and 1:1 line of hourly wind speeds for WAU electrical cup anemometers 55 against substandard cup 40 for the day-time period (07h00-20h00) at Embori for 55-62 of 1993.

Table 57. Intercomparison of WAU electrical cup anemometers with the substandard (cup 40) at HIGH (daytime: 07h00-20h00) wind speeds for days 55-62 of 1993.

cup	const a	std err Y_{est}	coeff b	std err b	corr coef, r
10	0.28	0.18	0.99	0.01	0.9888
11	0.21	0.24	0.98	0.02	0.9808
12	0.13	0.12	1.00	0.01	0.9946
13	0.11	0.05	1.01	0.00	0.9992
14	0.12	0.04	0.99	0.00	0.9994
15	0.05	0.03	1.01	0.00	0.9997
38	0.08	0.02	1.01	0.00	0.9999
39	0.06	0.01	1.01	0.00	1.0000
40*	0.00	0.00	1.00	0.00	1.0000
41	−0.03	0.03	1.02	0.00	0.9998
43	−0.02	0.03	1.02	0.00	0.9997
44	−0.01	0.04	1.01	0.00	0.9995
55	−0.06	0.06	1.01	0.00	0.9989

$Y = a + b * X$

Table 58. Intercomparison of WAU electrical cup anemometers with the middle cup (cup 38) at HIGH (daytime: 07h00-20h00) wind speeds for days 25-32 of 1995. * is middle cup

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
55	−0.168	0.048	1.047	0.004	0.9992
61	−0.095	0.036	0.966	0.003	0.9995
43	−0.066	0.036	1.034	0.003	0.9995
13	−0.040	0.020	1.037	0.002	0.9999
14	−0.108	0.017	1.041	0.002	0.9999
15	−0.152	0.011	1.019	0.001	1.0000
38*	0.000	0.000	1.000	0.000	1.0000
60	−0.096	0.016	1.039	0.002	0.9999
40	−0.157	0.020	1.029	0.009	0.9998
41	−0.084	0.024	1.049	0.002	0.9998
12	−0.055	0.028	1.011	0.003	0.9997
11	−0.123	0.030	1.019	0.003	0.9997
10	−0.155	0.037	1.021	0.003	0.9995

$Y = a + b * X$

to 0.28.

We can also see from Table 57 and Figs. 208–211 that the gradient of the linear relation between individual cups (dependent variable) and cup 40 (independent variable) was within a range of 1.01 ± 0.01. The correlation coefficients, r, between individual cups and the substandard were very close to 1.000 and somewhat decreased with the distance from cup 40 to 0.9808 for cup 11. On the whole, all the cup anemometers satisfied equation $Y = a + b * X$ with intercept 'a' close to zero and the coefficient 'b' close to one. The r values were all close to 1.00.

(ii) Comparison with cup 38 during Cb3

Figs. 212 & 213 present scatter diagrams and 1:1 lines for day-time high wind speeds for cups 10 and 55 on cup 38 (cup 38 was the middle cup anemometer) for two arrangements, namely; (i) before exchanging six outer cups three on either side of the horizontal bar (22/1/–1/2/95 for 90 hrs) and (ii) after exchanging the outer cups (1/2/–3/2/95 for 28 hrs) (see first columns of Tables 58 & 59).

Figs. 212 & 213 and Tables 58 & 59 and 62 & 63 show that intercept values did not now decrease in magnitude the nearer the anemometers were to the middle cups as observed in Cb1. There was also no change in sign for the cups on the northern or southern sides of the central cup. The intercept 'a' values however approached zero in both cases. The correlation coefficient between cups was very high. This suggests that the topographic influence which we initially suspected to be due to the nearby valley during Cb1 calibration was now eliminated by halving the distance Figs. 212 & 213 over which cup anemometers were installed. The gradient of the linear relation between individual cups (dependent variable) and cup 38 (independent variable) was within a range of 1.022

± 0.022.

4.3.1 (c) Comparisons of WAU electrical anemometers during night-time (21h00–06h00) winds

(i) Comparison with the substandard (cup 40) during Cb1

Figs. 214–217 show the results of the comparison of individual anemometers 10, 11, 44 (later replaced with 61 for Cb2 and Cb3) and 55 to the substandard cup anemometer (cup 40) for 70 hrs from day 55 to 62 in the LOW night-time (21h00–06h00) wind speeds. Here the nighttime conditions (Table 60) were the reverse (*in sign)* of intercepts compared to the day-time ones (Table 59). The intercept values were negative on the north and positive on the south of the substandard. The values ranged from –0.34 to 0.23. We can also see from Table 59 and Figs. 214–217 that the gradients of the linear relations between individual cups (dependent variable) and cup 40 (independent variable) were within a range of 1.03 ± 0.05. The correlation coefficients, r, between individual cups and the substandard were very close to 1.00 but varying between 0.832 and 1.00 with the distance from cup 40. Again, all the cup anemometers satisfied equation $Y = a + b * X$ with intercept 'a' close to zero and the coefficient 'b' close to unity. However, here, in nighttime conditions , 'a' and 'b' were respectively, further from zero and from one than in day-time conditions reported in section 4.3.2 above.

The higher wind speeds within the nighttime range scattered a bit above the 1:1 diagonal line and more so for the cup anemometers north of the substandard (see Figs. 214 & 215). This aspect of the scatter was also attributed to more topographic influence for the slower nighttime

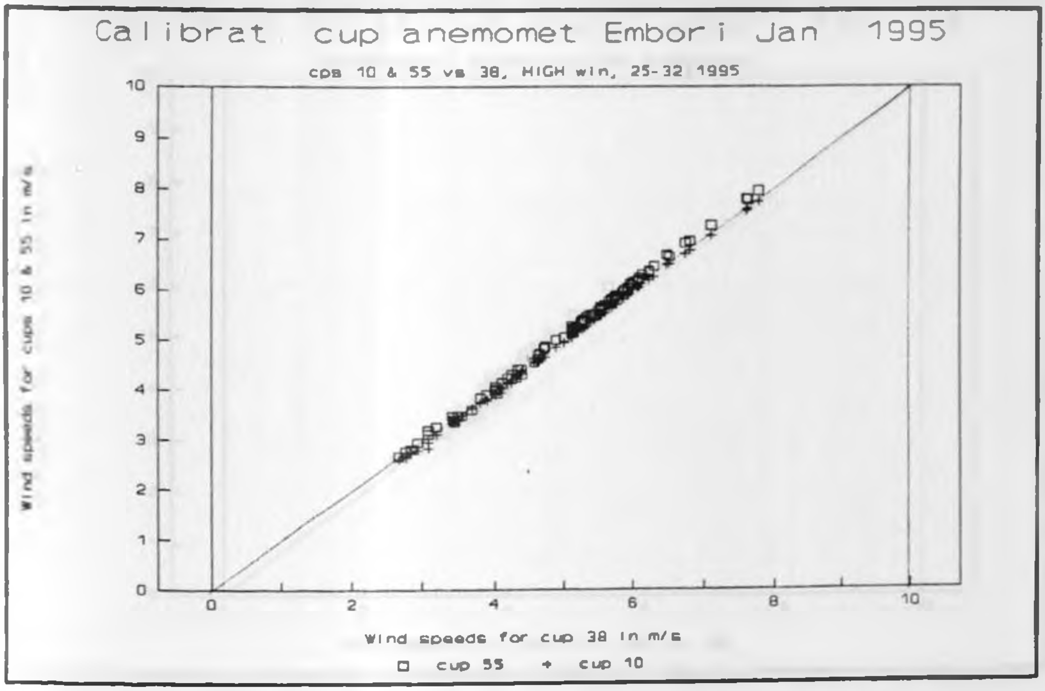


Fig. 212. The scatter plot and 1:1 lines of electrical cup anemometers 10 & 55 against middle cup 38 for day-time (07h00-20h00) conditions at Embori for DOY 25-32 of 1995.

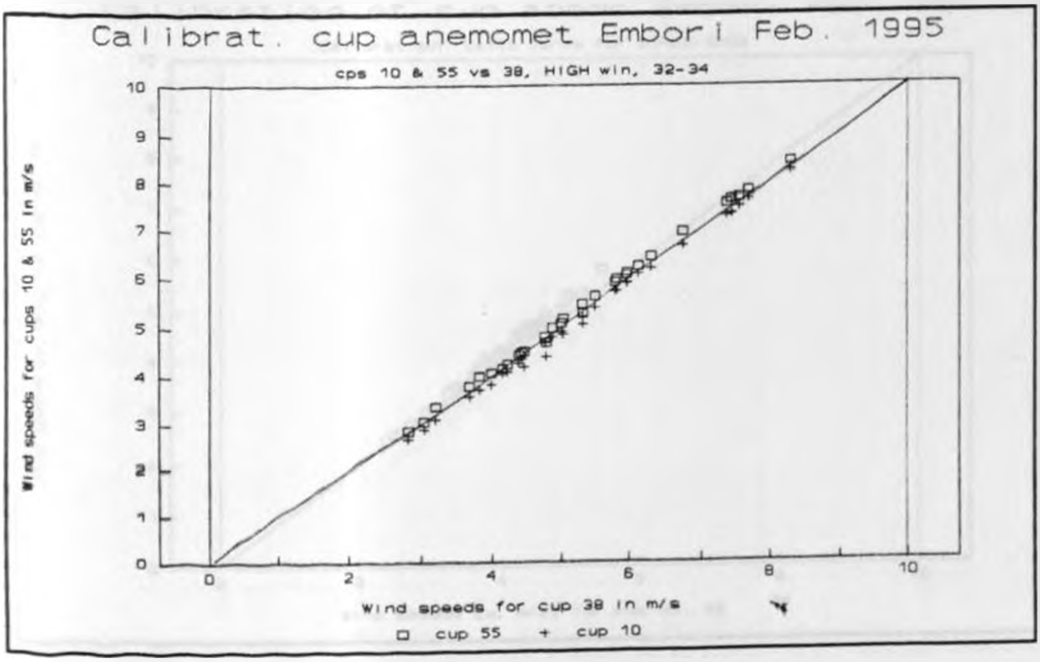


Fig. 213. The scatter plot and 1:1 lines of electrical cup anemometers 10 & 55 against middle cup 38 day-time (07h00-20h00) conditions at Embori for DOY 32-34 of 1995.

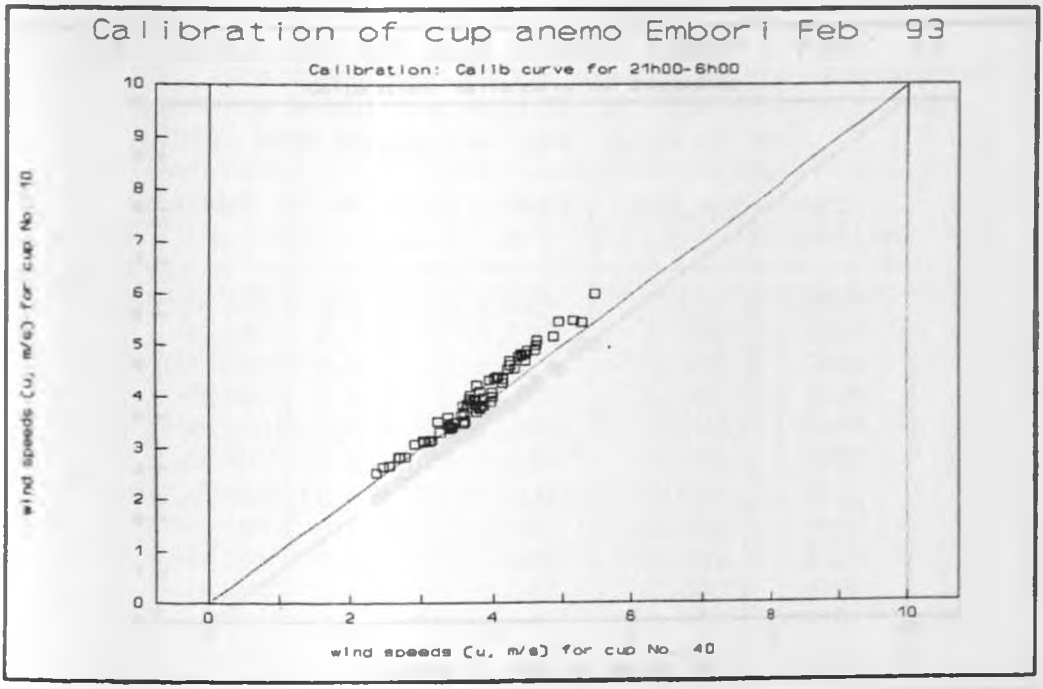


Fig. 214. The scatter plots and 1:1 line of hourly wind speeds for WAU electrical cup anemometer 10 against cup 40 for night-time (21h00-06h00) conditions at Embori for DOY 55-62 of 1993.

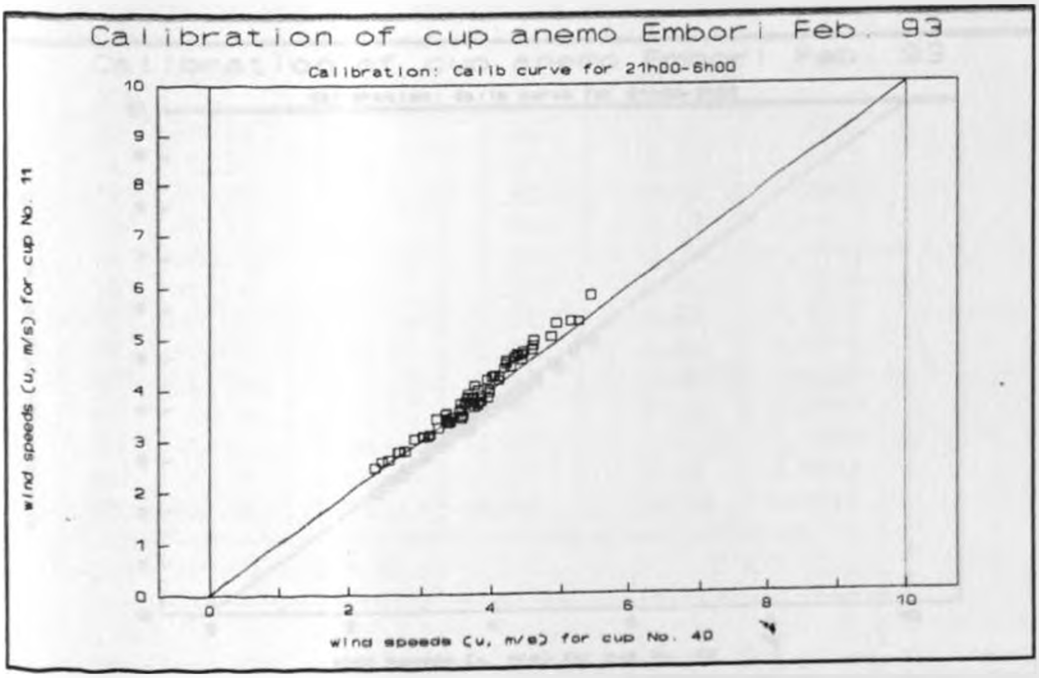


Fig. 215. The scatter plots and hourly wind speeds for WAU electrical cup anemometer 11 against substandar cup 40 for night-time (21h00-06h00) conditions at Embori for days 55-62 of 1993.

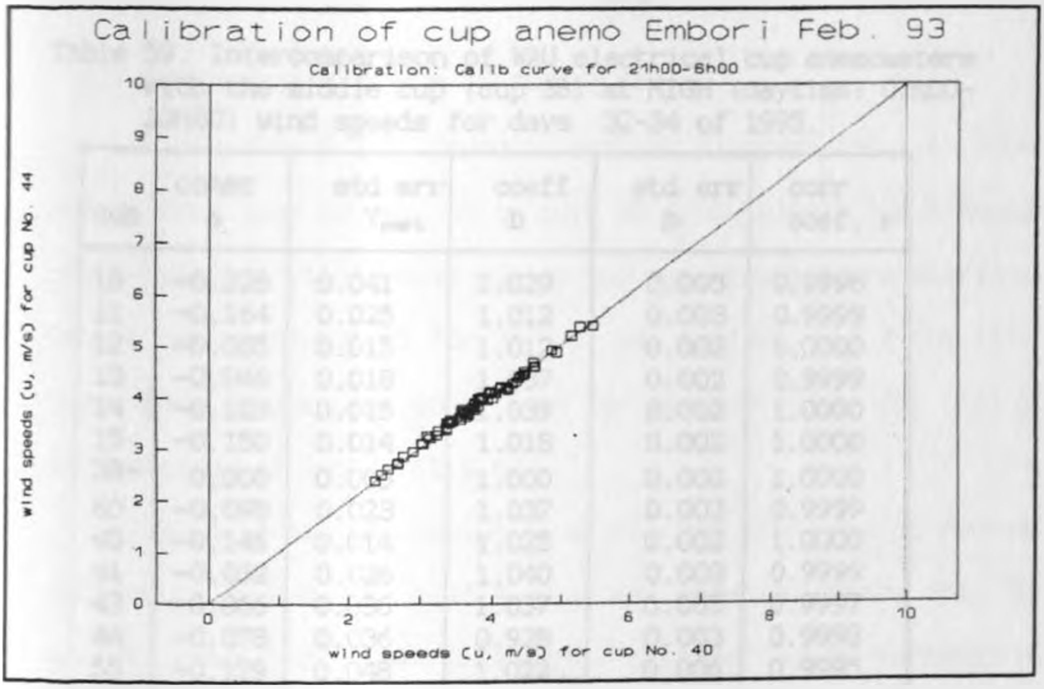


Fig. 216. The scatter plots and 1:1 line of hourly wind **speeds for WAU electrical cup anemometer 44 against** substandard cup 40 for night-time (21h00-06h00) conditions at Embori for DOY 55-62 of 1993.

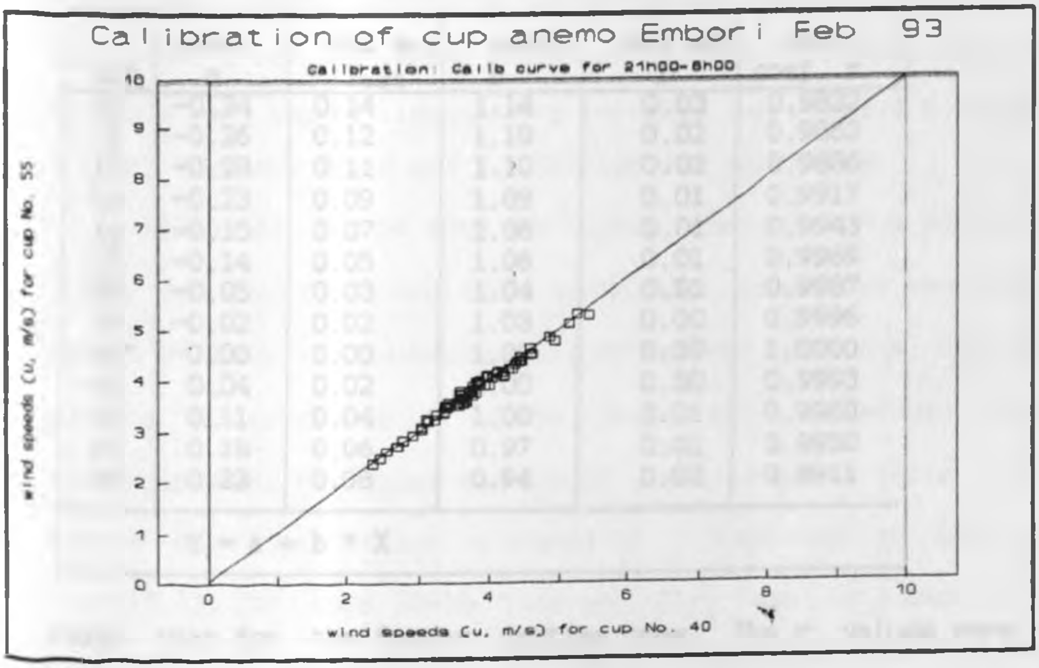


Fig. 217. The scatter plots and 1:1 line of hourly wind speeds for WAU electrical cup anemometer 55 against substandard cup 40 for night-time (21h00-06h00) conditions at Embori for Embori for 55-62 of 1993.

Table 59. Intercomparison of WAU electrical cup anemometers with the middle cup (cup 38) at HIGH (daytime: 07h00–20h00) wind speeds for days 32-34 of 1995.

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
10	−0.228	0.041	1.029	0.005	0.9996
11	−0.164	0.025	1.012	0.003	0.9999
12	−0.085	0.015	1.012	0.002	1.0000
13	−0.046	0.018	1.037	0.002	0.9999
14	−0.103	0.015	1.039	0.002	1.0000
15	−0.150	0.014	1.018	0.002	1.0000
38*	0.000	0.000	1.000	0.000	1.0000
60	−0.098	0.023	1.037	0.003	0.9999
40	−0.146	0.014	1.025	0.002	1.0000
41	−0.032	0.026	1.040	0.003	0.9999
43	−0.066	0.036	1.037	0.005	0.9997
44	−0.078	0.036	0.928	0.003	0.9998
55	−0.129	0.048	1.022	0.006	0.9995

$Y = a + b * X$

Table 60. Intercomparison of WAU electrical cup anemometers with the substandard cup (cup 40) at LOW (nighttime: 21h00–06h00) wind speeds for days 55–62 of 1993.

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
10	−0.34	0.14	1.14	0.03	0.9832
11	−0.26	0.12	1.10	0.02	0.9863
12	−0.28	0.11	1.10	0.02	0.9886
13	−0.23	0.09	1.09	0.01	0.9917
14	−0.15	0.07	1.06	0.01	0.9943
15	−0.14	0.05	1.06	0.01	0.9969
38	−0.05	0.03	1.04	0.01	0.9987
39	−0.02	0.02	1.03	0.00	0.9996
40*	0.00	0.00	1.00	0.00	1.0000
41	0.04	0.02	1.00	0.00	0.9993
43	0.11	0.04	1.00	0.01	0.9980
61	0.18	0.06	0.97	0.01	0.9950
55	0.23	0.08	0.94	0.02	0.9911

$Y = a + b * X$

winds than for the faster daytime ones. The r values were close to 1.000. There appear to be no cups that dot not fit a picture due to the environmental conditions.

(ii) Comparison with cup 38 during Cb3

Figs. 218 & 219 present scatter diagrams and 1:1 lines of wind speeds for cups 10 and 55 on cup 38 (the middle cup anemometer) for night-time LOW wind speeds during two cup arrangements (22/1/-1/2/95 for 70 hrs and 1/2/-3/2/95 for 20 hrs. see section 4.3.1 (b) (ii)) in Cb3. These show night-time conditions for section 4.3.1 (b) (ii) above (see first column of Tables 61 & 62).

Again we see in Tables 61 & 62 that there was no decrease in the intercepts towards the middle cups, as observed during Cb1. There was a marked trend of the intercepts towards zero (origin) in both arrangements. The correlation coefficients (r) between cup anemometers was again very high. This confirmed the absence of valley topographic influence. This influence was eliminated by reducing the distance over which cup anemometers were installed to half of that in Cb1. The gradients 'b' of the linear relations between individual cups (dependent variable) and cup 38 (independent variable) were within a range of 1.019 ± 0.023 for days 25-32 and 1.000±0.029 for days 32-34.

Tables 63 and 64 show the bulked (day-time plus night-time) wind speeds for days 25-32 and 32-34 during Cb3. We observe very high r values even for the bulked as well as for the individual day/night-time periods. The gradients 'b' of the linear relations between individual cups (dependent variable) and cup 38 (independent variable) for the bulked data were within a range of 1.024±0.022 for days 25-32 and 1.017±0.031 for days 32-34. This indicated less influence of the local topographical features with decrease in distance over which the cups were installed for calibration, as observed for unbulked data.

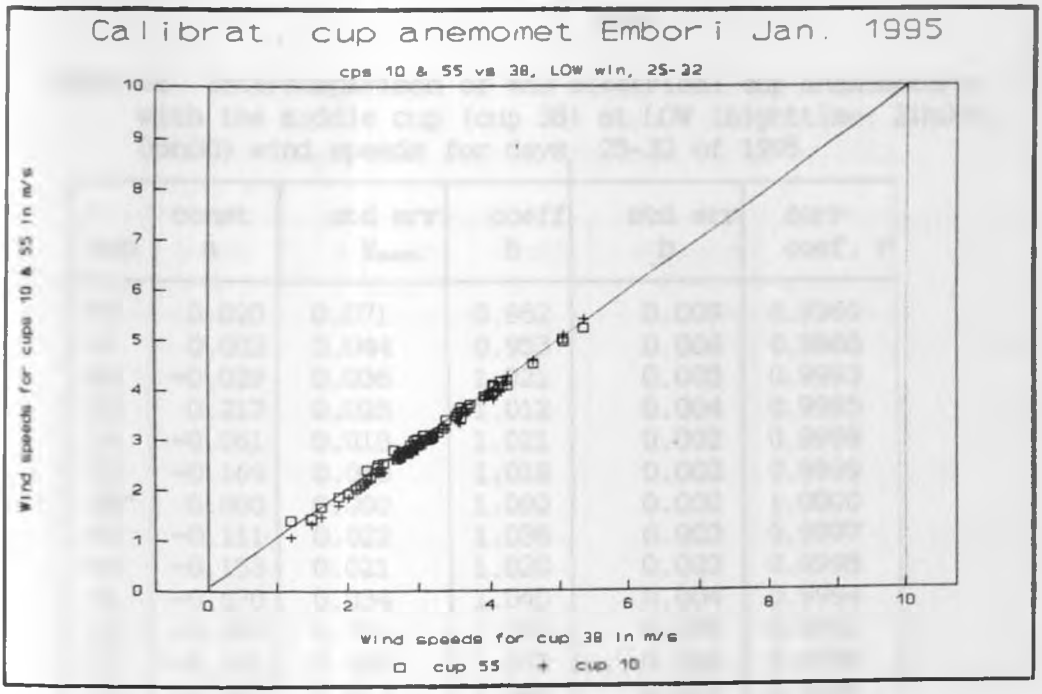


Fig. 218. The scatter plot and 1:1 line of hourly wind speeds for WAU electrical cup anemometers 10 & 55 against middle cup 38 for night-time (21h00-06h00) conditions at Embori for DOY 25-32 of 1995.

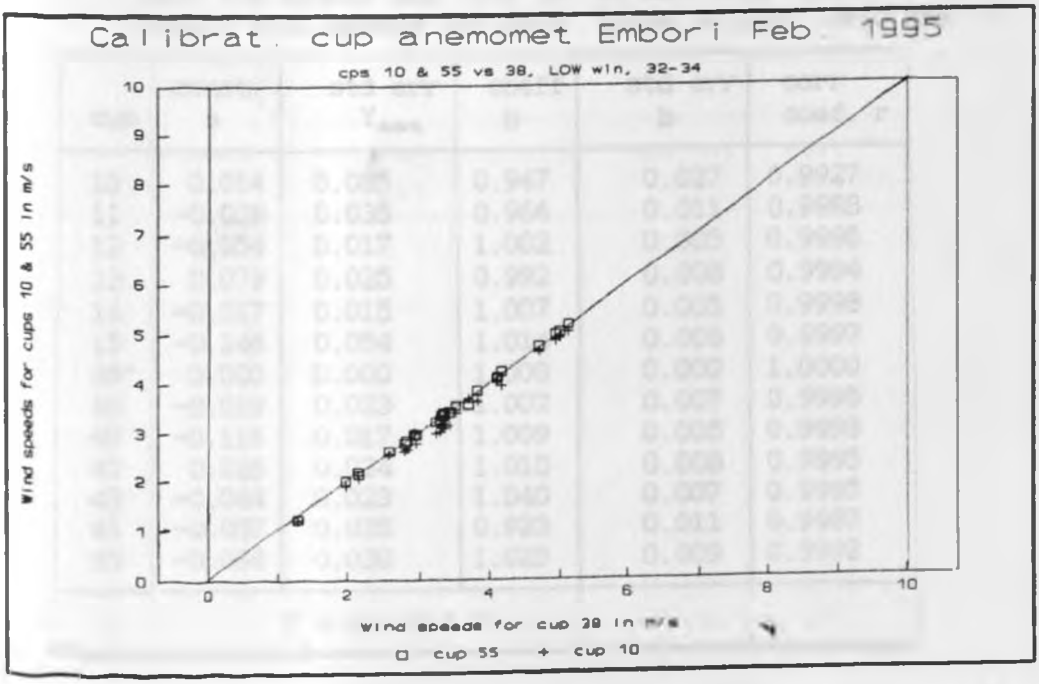


Fig. 219. The scatter plot and 1:1 line of hourly wind speeds WAU electrical cup anemometers 10 & 55 against middle cup 38 for night-time (21h00-06h00) conditions at Embori for days 32-34 of 1995.

Table 61. Intercomparison of WAU electrical cup anemometers with the middle cup (cup 38) at LOW (nighttime: 21h00–06h00) wind speeds for days 25–32 of 1995.

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
55	0.020	0.071	0.982	0.009	0.9969
61	0.002	0.044	0.953	0.006	0.9988
43	−0.029	0.036	1.021	0.005	0.9993
13	0.217	0.028	1.012	0.004	0.9995
14	−0.061	0.018	1.021	0.002	0.9998
15	−0.169	0.013	1.018	0.002	0.9999
38*	0.000	0.000	1.000	0.000	1.0000
60	−0.111	0.022	1.036	0.003	0.9997
40	−0.153	0.021	1.020	0.003	0.9998
41	−0.070	0.034	1.040	0.004	0.9994
12	−0.080	0.039	1.020	0.005	0.9991
11	−0.191	0.045	1.035	0.006	0.9989
10	−0.245	0.053	1.046	0.007	0.9985

$Y = a + b * X$,

Table 62. Intercomparison of WAU electrical cup anemometers with the middle cup (cup 38) at LOW (nighttime: 21h00–06h00) wind speeds for days 32–34 of 1995. N=20 hrs

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
10	0.014	0.085	0.947	0.027	0.9927
11	−0.028	0.035	0.966	0.011	0.9988
12	−0.054	0.017	1.002	0.005	0.9998
13	0.079	0.025	0.992	0.008	0.9994
14	−0.017	0.015	1.007	0.005	0.9998
15	−0.146	0.054	1.014	0.006	0.9997
38*	0.000	0.000	1.000	0.000	1.0000
60	−0.019	0.023	1.007	0.007	0.9995
40	−0.116	0.017	1.009	0.005	0.9998
41	0.026	0.024	1.010	0.008	0.9995
43	−0.044	0.023	1.040	0.007	0.9995
61	−0.037	0.035	0.923	0.011	0.9987
55	−0.064	0.030	1.025	0.009	0.9992

$Y = a + b * X$

Table 63. Intercomparison of WAU electrical cup anemometers with the middle cup (cup 38) for bulked data (nighttime plus daytime) wind speeds for days 25–32 of 1995. N=160 hrs

cup	const a	std err Y_{est}	coeff b	std err b	corr coef, r
55	−0.148	0.071	1.040	0.004	0.9988
61	−0.031	0.040	0.964	0.002	0.9955
43	−0.064	0.037	1.033	0.002	0.9967
13	−0.044	0.029	1.036	0.002	0.9998
14	−0.119	0.023	1.041	0.001	0.9999
15	−0.173	0.013	1.022	0.001	1.0000
38*	0.000	0.000	1.000	0.000	1.0000
60	−0.129	0.021	1.044	0.001	0.9999
40	−0.182	0.023	1.032	0.001	0.9999
41	−0.099	0.099	1.051	0.002	0.9998
12	−0.056	0.033	1.012	0.002	0.9997
11	−0.154	0.039	1.024	0.002	0.9996
10	−0.185	0.046	1.027	0.003	0.9995

$Y = a + b * X$

Table 64. Intercomparison of WAU electrical cup anemometers with the middle cup (cup 38) for bulked data (nighttime plus daytime) wind speeds for days 32–34 of 1995. N=48 hrs

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
10	−0.212	0.072	1.025	0.006	0.9991
11	−0.152	0.036	1.009	0.003	0.9998
12	−0.078	0.016	1.011	0.001	1.0000
13	−0.045	0.030	1.035	0.003	0.9999
14	−0.105	0.021	1.038	0.002	0.9999
15	−0.151	0.016	1.018	0.001	1.0000
38*	0.000	0.000	1.000	0.000	1.0000
60	−0.106	0.027	1.038	0.002	0.9999
40	−0.165	0.019	1.027	0.002	0.9999
41	−0.065	0.032	1.044	0.003	0.9998
43	−0.030	0.032	1.032	0.003	0.9998
61	−0.041	0.031	0.922	0.003	0.9998
55	−0.072	0.044	1.032	0.004	0.9997

$Y = a + b * X$

4.3.1 (d) Intercomparison of Woelfle anemographs and the WAU cups

(i) Calibration during Cb1

Figs. 220 & 221 show comparisons of Woelfle anemographs on the north and south of the electrical anemometers during daytime and nighttime in Cb1. WA was installed on the northern side of the horizontal bar of anemometers at 1.0 m from cup 10. WB was installed on the southern side at 1.0 m from cup 55 (see Plate 13). We can see from Fig. 220, which relates the two instruments during daytime (07h00-20h00), that the two were very highly correlated with each other (with r=0.9795) they were only 9.2 m apart. This r value is, nevertheless, smaller than among the electrical cup anemometers, but in the same order of magnitude as a comparison between the outermost electrical cups would be at night. During the low night-time winds (Fig. 221) the relationship was still good but the correlation was relatively low (with r=0.9510). This is appreciably smaller than for the electrical cup anemometers at night. The bulked data (day-time plus night-time) winds were also highly correlated (with r=0.9818) but the regression constants remain influenced by the local terrain. We derived the linear regression equations between WA and WB. These are given below:

(a) high daytime winds (07h00 - 20h00):

$$WB = 0.04 + 0.97*WA, \ r = 0.9795$$

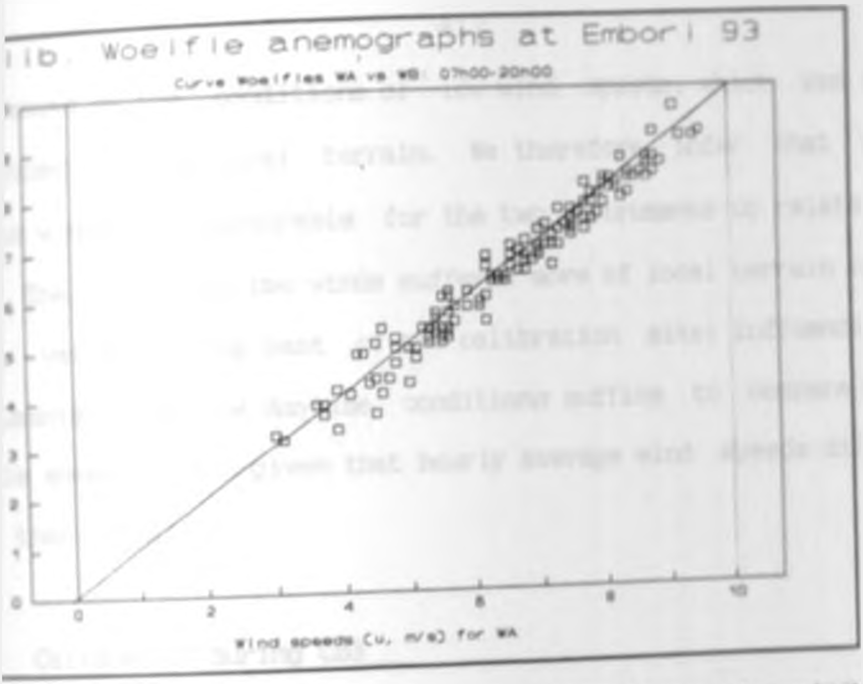
(b) low nighttime winds (21h00 - 06h00):

$$WB = 0.57 + 0.87*WA, \ r = 0.9510$$

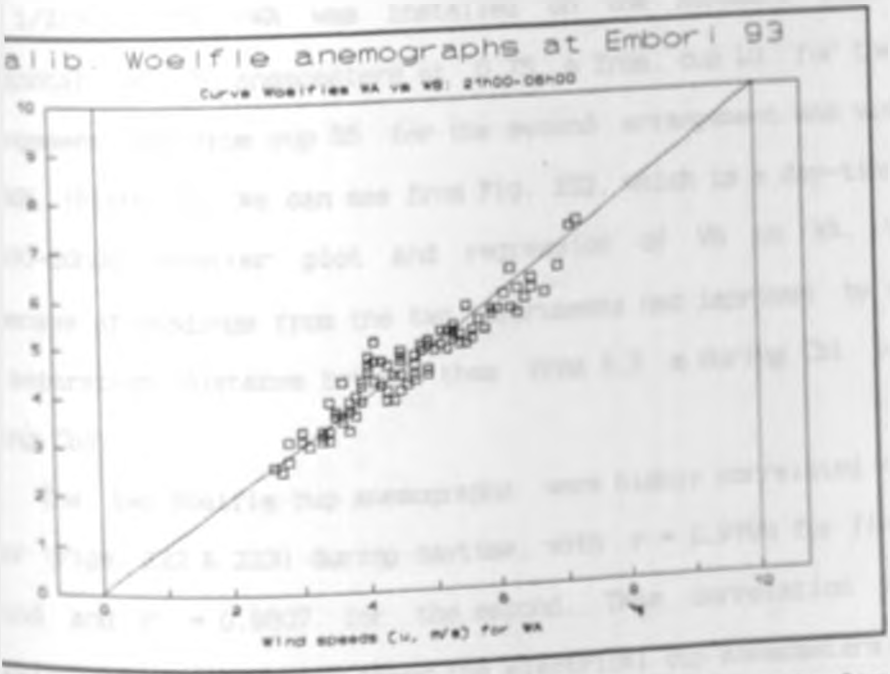
(c) bulked (day & night times) data (07h00 - 06h00):

$$WB = 0.23 + 0.95*WA, \ r = 0.9818$$

The two instruments correlating better in the high daytime winds than in the low night winds, at night the intercept values receded from zero and the gradient from one, as in (b). The bulked data equation was



20. The scatter plot and 1:1 line of hourly wind
for Woelfle anemograph (WB, Ser. Nr. 31587)
t anemograph (WA, Ser. Nr. 341836) for day-time
-20h00) conditions for DOY 57-67 of 1993.



221. The scatter plot and 1:1 hourly wind speeds for
'lle anemograph (WB, Ser. Nr. 31587) against
ograph (WA, Ser. Nr. 341836) for night-time
itions for DOY 57-67 of 1993

influenced by the conditions of low wind speeds. which was in turn influenced by the local terrain. We therefore infer that the high daytime winds were favourable for the two instruments to relate to each other. The low night-time winds suffered more of local terrain (e.g. the nearby valley on the east of the calibration site) influence on the instruments. Thus the daytime conditions suffice to compare the two Woelfle anemographs, given that hourly average wind speeds did not get lower than 2.5 m/s.

(ii) Calibration during Cb3

Figs. 222-225 show comparisons of Woelfle anemographs (WA & WB) on the north and south of the electrical anemometers during day-time and nighttime for two arrangements in Cb3 mentioned above (i.e. 25/1/-1/2/95 and 1/2/3-3/2/95). WA was installed on the northern side of the horizontal bar of anemometers at 0.75 m from cup 10 for the first arrangement and from cup 55 for the second arrangement and vice versa for WB. (Plate 13). We can see from Fig. 222, which is a day-time (07h00-20h00) scatter plot and regression of WB on WA. that the closeness of readings from the two instruments had improved by reducing the separation distance between them from 9.2 m during Cb1 to 5.1 m during Cb3.

The two Woelfle cup anemographs were highly correlated with each other (Figs. 222 & 223) during daytime. with r = 0.9784 for first period and r = 0.9807 for the second. This correlation is. again nevertheless. smaller than among the electrical cup anemometers and also smaller than for a comparison between the outermost electrical cups at night. During the low night-time winds (Figs. 222 & 223) the relationship was still good but the correlations were much lower but

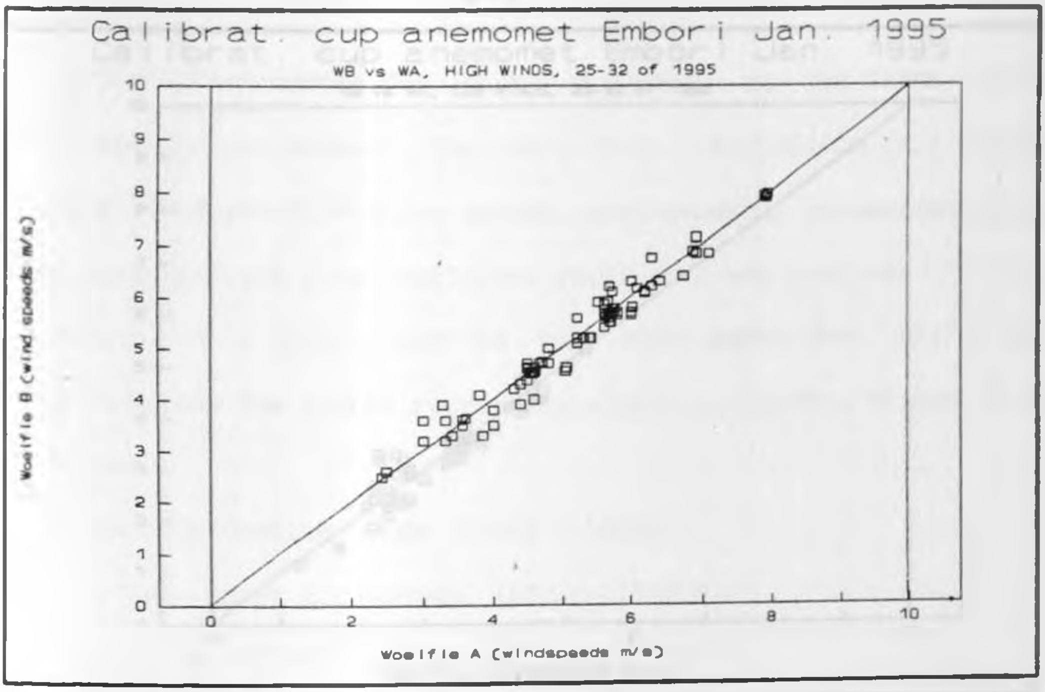


Fig. 222. The scatter plots and 1:1 line of hourly wind speeds for Woelfle anemograph (WB, Ser. Nr. 31587) against anemograph (WA, 341836) for day-time for DOY 25-32 of 1995.

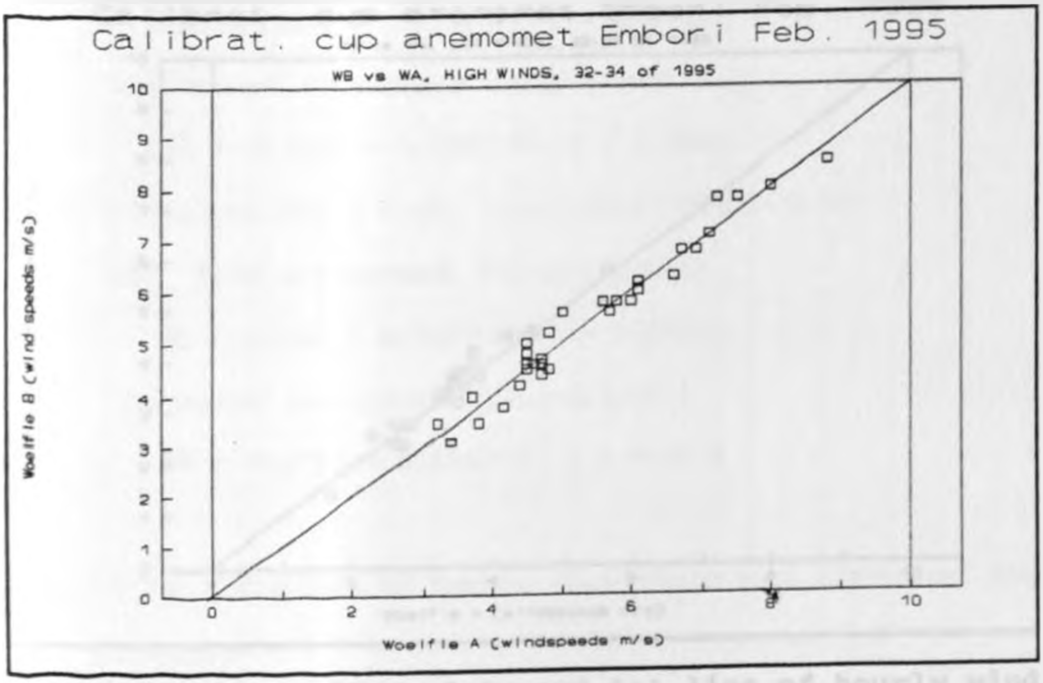


Fig. 223. The scatter plots and 1:1 line of hourly wind speeds for Woelfle anemograph (WB, Ser. Nr. 31587) against anemograph (WA, Ser. Nr. 341836) for day-time for DOY 32-34 of 1995.

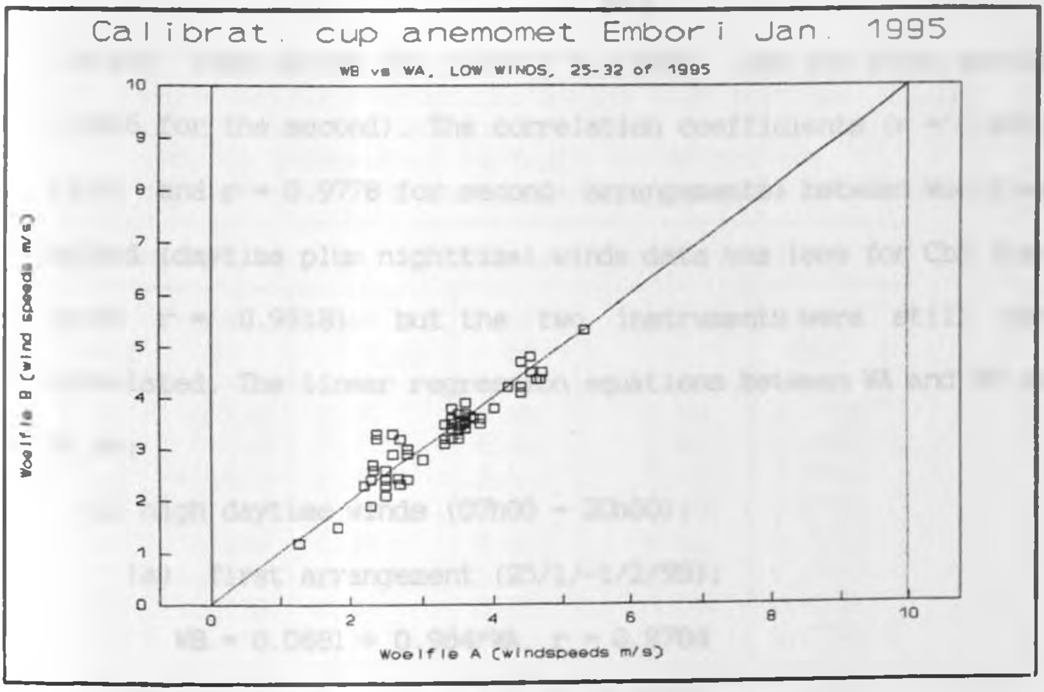


Fig. 224. The scatter plots and 1:1 of hourly wind speeds for Woelfle anemograph (WB, Ser. Nr. 31587) against anemograph (WA, Ser. Nr. 341836) for night- time for DOY 25-32 of 1995.

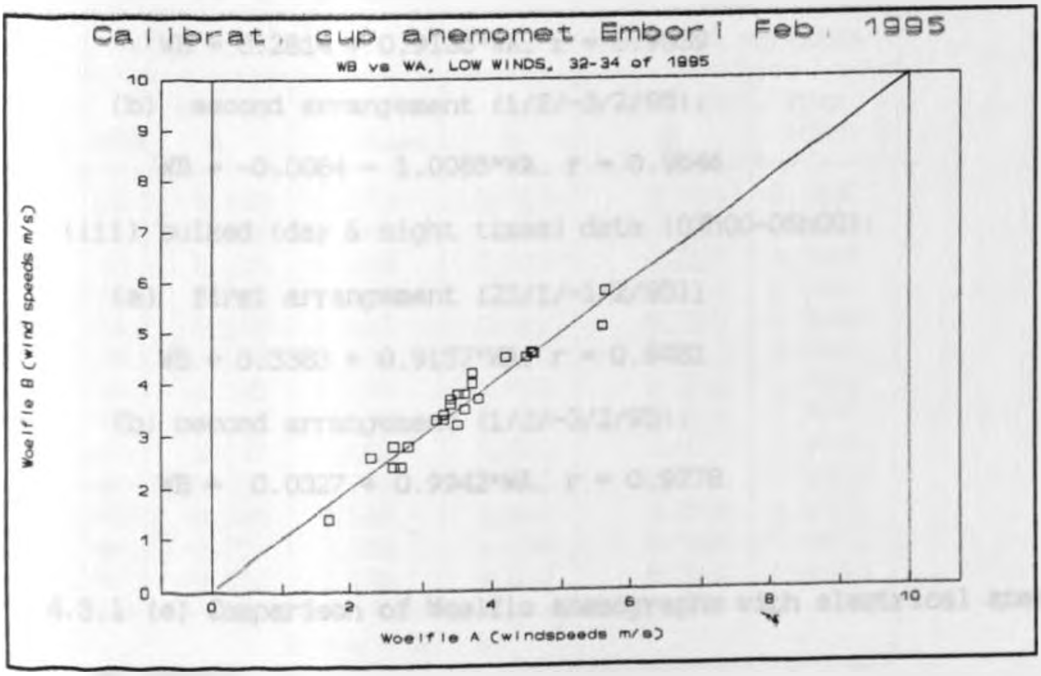


Fig. 225. The scatter plots and 1:1 line of hourly wind speeds for Woelfle anemograph (WB, Ser. Nr. 31587) against anemograph (WA, Ser. Nr. 341836) for night-time for DOY 32-34 of 1995.

better than during Cb1 (with r = 0.9339 now for first period and r = 0.9646 for the second). The correlation coefficients (r = 0.9481 for the first and r = 0.9778 for second arrangements) between Woelfles for the bulked (daytime plus nighttime) winds data was less for Cb3 than for Cb1 (with r = 0.9818), but the two instruments were still very highly correlated. The linear regression equations between WA and WB were found to be;

(i) high daytime winds (07h00 - 20h00):

(a) first arrangement (25/1/-1/2/95);

WB = 0.0681 + 0.984*WA, r = 0.9784

(b) second arrangement (1/2/-3/2/95);

WB = 0.0344 + 0.9986*WA, r= 0.9807

(ii) low nighttime winds (21h00–06h00):

(a) first arrangement (25/1/-1/2/95);

WB = 0.2814 + 0.9136*WA, r = 0.9339

(b) second arrangement (1/2/-3/2/95);

WB = -0.0084 + 1.0085*WA, r = 0.9646

(iii) bulked (day & night times) data (07h00–06h00):

(a) first arrangement (25/1/-1/2/95);

WB = 0.3383 + 0.9157*WA, r = 0.9481

(b) second arrangement (1/2/-3/2/95);

WB = 0.0327 + 0.9942*WA, r = 0.9778

4.3.1 (e) Comparison of Woelfle anemographs with electrical anemometers at Embori

(i) Comparison of WA & WB with WAU cups during Cb1

Tables 65 (a & b) and 66 (a & b) show the comparisons of electrical anemometers with the Woelfle anemographs at Embori during

Table 65. Intercomparison of WAU electrical cup anemometers with Woelfle anemographs during HIGH (daytime: 07h00-20h00) winds at Embori(days 55-62 of 1993). (a) woelfle (WA) as independent variable. N= 98 hrs and (b) woelfle (WB) as independent variable. N= 76 hrs.

(a) WA (Sr. Nr. 341836) as independent variable

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
10	0.120	0.28	0.83	0.02	0.9715
11	0.040	0.31	0.84	0.02	0.9661
12	-0.002	0.27	0.84	0.02	0.9749
13	0.018	0.28	0.85	0.02	0.9728
14	0.038	0.28	0.83	0.02	0.9723
15	-0.051	0.28	0.85	0.02	0.9727
38	-0.018	0.28	0.85	0.02	0.9728
39	-0.031	0.28	0.85	0.02	0.9728
40	-0.094	0.28	0.84	0.02	0.9727
41	-0.131	0.29	0.86	0.02	0.9721
43	-0.119	0.29	0.85	0.02	0.9720
44	-0.102	0.29	0.85	0.02	0.9714
55	-0.149	0.30	0.85	0.02	0.9697

$Y = a + b * X$

(b) WB (Sr. Nr. 31587) as independent variable

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
10	0.332	0.173	0.813	0.014	0.9892
11	0.286	0.162	0.805	0.013	0.9900
12	0.225	0.164	0.817	0.013	0.9901
13	0.226	0.165	0.823	0.014	0.9901
14	0.232	0.161	0.812	0.013	0.9903
15	0.138	0.159	0.830	0.013	0.9910
38	0.165	0.157	0.829	0.012	0.9912
39	0.147	0.154	0.828	0.013	0.9915
40	0.077	0.152	0.822	0.013	0.9915
41	0.038	0.149	0.843	0.012	0.9923
43	0.048	0.147	0.843	0.012	0.9925
44	0.051	0.141	0.836	0.012	0.9931
55	-0.013	0.139	0.839	0.011	0.9932

$Y = a + b * X$

Table 66. Intercomparison of WAU electrical cup anemometers with Woelfle anemographs during LOW (nighttime: 21h00-06h00) winds at Embori (days 55-62 of 1993). (a) woelfle (WA) as independent variable, N= 70 hrs and (b) woelfle (WB) as independent variable, N= 50 hrs.

(a) WA (Sr. Nr. 341836) as independent variable

cup	const a	std err Y_{est}	coeff b	std err b	corr coef, r
10	0.340	0.228	0.771	0.030	0.9526
11	0.425	0.221	0.738	0.029	0.9515
12	0.417	0.223	0.737	0.029	0.9508
13	0.476	0.223	0.730	0.030	0.9495
14	0.552	0.221	0.708	0.029	0.9475
15	0.580	0.224	0.698	0.029	0.9447
38	0.675	0.226	0.686	0.030	0.9422
39	0.705	0.226	0.674	0.030	0.9401
40	0.715	0.226	0.653	0.030	0.9366
41	0.772	0.236	0.653	0.031	0.9317
43	0.840	0.239	0.642	0.031	0.9277
44	0.913	0.249	0.625	0.033	0.9919
55	0.963	0.254	0.604	0.033	0.9099

$Y = a + b * X$

(b) WB (Sr. Nr. 31587) as independent variable

cup	const a	std err Y_{est}	coeff b	std err b	corr coef, r
10	-0.012	0.293	0.865	0.049	0.9307
11	0.045	0.278	0.834	0.047	0.9323
12	0.015	0.275	0.837	0.046	0.9345
13	0.045	0.268	0.835	0.045	0.9371
14	0.103	0.257	0.816	0.043	0.9392
15	0.089	0.248	0.812	0.042	0.9426
38	0.152	0.236	0.805	0.040	0.9456
39	0.167	0.230	0.797	0.038	0.9485
40	0.180	0.220	0.774	0.037	0.9495
41	0.190	0.217	0.782	0.036	0.9519
43	0.248	0.212	0.773	0.036	0.9529
44	0.300	0.212	0.759	0.035	0.9515
55	0.326	0.208	0.742	0.035	0.9508

$Y = a + b * X$

day- and night-time respectively. The correlation coefficients between anemometers and anemographs were generally again higher for the daytime than for the night time winds. All anemometers were more highly correlated with the southern Woelfle (WB), (with an average r of 0.9914 ± 0.0011) (Table 65b) than with the northern Woelfle (WA) (with an average r of 0.9719 ± 0.0021) for the day time winds (Tables 65a).

Table 66a & 66b show r for night-time wind speed data during Cb1. As expected the anemometers closer to WA were more correlated with the former than those farther away (r = 0.9526 for cup 10 to r = 0.9099 for 55 nearest to WB) (see Table 66a). Conversely the anemometers closer to WB were more correlated with WB (r = 0.9529 for cup 43 to r = 0.9307 for cup 10) than those farther away. The conditions were more pronounced during night- than day-time.

(ii) Comparison of WA & WB with WAU cups during Cb3

Tables 67a & 67b and 68a & 68b show the comparisons of electrical anemometers with the Woelfle anemograph (WA) at Embori during day- and night-time respectively for the first arrangement (25/1/-1/2/95) and for second arrangement (1/2/-3/2/95) as indicated in section 4.3.1 (b) (ii) Here again the correlation coefficients between anemometers and WA were generally higher for the daytime than for the nighttime winds. However, the values of the correlation coefficients between WAU cup anemometers and the woelfle anemographs were lower for the Cb3 than for Cb1, when the cup anemometers were barely four months old. The reduction in correlation values between the electrical cup anemometers and the Woelfle anemographs was more therefore due to ageing of the anemographs which have been in use much longer before they were deployed for this exercise. The ageing of anemographs seemed more likely than other factors such: instrument type, shape of cups, round-off errors, effects of threshold and dynamic zeroes of the latter with also give same response. The comparison of WAU electrical anemometers with

Table 67. Intercomparison of WAU electrical cup anemometers with Woelfle anemographs (WA) during HIGH (daytime: 07h00-20h00) winds at Embori (a) for the period 25-32 of 1995, N= 87 hrs and (b) for the period 32-33 of 1995, N= 31 hrs.

(a) HIGH: for the period 25-32 of 1995, N= 87 hrs

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
55	-0.218	0.340	0.996	0.032	0.9595
61	0.086	0.305	0.920	0.028	0.9616
43	0.072	0.329	0.984	0.031	0.9611
13	0.097	0.333	0.987	0.031	0.9604
14	0.030	0.336	0.990	0.031	0.9601
15	-0.019	0.328	0.970	0.031	0.9603
38	0.129	0.321	0.952	0.030	0.9605
60	0.040	0.336	0.989	0.031	0.9599
40	-0.019	0.334	0.978	0.031	0.9595
41	0.058	0.344	0.997	0.032	0.9587
12	0.017	0.328	0.962	0.031	0.9596
11	0.012	0.332	0.968	0.031	0.9591
10	-0.018	0.336	0.970	0.031	0.9585
WB	0.068	0.242	0.984	0.023	0.9784

$Y = a + b * X$

(b) HIGH: for the period 32-34 of 1995, N= 31 hrs.

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
10	-0.249	0.418	1.007	0.054	0.9601
11	-0.230	0.416	0.995	0.054	0.9596
12	-0.107	0.412	0.990	0.054	0.9600
13	-0.068	0.427	1.013	0.056	0.9589
14	-0.121	0.429	1.015	0.056	0.9587
15	-0.160	0.423	0.993	0.055	0.9581
38	-0.012	0.412	0.976	0.054	0.9588
39	-0.100	0.433	1.011	0.056	0.9577
40	-0.160	0.423	1.001	0.055	0.9588
41	-0.049	0.425	1.016	0.055	0.9595
43	-0.089	0.437	1.013	0.057	0.9571
44	-0.005	0.401	0.898	0.052	0.9542
55	-0.063	0.416	1.003	0.054	0.9601
WB	0.034	0.284	0.999	0.037	0.9807

$Y = a + b * X$

the WB gave average correlation coefficients (r) for daytime conditions of 0.9549±0.0017 for N=87, for the first arrangement in Cb3 before the outer cups were interchanged and 0.9578±0.0025 for N=31, for the second arrangement Cb3 after the outer cups were interchanged. The average r between cup anemometers and WB for night-time conditions were obtained as 0.8949 ± 0.0025 for N=64, for the first arrangement in Cb3 and 0.8468±0.0062 for N=26, for the second arrangement in Cb3 (Tables 66 and 67).

When the day-time and night-time data were bulked (pooled) the average r of cup anemometers with WB anemograph were 0.9468 ±0.0013 for N=151, for the first arrangement and 0.9509±0.0020 for N=57, for the second arrangement both in Cb3. Tables 69a & 69b present comparisons of WA with cup anemometers for the bulked wind speed data during the two periods indicated above. We again observe high correlations during this period. As already pointed out the electrical cup anemometers were correlated better with the Woelfle anemographs during daytime than during nighttime.

Intercomparisons of WAU electrical cup anemometers (Table 70) shows the ratios of cup anemometers to the substandard (cup 40) during Cb1 for day (D) and night (N) conditions to lie in the range 1.02 ± 0.01. On the mean, cups read 2% more than the substandard (cup 40). This range also applies to all individual cups (Tables 70). The intercomparisons with extreme cup 10 during Cb2 (Table 70) show the ratios to lie between 0.99±0.02 and 1.03±0.02. Most cups were reading within 2% of cup 10. The intercomparisons with the middle cup (cup 38) during Cb3 Table 68a & 68b show the ratios to lie between 0.99±0.01 and 1.01±0.01 for most cups for day and nighttime conditions. On the whole the electrical cups were very close to each other, within a range of 1%.

Table 71 shows the ratios of anemographs to the mean hourly wind speeds during the calibration periods Cb1, Cb2 and Cb3 (a & b). The anemographs compare reasonably well with the WAU electrical anemometers. The mean ratios show that cup anemographs were reading 10-11% more than the WAU electrical anemometers. Kainkwa (1991), working under Indian Ocean beach conditions in Dar es Salaam, found also that anemographs read 10% more than electrical anemometers, although he used Bottemanne conical cups of 21 cm diameter. In our case we have used WAU conical cup anemometers of 15 cm diameter.

The electrical cup anemometers which we used here, as well as the Bottemanne anemometers of Kainkwa, were made by the Mechanical Workshop/ Laboratory of the Physics and Meteorology Department of Wageningen Agricultural University (The Netherlands). They were calibrated in the same wind tunnel. The nature of terrain used by Kainkwa (1991) was very different from our Embori site. In the Embori case there was inevitably a lateral difference in the loss of momentum close to the valley foreground especially at lower wind speeds during night time. Of course cup anemometers measure wind speeds at angles upto about 45° with the horizontal without errors. The main reason for the ratio is a higher speeds in m/s. Our calibrations show that no corrections were necessary to individual electrical cup anemometers during periods between or otherwise close to the times of calibrations and acceleration and a lower deceleration of the cups of the Woelfle anemographs. Also the anemographs have higher stalling speeds.

Smaller reasons for higher readings with anemographs as compared to electrical anemometers (also observed by Kainkwa, 1991) are round-off or subjectivity errors when manually evaluating the hourly wind speeds from the strip charts of the Woelfle mechanical wind recorders

Table 68. Intercomparison of WAU electrical cup anemometers with Woelfle anemographs (WA) during LOW (night-time: 21h00-06h00) winds at Embori (a) for the period 25-32 of 1995, N= 64 hrs and (b) for the period 32-34 of 1995, N= 26 hrs.

(a) LOW: for the period 25-32 of 1995. N= 64 hrs

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
55	0.030	0.390	0.933	0.062	0.8865
61	0.013	0.375	0.904	0.060	0.8878
43	−0.016	0.404	0.969	0.064	0.8869
13	0.048	0.400	0.957	0.064	0.8860
14	−0.030	0.405	0.963	0.064	0.8852
15	−0.131	0.405	0.960	0.064	0.8845
38	0.042	0.398	0.939	0.063	0.8838
60	−0.059	0.414	0.971	0.066	0.8823
40	−0.103	0.409	0.957	0.065	0.8820
41	−0.003	0.412	0.969	0.066	0.8804
12	−0.010	0.411	0.950	0.065	0.8794
11	−0.116	0.416	0.962	0.066	0.8797
10	−0.160	0.422	0.969	0.067	0.8783
WB	0.281	0.280	0.914	0.044	0.9339

$Y = a + b * X$

(b) LOW: for the period 32-34 of 1995. N= 26 hrs

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
10	−0.095	0.402	0.948	0.087	0.9117
11	0.113	0.414	0.883	0.090	0.8950
12	−0.053	0.431	0.966	0.094	0.9033
13	0.138	0.429	0.936	0.093	0.8991
14	0.069	0.437	0.941	0.095	0.8966
15	−0.032	0.438	0.940	0.095	0.8962
38	0.097	0.435	0.930	0.094	0.8954
60	0.009	0.437	0.960	0.095	0.9002
40	−0.042	0.441	0.946	0.096	0.8962
41	0.039	0.436	0.968	0.095	0.9009
43	0.165	0.456	0.930	0.099	0.8869
61	−0.413	0.413	1.016	0.090	0.9179
55	0.055	0.446	0.945	0.097	0.8939
WB	−0.008	0.259	1.008	0.056	0.9646

$Y = a + b * X$

Table 69. Intercomparison of WAU electrical cup anemometers with Woelfle anemographs (WA) for BULKED data (daytime plus nighttime) winds at Embori (a) for the period 25-32 of 1995, N= 151 hrs and (b) for the period 32-34 of 1995, N = 57 hrs.

(a) BULKED: the period 25-32 of 1995, N= 151 hrs

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
55	−0.042	0.444	0.956	0.025	0.9534
61	0.071	0.410	0.884	0.023	0.9536
43	0.048	0.442	0.947	0.025	0.9530
13	0.071	0.445	0.948	0.025	0.9526
14	−0.001	0.449	0.953	0.025	0.9523
15	−0.057	0.441	0.935	0.025	0.9521
38	0.115	0.432	0.914	0.024	0.9519
60	−0.006	0.454	0.954	0.025	0.9513
40	−0.060	0.450	0.943	0.025	0.9510
41	0.027	0.460	0.960	0.026	0.9506
12	−0.066	0.443	0.924	0.025	0.9505
11	−0.029	0.450	0.934	0.025	0.9501
10	−0.059	0.453	0.937	0.026	0.9498
WB	0.338	0.451	0.916	0.025	0.9481

$Y = a + b * X$

(b) BULKED: for the period 32-34 of 1995, N= 57 hrs

cup	const a	std err Y_{est}	coeff b	std err b	corr coef. r
10	−0.315	0.415	1.016	0.037	0.9660
11	−0.252	0.423	0.994	0.037	0.9634
12	−0.167	0.422	1.000	0.037	0.9638
13	−0.140	0.433	1.022	0.038	0.9635
14	−0.197	0.438	1.024	0.039	0.9629
15	−0.237	0.433	1.004	0.038	0.9622
38	−0.084	0.426	0.987	0.038	0.9623
60	−0.197	0.437	1.025	0.039	0.9630
40	−0.256	0.436	1.014	0.038	0.9626
41	−0.161	0.437	1.032	0.039	0.9637
43	−0.117	0.450	1.015	0.040	0.9603
61	−0.106	0.414	0.909	0.037	0.9529
55	−0.172	0.437	1.018	0.039	0.9626
WB	0.033	0.325	0.994	0.029	0.9778

$Y = a + b * X$

Table 70. Ratios of mean wind speeds recorded with WAU electrical cup anemometers to substandard (cup 40), to extreme cup (cup 10) and to middle cup (cup 38), during calibration periods (Cb1, Cb2 & Cb3a & Cb3b) at Embori. Cb1 is calibration done from 28/2-6/3/1993, Cb2 is calibration done from 4-28/5/1994, Cb3 is calibration done from 25/1-3/2/1995 (a & b are first and second arrangement for Cb3 see Text), D is daytime (07h00-20h00) and N is nighttime (21h00-06h00).

ratios	cups/cup40		cups/cup10		cups/cup38				
Calib. periods	Cb1		Cb2		Cb3a		Cb3b		
Day/night-time	D	N	D	N	D	N	D	N	averg
ratios	1.02	1.02	0.99	1.03	1.01	0.99	1.00	0.99	1.01
std dev	0.00	0.01	0.02	0.02	0.00	0.01	0.01	0.01	0.06

Table 71. Ratios of mean wind speeds recorded with Woelfle anemographs (WA & WB) to those recorded with WAU electrical cup anemometers during calibrations at Embori. Cb1 is calibration done from 28/2 -6/3/1993, Cb2 is calibration done from 4-28/5/1994, Cb3 is calibration done from 25/1 -3/2/1995 (a & b) are first and second arrangement see Text), D is daytime (07h00-20h00) and N is nighttime (21h00-06h00).

ratios	Cb1		Cb2		Cb3a		Cb3b		averg
Day/night-time	D	N	D	N	D	N	D	N	
WA/cups	1.19	1.21	1.08	1.26	1.01	1.06	1.03	1.07	1.11
std dev	0.06	0.08	0.14	0.17	0.02	0.03	0.01	0.02	0.06
WB/cups	1.18	1.21	1.03	1.16	1.02	1.06	1.04	1.08	1.10
std dev	0.04	0.07	0.15	0.25	0.01	0.04	0.03	0.05	0.08
Average ratio	1.18	1.21	1.06	1.21	1.02	1.06	1.04	1.08	1.11
std dev	0.05	0.08	0.14	0.20	0.02	0.03	0.02	0.04	0.07

(anemographs). Kainkwa (1991) used a datalogger which read wind speed data after every 30 minutes in printed form to two decimal places. In our case the CR10 read 10 sec wind speed data and stored their 15 minute averages for future retrieval. The data were then later retrieved with the Lap-top computer and imported into the LOTUS work-sheet. Experience has shown that when using electrical cup anemometers to measure wind speeds one should pay particular attention to:

(i) the type of instruments to use with regard to manufacturers.

(ii) the shape of the cups (conical or hemispherical or otherwise).

(iii) the threshold and the dynamic zero of the anemometers.

(iv) the sampling period,

(v) the type of terrain.

In the actual field measurements we used Woelfle anemographs mainly as wind direction indicators and WAU anemometers to measure wind speed.

4.3.2 Strong winds at Matanya

4.3.2 (a) Experimental periods for wind measurements

Table A6 (Appendix) gives the experimental periods: 93P1. ..... 93P10 for 1993 and 94P1, ..., 94P10 for 1994 at Matanya. The calendar dates and days of the year (DOY) corresponding to these experimental periods are also given in Table A6. These periods cover the seasons of strong winds of June-September. The WAU cup anemometers were initially set to 1.00 m at the planting time. The anemometers were thereafter adjusted as the maize plant increased in height, to remain at 0.20 m above the tallest plant element in the vicinity. The heights to which WAU cup anemometers were adjusted and dates are given in Appendix Table A5. Fig. 8 gives the set up of the entire Matanya station during the periods of our experiments, including positions of cup anemometers in agroforestry (AF) and non-agroforestry (NAF). Fig. 10 and Appendix Table A7 give the layout of WAU electrical cup anemometers and a Woelfle cup anemograph (WB) in the AF plot at Matanya. The AF plot bordered fruit trees in the north. The remaining three sides were fenced with a hedge of a shrub known as *Coleus barbatus*, which we refer to as a live-fence. Cups in positions A1, A2, A3 and A4 (i.e. cup 10, 11, 12 and 13) were installed at 2H (where H is the height of the *Coleus barbatus* live-fence) from the western side (WH) of the live-fence (Fig. 8) and 3.5 m from nearest tree row (shown in Fig. 9 as D(TR3)). Cups in positions A5, A6, A7 and A8 (i.e. cups 14, 15, 38 and 39) were installed in the central part of AF plot between *Grevillea robusta* trees at 7H from either the western (WH) or the eastern (EH) sides of the live-fence. Each cup was installed at 2.5 m from the nearest *Grevillea robusta* tree. Cups A9, A10, A11 and A12 (cup 40, 41, 43 and 44, later 61) were installed at 2H from the eastern (EH) side of the live-fence and 3.5 m from nearest tree row (shown in Fig. 9 as B(TR1)). WAU cup anemometer 55 was installed in the open area at 60 m (or 30H) from the eastern hedge and 68.8 m (or 34.5H) from the nearest WAU anemometer in the AF (Fig. 8). The within cup anemometer row spacing was 3H and the between cup row spacing was 5H.

Fig. 10 shows five small gaps (GP1, ..., GP5) and one bigger gap (DGP) in the live-fence around *Grevillea robusta* trees. Table 72 give the relative sizes of the gaps in the live-fence. GP1 was in the western side of the live-fence (WH). GP2 was a small gap at the corner between SH and WH. These two gaps could play a role in airflow into the AF . According to Table 72, we think the gaps were too small to have had any major impact on general protection by this side of the live-fence.

Table 72. Relative sizes of gaps in the live-fence around Matanya AF. (WH, EH and SH refer to the western, eastern and southern sides of the live -fence. The northern side borders the fruit trees and has no role in the AF *Grevillea* side). H is the hedge height which is about 2.0 m.

	Gaps	width	area
WH	GP1	0.3H	0.3H X 1H
WH	GP2	0.2H	0.2H X 1H
EH	GP3	0.2H	0.2H X 1H
EH	GP4	0.4H	0.4H X 1H
EH	GP5	0.3H	0.3H X 1H
SH	DGP	2H	2H X 1H

GP1 measured 0.3H wide while GP2 had a width of 0.2H. Other three small gaps (GP3. .... GP5) were on the eastern side (EH) of the live-fence, which had lodged due to the strong outflow of air from the AF. which lowered a part of EH by 0.25H for a width of 1H on the lee. This side was leeward of the approaching wind and it was obvious that these gaps and the lodging only influenced the airflow out of the AF but not the inflow. The gap of main importance that caused major tunnelling effects into the AF was the deliberate gap (DGP). which we had left for access into the AF plot. The farmers in Matanya area also leave such gaps for access into their small-scale farms. When such gaps become problematic because of persistent strong winds the farmers seal them up and open new ones on the leeward sides. as long as these new ones do not lead to their neighbours farms. The DGP measured 2H wide. The area of DGP exposed to the southerly winds was therefore 2H X 1H. The smaller gaps became relatively wider in the dry season (late January to early March. which was not in the season of strong winds) when there was less foliage. because the leaves dried and fell off due to lack of water. The gaps partially filled up in rainy seasons (LR & SR) as the new foliage grew. thereby reducing porosity of the live-fence. The DGP was generally unaffected even in the dry seasons.

4.3.2 (b) Monthly wind directions

The results of relative per cent wind direction frequency roses at Matanya. taken at a height of 2.0 m. are given in Figs. 226-231 & 238-245 in the open (control) area and in Figs. 232-237 & 246-253 in the AF plot. The results include the period of strong destructive winds that blew from between south and south-east from June to September of 1993 and 1994. Sometimes strong winds blow from south-westerly directions. as in July of 1994 (see Fig. 239).

The results presented here were worked out from the strip charts of the two Woelfle cup anemographs (WA & WB). These two instruments were also used in the calibration exercises at Embori.

We learn from 1993 results (Figs. 226-231 & 232-237) that the winds which blew over Matanya from June to September were predominantly southerly, with rather small south-easterly components. The 1994 results for the NAF (i.e. with WA, Sr. Nr. 341836) show that the strong winds blew mainly from between south and south-west in June (Fig. 246). In July 1994 the strong winds blew from between south-west, south and south-east (Fig. 239) and mainly from south-east with frequencies of up to 100% in August and September (Fig. 240 & 241). It continued blowing from south-east in October and November, albeit with variable frequency as it reversed to become northerly and then north-easterly components from December through January (Figs. 244-245). The 1994 results for the WB (i.e. Sr. No. 31587) AF show that in Matanya AF the strong winds were blowing predominantly from the south between June and October (Figs. 246-250), with a small south-easterly component in July. The strong winds continued to blow from between south-west and south-east in October and November as it changed direction to become northerly and north-easterly from December through January (Fig. 251-253). The southerly, south-easterly and south-westerly winds which blow over Matanya area from June to September, as already discussed above, were very strong and therefore very destructive. They originate from the south-east monsoon winds which normally blow from the Indian ocea towards the Arabian desert (Griffiths, 1972, see appendix Fig. A5). A they pass over the Kenyan highlands they get channelled between Mt Kenya and Aberdare Mts. becoming very strong over eastern parts of

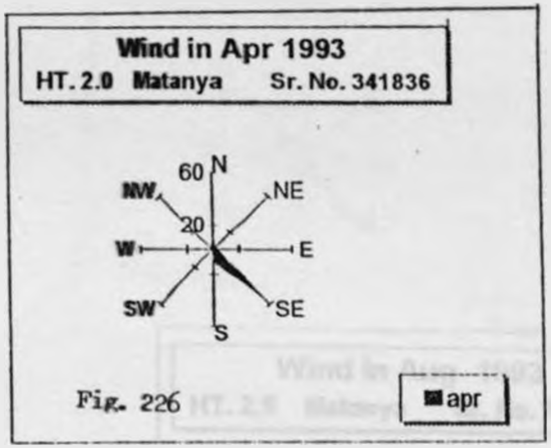


Fig. 226

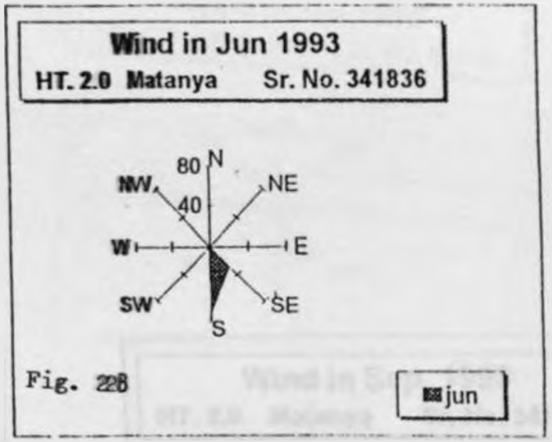


Fig. 228

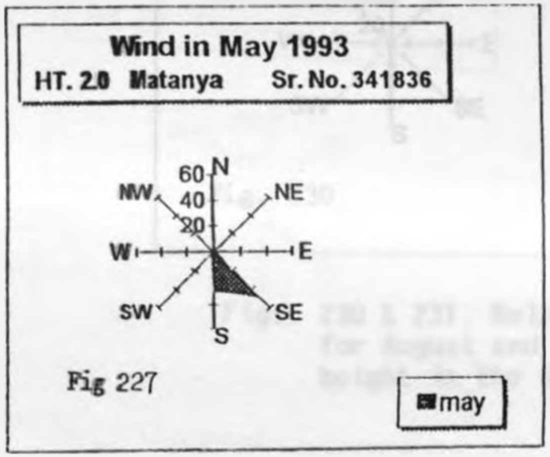


Fig 227

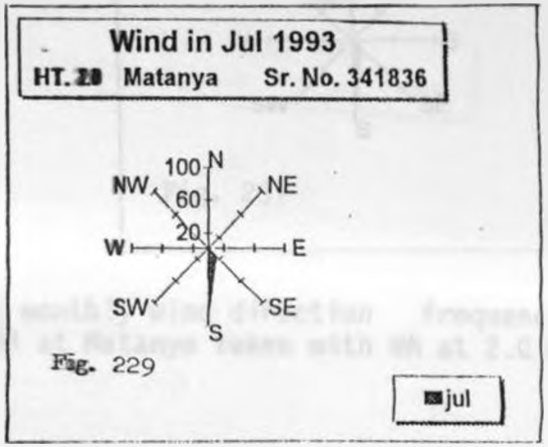


Fig. 229

Figs. 226-229. Relative per cent monthly wind direction frequencies for April till July 1993 at Matanya taken with WA at 2.0 m height in the open (NAF).

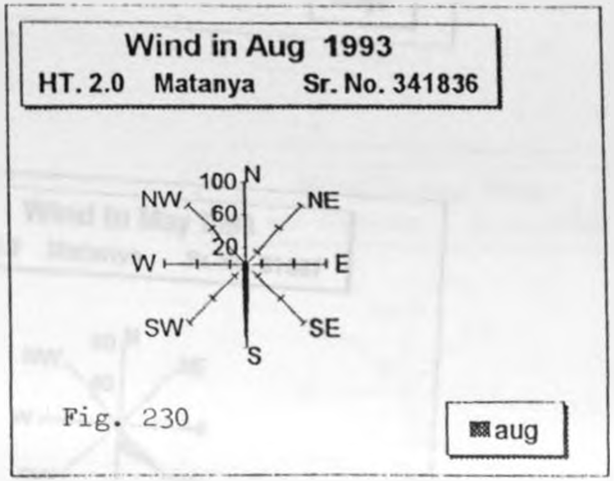


Fig. 230

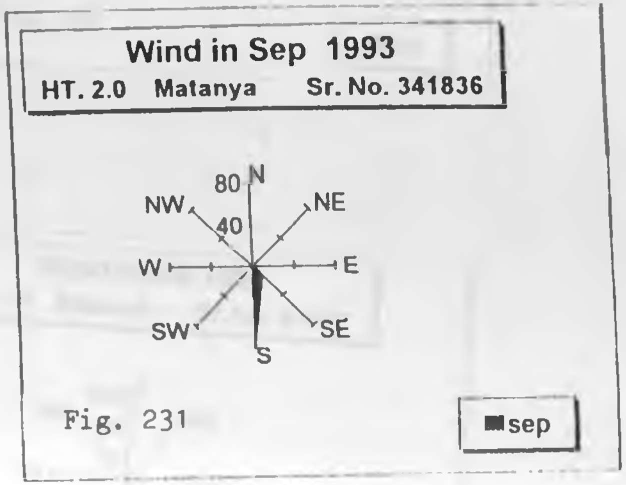


Fig. 231

Figs. 230 & 231. Relative per cent monthly wind direction frequencies for August and September 1993 at Matanya taken with WA at 2.0 m height in the open (NAF).

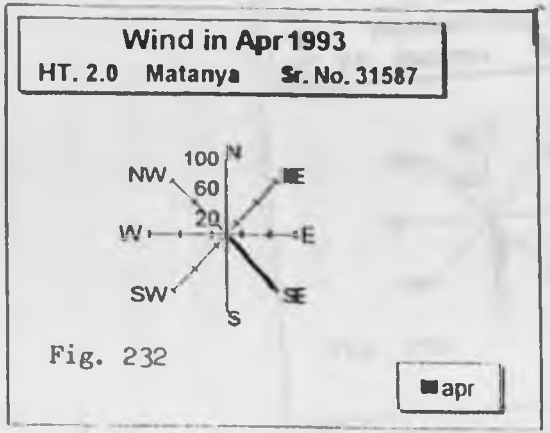


Fig. 232

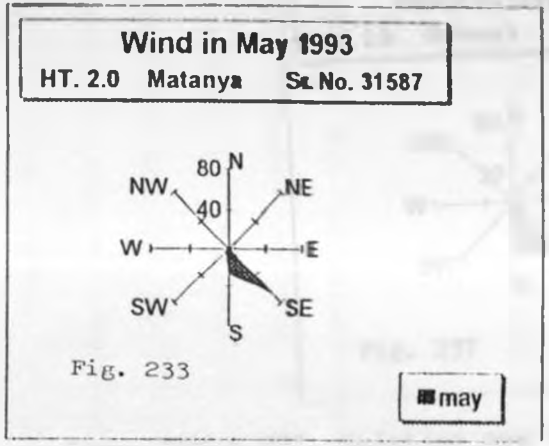


Fig. 233

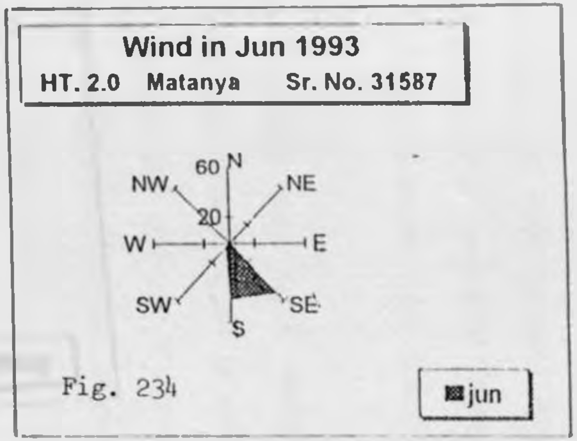


Fig. 234

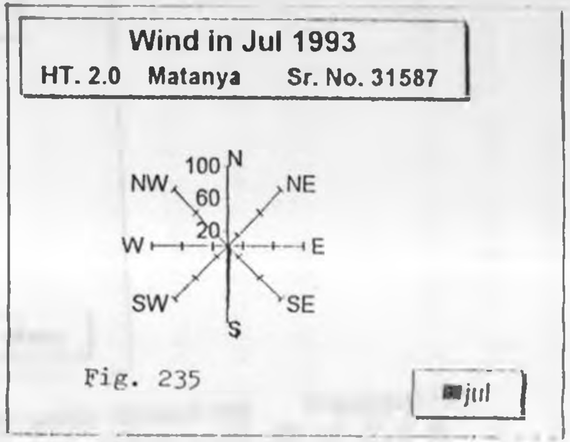


Fig. 235

Figs. 232-235. Relative per cent monthly wind direction frequencies for April till July 1993 at Matanya taken with WB at 2.0 m height AF.

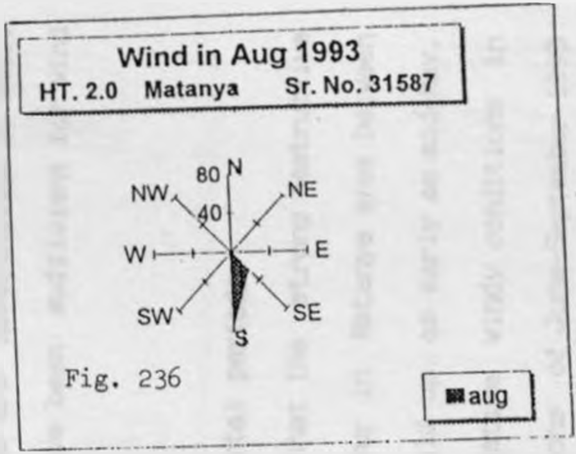


Fig. 236

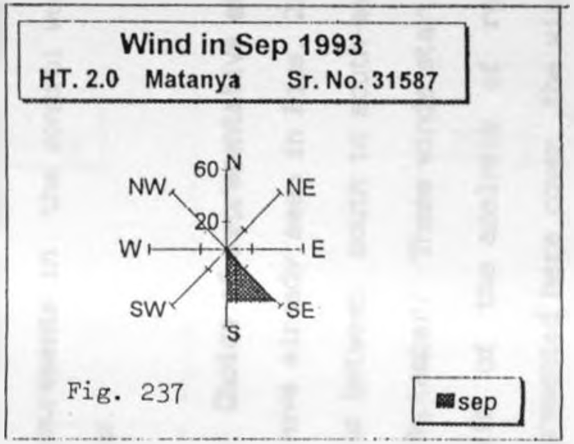


Fig. 237

Figs. 236 & 237. Relative per cent monthly wind direction frequencies for August and September 1993 at Matanya taken with WB at 2.0 m height AF.

Laikipia district around Matanya area. Compared to Figs. 226-229 there was a slight shift in westward in Figs. 232-237 and a slight shift eastward in Figs. 236 & 237. Compared to Figs. 238-241) there is in June/July a slight shift in eastward in Figs. 246-253 but in August/September the shift is clearly westward (from SE to S dominance). Compared to Figs. 242-245 there is a slight westward shift continued for October and November. In December no shift shows up and in January, if any, it is somewhat eastward. These shifts are nevertheless so small that measurements in the control would have been sufficient for wind directions.

4.3.2 (c) Choice of representative experimental periods

We have already seen in Figs. 226-253 that the strong destructive winds from between south to south-east occur in Matanya area between June and September. These winds start to build up as early as mid-May. The results of the analysis of representative windy conditions in Matanya presented here cover the windy seasons of June-September 1993 and 1994 (see appendix Table A6). Figs. 254-256 & 257-259 and Tables 73 & 74 show mean daily wind speeds for experimental periods at 09h00-08h00 (local time) the following day to coincide with the daily Piche readings.

As we have seen in section 4.1 the LR93 and LR94 maize crops were planted on 15/4/93 and 14/4/94. The plants attained their maximum heights in the fourth and third weeks of June respectively for 1993 and 1994 crops (appendix Table A5). Due to poor rainfall distribution the plants could not grow taller than 2.4 and 2.2 m in LR93 and LR94 respectively. The strong winds from June to September dry the soil further and lodge the plants, tear and snap the rapidly drying leaves

Fig. 238

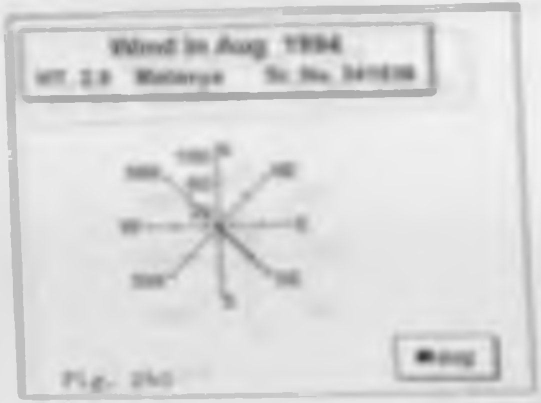


Fig. 240

Fig. 239

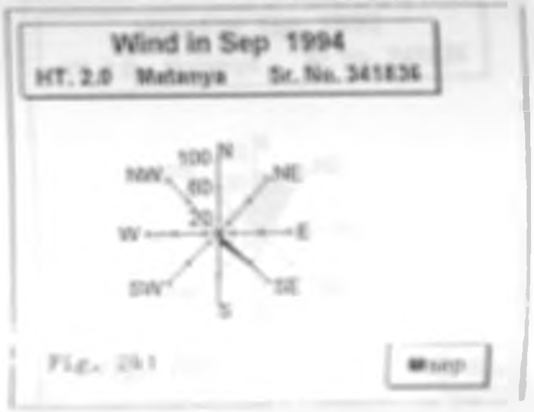


Fig. 241

Figs. 238-241. Relative per cent monthly wind direction frequencies for June 1994 till September 1994 at Matanya taken with WA at 2.0 m height AGL.

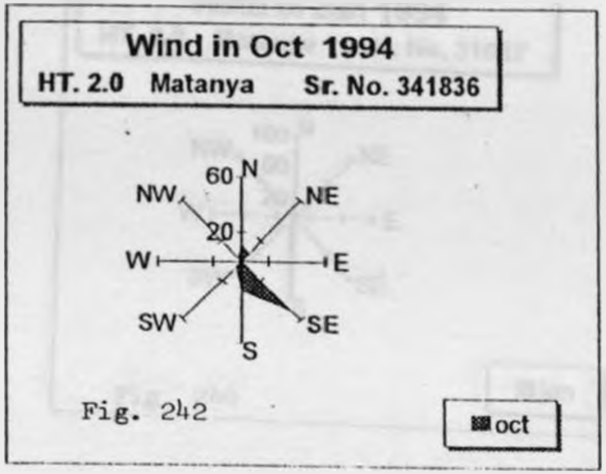


Fig. 242

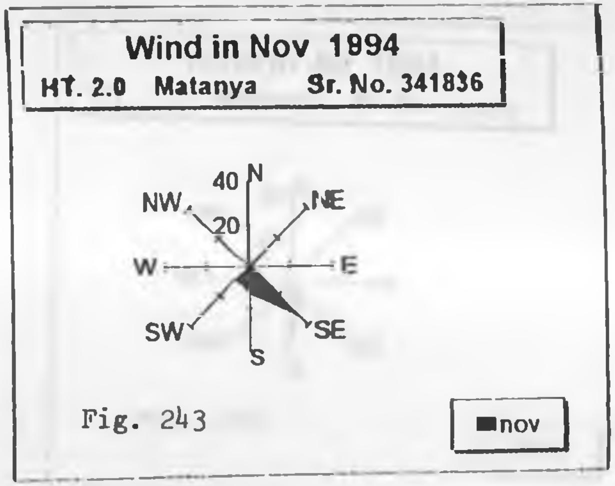


Fig. 243

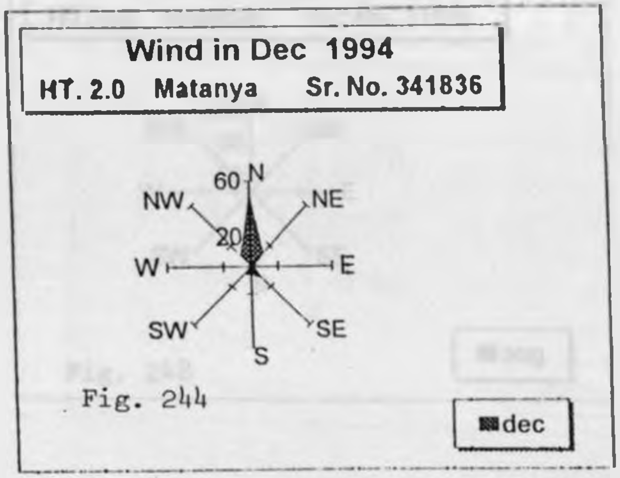


Fig. 244

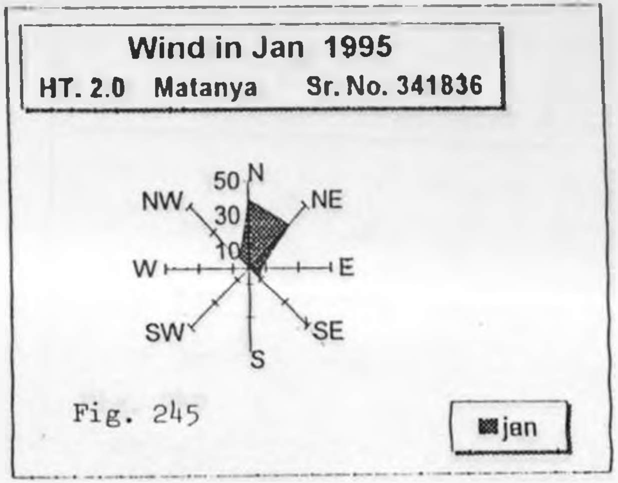


Fig. 245

Figs. 242-245. Relative per cent monthly wind direction frequencies for October 1994 till January 1995 at Matanya taken with WA at 2.0 m height NAF.

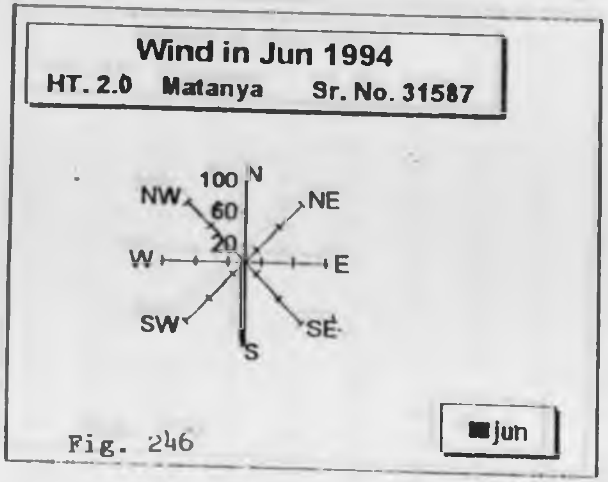


Fig. 246

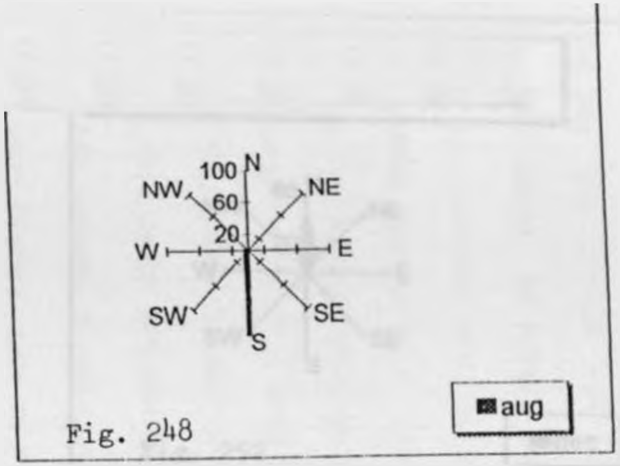


Fig. 248

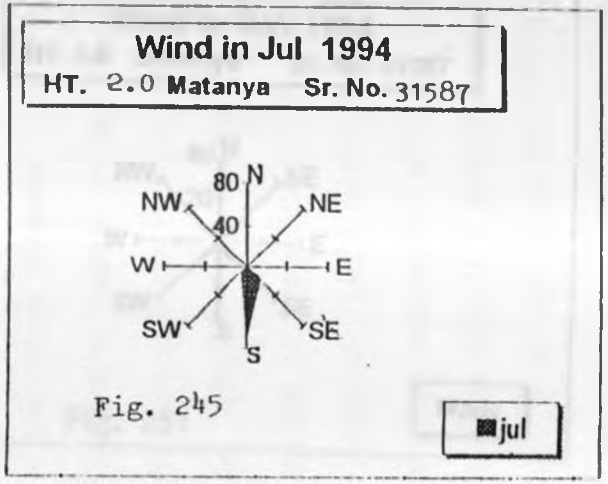


Fig. 245

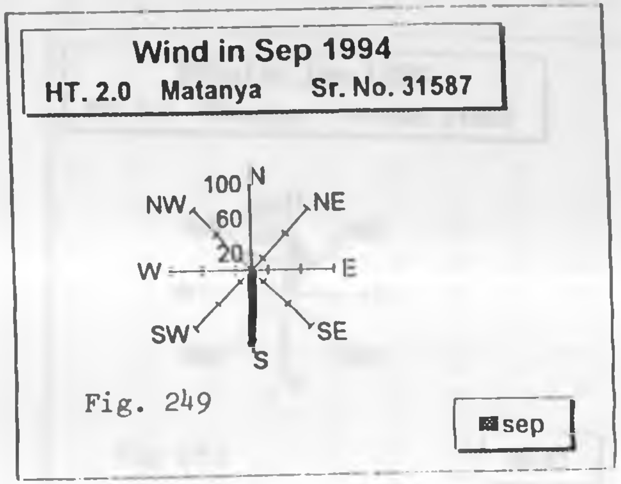


Fig. 249

Figs. 246-249. Relative per cent monthly wind direction frequencies for June 1994 till September 1994 at Matanya taken with WB at 2.0 m height AF.

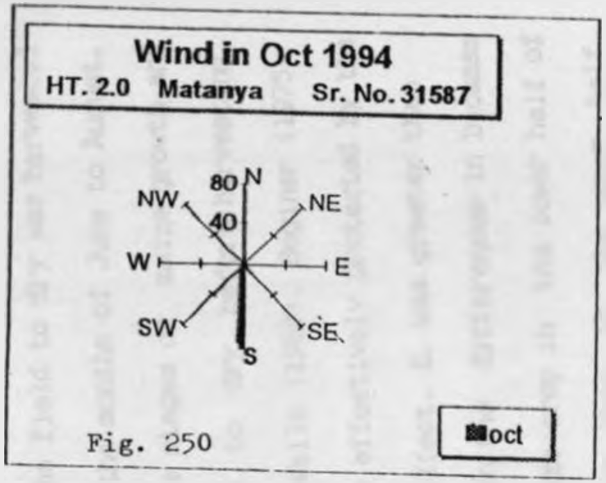

Wind in Oct 1994
HT. 2.0 Matanya Sr. No. 31587

Fig. 250

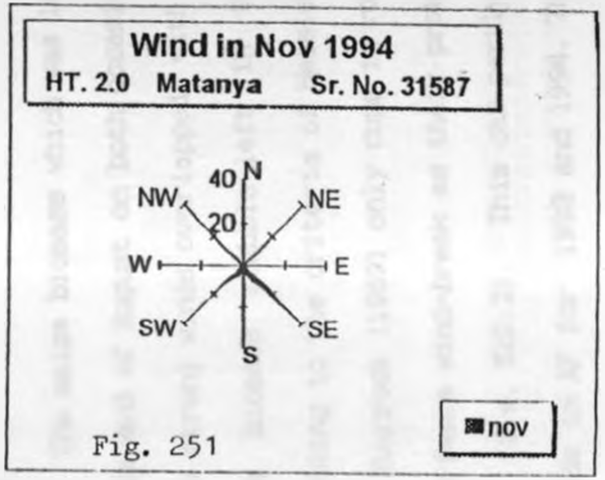

Wind in Nov 1994
HT. 2.0 Matanya Sr. No. 31587

Fig. 251

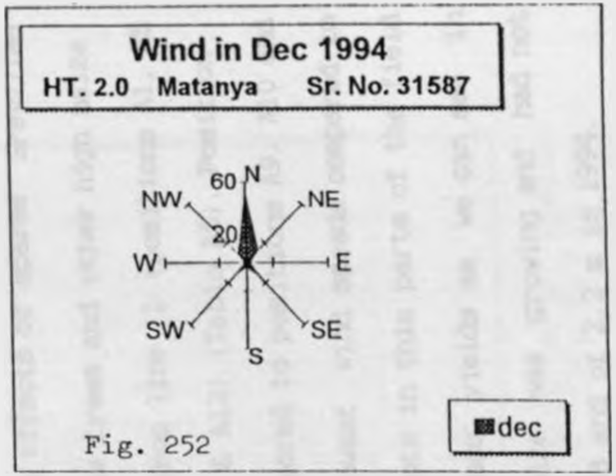

Wind in Dec 1994
HT. 2.0 Matanya Sr. No. 31587

Fig. 252

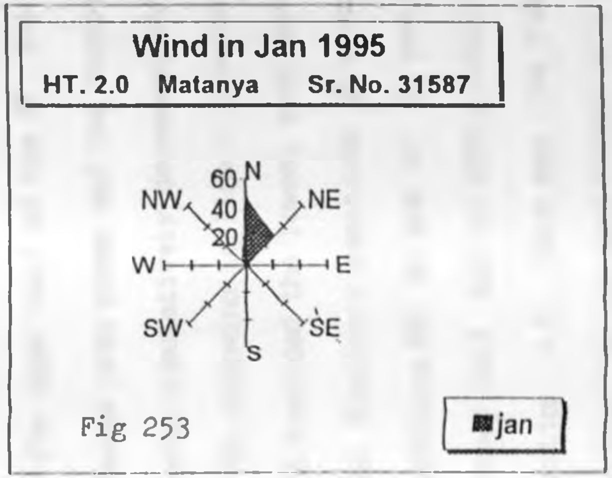

Wind in Jan 1995
HT. 2.0 Matanya Sr. No. 31587

Fig 253

Figs. 250-253. Relative per cent monthly wind direction frequencies for October 1994 till January 1995 at Matanya taken with WB at 2.0 m height AF.

and stems and remove and re-distribute mulch materials in mulched plots.

The maize biomass which was left in the field to dry was harvested at the end of August on both occasions. In the months of June to August, these strong winds overlapped with the late stages of maize growth and maize biomass stubble left in the field to dry before harvesting. According to the criteria of Heisler and Dewalle (1988), Seginer (1975) and Sturrock (1969) only cups in row 1 were effectively protected by the live-fence wind-break as their protective effect, E, was greater than 0.2 (i.e. E≥0.2). This can partly explain the differences in biomass yields in AF for 1993 and 1994. The LR maize crop in the lower half of AF were taller and yielded more biomass than in the upper half. Similarly in AFM1 plot (section 4.1, Figs. 74-77 and Figs. 90 & 92). Maize rows 17-29 (Fig. 9) in all the four plots AFM1, AFM2, AFL1 & AFL2) were in the lower half of AF. The maize biomass were higher than those in the upper half of the AF. The sheltering effects of sparse *Grevillea robusta* tree stems and the canopies of these trees and other high maize plants cumulatively decreased wind speeds from line 1 (positions A1, A5 & A9) downwind to line 4 (positions A4, A8 & A12) (Table A5). Position A12 recorded the lowest wind speeds as compared to positions A9, A10 and A12. Similarly positions A8 recorded the lowest wind speeds compared to positions A5, A6 and A7 in row 2. The plants in this parts of the field (lower half and in AFM1) had higher biomass yields as we can see in section 4.1. This was the time when maize was growing and had not reached the maximum height of 2.4 m in 1993 and of 2.2 m in 1994.

To determine the effects of strong winds on the maize crop we chose three representative experimental periods (93P4, 93P7 & 93P10) in

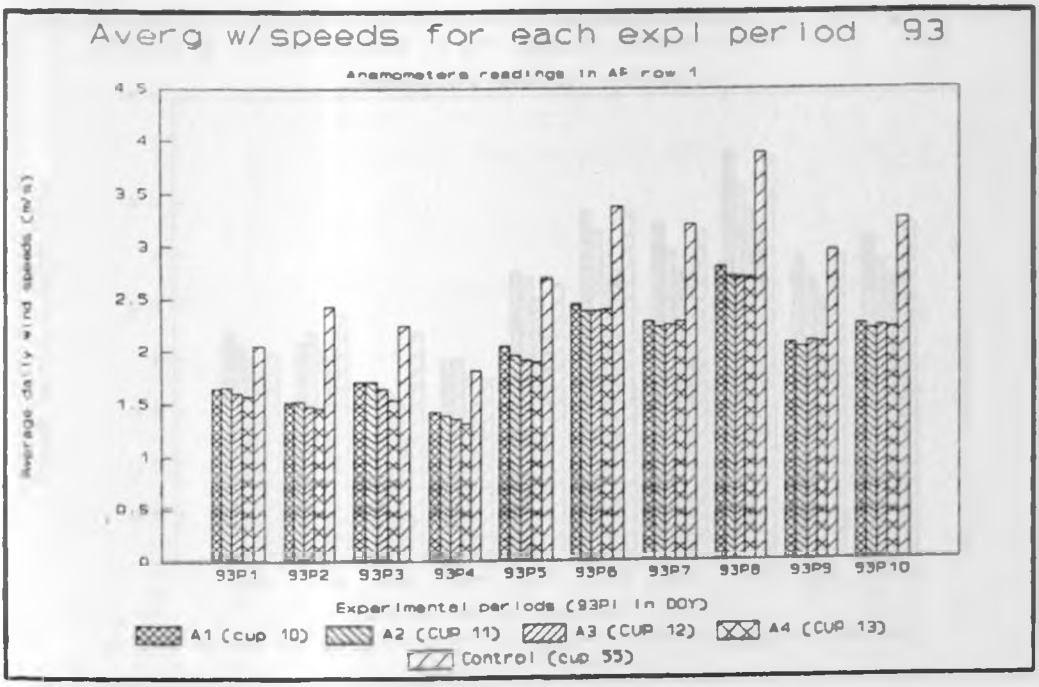


Fig. 254. Intercomparison of mean daily wind speeds recorded by cup anemometers (cups 10, 11, 12 & 13) in row 1 in AF and control during windy season at Matanya in 1993 (Fig. 102b).

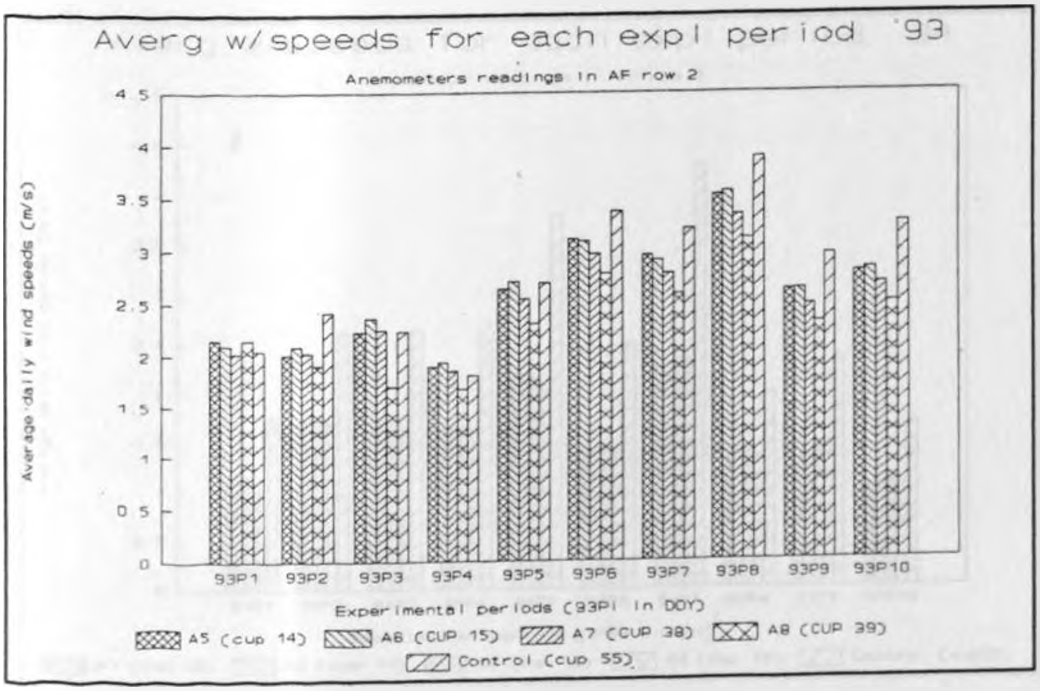


Fig. 255. Intercomparison of mean daily wind speeds recorded by cup anemometers (cups 14, 15, 38 & 39) in row 2 in AF and control during windy season at Matanya in 1993.

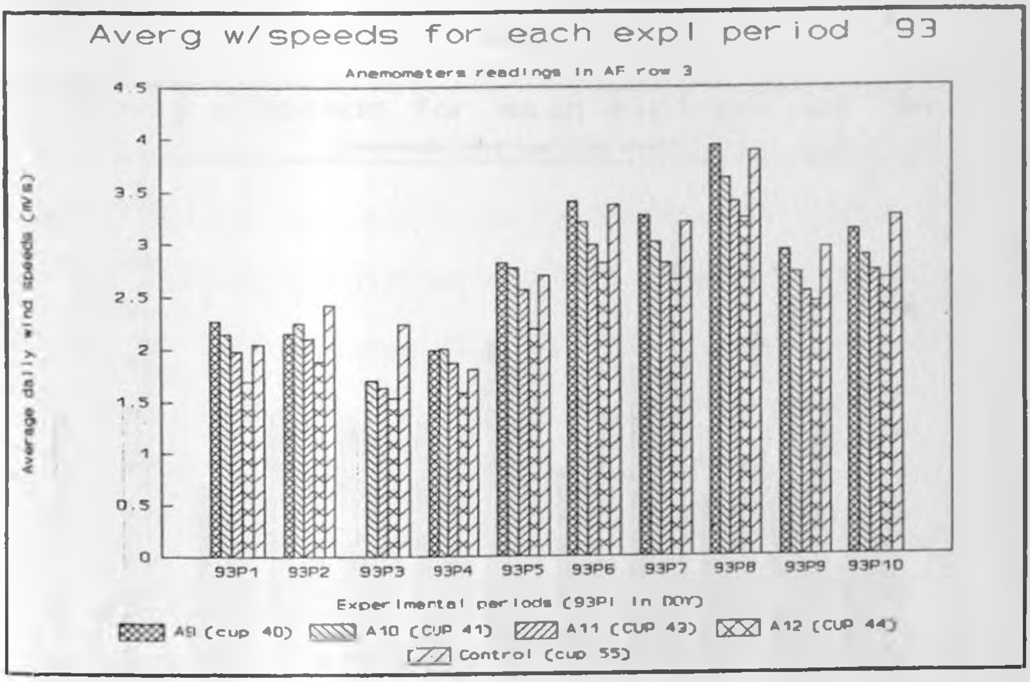


Fig. 256. Intercomparison of mean daily wind speeds recorded by anemometers (cups 40, 41, 43 & 44) in row 3 in AF and control during windy season at Matanya in 1993.

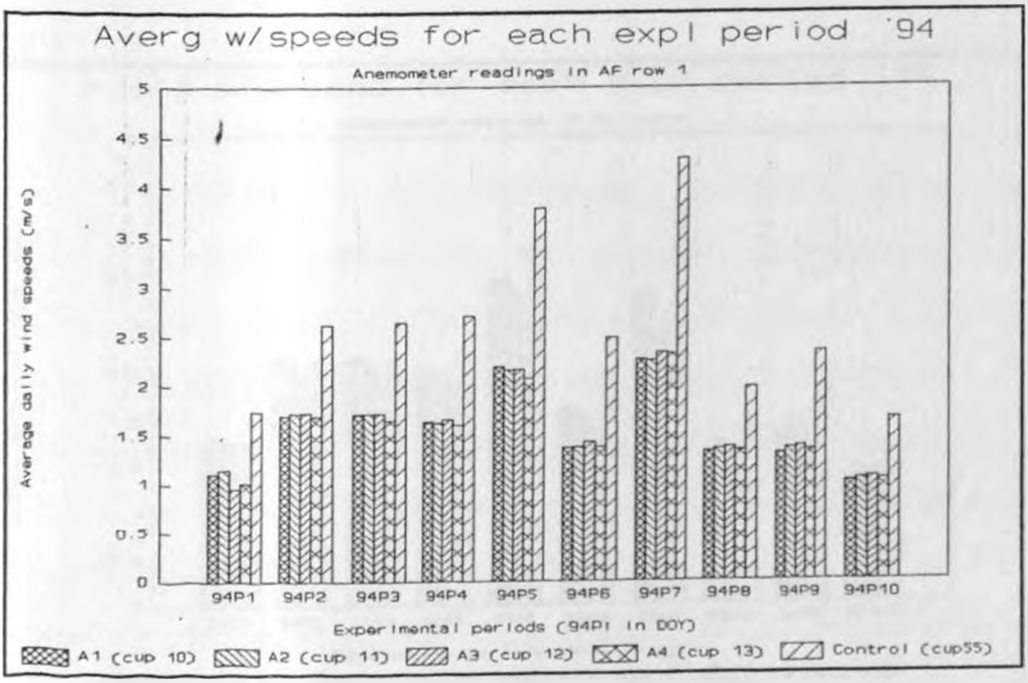


Fig. 257. Intercomparison of mean daily wind speeds recorded by cup anemometers (cups 10, 11, 12 & 13) in row 1 in AF and control during windy season at Matanya Matanya in 1994.

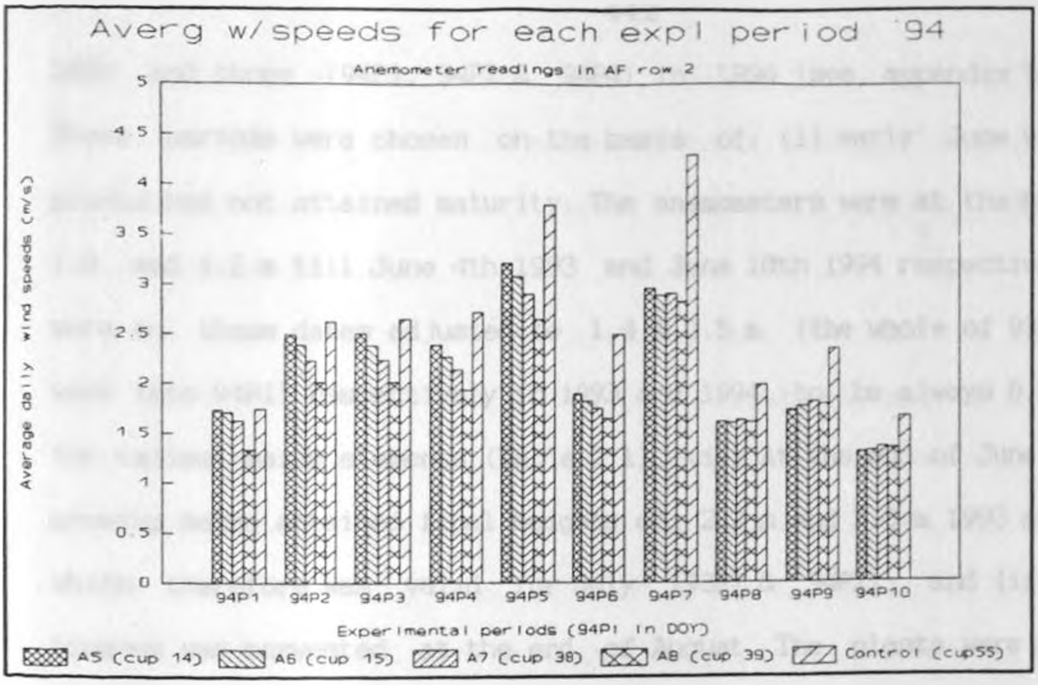


Fig. 258. Intercomparison of mean wind speeds recorded by cup anemometers (cups 14, 15, 38 & 60) in row 2 in AF and control during windy season at Matanya in 1994.

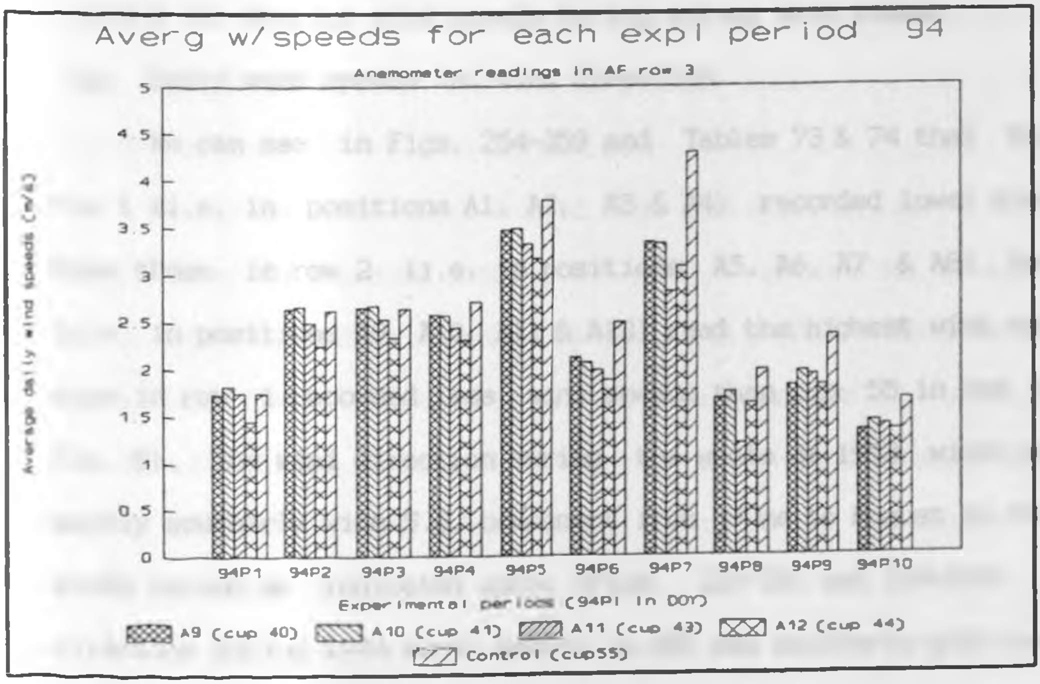


Fig. 259. Intercomparison of mean daily wind speeds recorded by cup anemometers (cups 40, 41, 43 & 61) in row 3 in AF and control during windy season at Matanya in 1994.

LR93 and three (94P1, 94P2 & 94P4) in LR94 (see appendix Table A6). These periods were chosen on the basis of: (i) early June when maize plants had not attained maturity. The anemometers were at the heights of 1.0 and 1.2 m till June 4th 1993 and June 10th 1994 respectively. They were on these dates adjusted to 1.4 & 1.5 m (the whole of 93P4 & one week into 94P1) respectively in 1993 and 1994, to be always 0.2 m above the tallest maize elements (Table 2.1). (ii) At the end of June the fast growing maize attained final heights of 2.2 m and 2.0 m 1993 and 1994, which therefore was valid for July (93P7 & 94P2): and (iii) maize biomass was harvested at the end of August. The plants were still at heights they attained at the end of June (93P10 & 94P4) (see also Figs. 254-259).

4.3.2 (d) Average wind speeds during strong wind season.

(i) Daily wind speeds and wind direction.

We can see in Figs. 254-259 and Tables 73 & 74 that the cups in row 1 (i.e. in positions A1, A2, A3 & A4) recorded lower wind speeds than those in row 2 (i.e. in positions A5, A6, A7 & A8). Row 3 cups (i.e. in positions A9, A10, A11 & A12) read the highest wind speeds. All cups in row 1 recorded less wind speeds than cup 55 in the open (see Fig. 8). The wind direction during the whole of 1993 windy season was mainly southerly with S.E. component from June to August in the strong winds period as indicated above (Figs. 228-230 and 234-236). The wind direction during 1994 windy season in NAF was southerly with south west in June (Figs. 238) and both southwest and southeast components in July (Figs. 239). From August to November the winds were generally south easterly which shifted to become north-easterly in November and mainly Northerly in December (Fig. 240-245). In the AF the wind direction in

1994 was mainly southerly from June to October. November was transition period as the wind direction seemed to be diffuse and later in December and January blew from mainly north with north easterly component in January (Figs. 246-253).

We learn from the results presented here that WAU cup anemometers were progressively protected from the southerly and south-easterly winds by the *Coleus barbatus* live-fence sides SH and WH (Fig. 10) and *Grevillea robusta* tree stems. Row 1 cups were most protected, with little difference among them, followed by row 2 position A8 becoming progressively somewhat more protected during periods of strong winds and then row 3 position A12 becoming somewhat better protected than the others during periods of strong winds. The intercomparison was done using cup 55 as the control. The cups on the leeward side of each row of *Grevillea robusta* trees were additionally and progressively protected by tree stems and canopies, but that influence appears to have only little difference among the places monitored.

We can see from Figs. 8 & 10 that positions A1, A5 & A9 in line 1 were located in unpruned local plot, AFL2. Positions A2, A6 and A10 in line 2 were located in unpruned mulched plot, AFM2. Positions A3, A7 & A11 in line 3 were located in pruned Local plot, AFL1, while positions A4, A8 and A12 in line 4 were located in pruned mulched plot, AFM1. During this period wind speeds in the open did not run higher than 4 m/s in 1993 and 4.5 in 1994.

The microclimate on the leeward side of the windbreak shelter differed significantly (maximum of 1.1 m/s for a wind speed near 4 m/s for 1993 and of 2 m/s a wind speed near 4.5 m/s in 1994) from that of unsheltered areas. At the larger DGP gap, largest changes occurred in

Table 73 Average wind speeds and standard deviations at Matanya for experimental periods of 1993. (#-cup 40 kept in field office to act as substandard during calibration)

		"Positions of WAU cup anemometers in the AF plot													
		row 1				row 2				row 3					control
period	DOY	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	avg	55
93P1	119-126	1.63	1.65	1.59	1.57	2.16	2.11	2.03	2.15	2.27	2.15	1.98	1.69	1.70	2.05
		0.37	0.38	0.39	0.39	0.60	0.56	0.54	0.64	0.68	0.65	0.61	0.83	0.47	0.56
93P2	133-147	1.52	1.52	1.47	1.46	2.01	2.09	2.03	1.91	2.15	2.25	2.10	1.88	1.60	2.42
		0.40	0.41	0.41	0.40	0.57	0.62	0.60	0.54	0.63	0.68	0.64	0.58	0.46	0.74
93P3	148-153	1.70	1.70	1.63	1.54	2.24	2.37	2.25	1.70	#	1.70	1.63	1.54	1.43	2.24
		0.75	0.79	0.71	0.67	0.85	0.92	0.90	0.75	#	0.79	0.71	0.67	0.61	0.85
93P4	154-165	1.41	1.38	1.35	1.31	1.89	1.94	1.85	1.67	1.99	2.00	1.86	1.58	1.44	1.81
		0.60	0.59	0.53	0.50	0.70	0.74	0.71	0.63	0.73	0.75	0.70	0.60	0.55	0.79
93P5	165-175	2.04	1.96	1.90	1.88	2.64	2.71	2.54	2.31	2.82	2.77	2.56	2.19	2.02	2.69
		0.54	0.52	0.48	0.46	0.60	0.64	0.61	0.55	0.65	0.67	0.61	0.53	0.49	0.81
93P6	175-182	2.44	2.37	2.37	2.38	3.11	3.09	2.96	2.78	3.41	3.20	2.99	2.81	2.42	3.37
		0.49	0.47	0.44	0.44	0.62	0.63	0.61	0.57	0.68	0.64	0.58	0.62	0.48	0.96
93P7	182-209	2.27	2.22	2.24	2.27	2.95	2.91	2.78	2.59	3.26	3.01	2.81	2.65	2.28	3.20
		0.22	0.21	0.20	0.20	0.31	0.30	0.28	0.25	0.35	0.32	0.28	0.28	0.23	0.33
93P8	209-216	2.79	2.71	2.70	2.69	3.53	3.56	3.34	3.11	3.93	3.63	3.40	3.24	2.76	3.88
		0.32	0.30	0.27	0.27	0.42	0.42	0.39	0.36	0.46	0.41	0.40	0.38	0.31	0.46
93P9	216-225	2.06	2.02	2.08	2.07	2.62	2.62	2.48	2.30	2.93	2.72	2.54	2.44	2.06	2.95
		0.38	0.37	0.36	0.36	0.51	0.52	0.48	0.44	0.58	0.53	0.49	0.49	0.39	0.63
93P10	229-236	2.24	2.19	2.22	2.20	2.78	2.82	2.68	2.50	3.12	2.87	2.72	2.65	2.21	3.25
		0.67	0.64	0.61	0.58	0.74	0.77	0.72	0.68	0.85	0.81	0.75	0.74	0.61	0.90
	avg	2.01	1.97	1.95	1.94	2.59	2.62	2.49	2.30	2.88	2.63	2.46	2.35	2.01	2.79
	std	0.47	0.47	0.44	0.43	0.59	0.61	0.58	0.54	0.62	0.63	0.58	0.57	0.47	0.70

Table 74. Average wind speeds and standard deviations at Matanya for experimental periods of 1994.

		[a]Positions of WAU cup anemometers in the AF plot													
		row 1				row 2				row 3					control
period	DOY	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	avg	55
94P1	155-174	1.11	1.16	0.96	1.02	1.73	1.71	1.63	1.33	1.73	1.82	1.74	1.45	1.24	1.75
	std	0.58	0.59	0.51	0.49	0.83	0.83	0.80	0.26	0.80	0.89	0.88	0.74	0.59	0.88
94P2	185-196	1.70	1.73	1.73	1.70	2.50	2.39	2.23	2.01	2.65	2.67	2.50	2.25	1.86	2.62
	std	0.69	0.66	0.62	0.59	0.90	0.88	0.80	0.76	0.91	0.95	0.90	0.84	0.68	0.93
94P3	196-215	1.72	1.72	1.73	1.66	2.51	2.39	2.24	2.01	2.66	2.67	2.53	2.34	1.87	2.64
	std	0.67	0.64	0.61	0.57	0.89	0.87	0.82	0.75	0.92	0.95	0.93	0.88	0.68	0.96
94P4	216-235	1.65	1.63	1.66	1.60	2.39	2.27	2.13	1.93	2.58	2.57	2.43	2.31	1.80	2.71
	std	0.60	0.57	0.54	0.51	0.79	0.77	0.72	0.66	0.82	0.84	0.82	0.78	0.60	0.94
94P5	235-243	2.20	2.16	2.17	2.08	3.21	3.07	2.90	2.64	3.47	3.48	3.32	3.17	2.42	3.79
	std	0.63	0.60	0.57	0.54	0.74	0.73	0.69	0.68	0.78	0.80	0.79	0.77	0.59	0.94
94P6	256-258	1.37	1.37	1.42	1.37	1.89	1.82	1.75	1.64	2.12	2.07	1.99	1.88	1.48	2.49
	std	0.65	0.63	0.62	0.60	0.82	0.81	0.77	0.72	0.90	0.89	0.90	0.83	0.65	1.15
94P7	264-271	2.26	2.25	2.33	2.32	2.95	2.88	2.90	2.82	3.34	3.32	2.82	3.08	2.38	4.29
	std	0.75	0.74	0.75	0.73	1.00	1.00	0.97	0.94	1.13	1.14	1.55	1.05	0.84	1.45
94P8	271-284	1.33	1.35	1.37	1.33	1.61	1.60	1.63	1.61	1.68	1.74	1.19	1.62	1.29	1.98
	std	0.73	0.74	0.76	0.74	0.87	0.90	0.91	0.89	0.93	0.96	1.09	0.93	0.75	1.20
94P9	284-291	1.30	1.36	1.37	1.34	1.72	1.77	1.81	1.78	1.81	1.96	1.92	1.81	1.43	2.34
	std	0.73	0.75	0.76	0.74	0.93	1.00	0.99	0.99	1.01	1.13	1.14	1.08	0.80	1.46
94P10	292-311	1.02	1.04	1.06	1.03	1.30	1.31	1.35	1.34	1.32	1.43	1.38	1.33	1.07	1.66
	std	0.55	0.57	0.58	0.55	0.69	0.75	0.74	0.74	0.75	0.84	0.86	0.83	0.60	1.12
	avg	1.57	1.58	1.58	1.55	2.18	2.12	2.05	1.81	2.59	2.37	2.18	2.12	1.69	2.63
	std	0.66	0.65	0.63	0.61	0.85	0.85	0.82	0.74	1.00	0.94	0.99	0.87	0.69	1.10

wind structure and furthest away from WH turbulence which extended some distance on the lee of the southern (SH) and the western (WH) side of the *Coleus barbatus* live-fence. The cups which were directly opposite DGP (A9; A10; A11 positions in that order as well as A5; A6; A7 positions in that order and particularly earlier in the measuring periods) read occasionally even higher wind speeds than the control (cup 55 in the open). A12 was again most protected. The fact that A5, A6 and A7 were indeed protected shows that also WH protection must be involved. The high speeds resulted from the tunnelling and turbulent kinetic energy that was created at the DGP. The relatively calm areas with wind speeds below the open must have benefitted somewhat the plant water relations (e.g. Baldy, 1963; Radke and Hagstrom, 1976). As we have already pointed out in the introduction, rainfall was a major limiting factor in Matanya area. The protective role provided by the live-fence must have increased water use efficiency (WUE) somewhat. Higher wind speeds at DGP resulted in induced turbulence, negatively affecting maize plant nearest the gap where maize plants were more bent than away from the DGP.

(ii) Spatial variations of wind speeds within and between rows.

In this section we have chosen the month of July for the period in Table A6 as the central month of the season with strong winds to present the results of spatial variations of average daily wind speeds within and between rows in AF in 1993 and 1994. The results for the other months of the strong winds season were similar to the July ones.

Figs. 260 & 261 and 258 & 263 show variations of wind speeds within and between rows 1, 2 & 3 in July 1993 and 1994. At this stage we take a difference of 0.5 m/s (which is twice more than the error limit of the instrument). We observe in Fig. 260 unimportant differences within the rows and between row 2 and row 3. In both Figs. 260 & 261 (in 1993) we see that row 1 was different from rows 2 and 3 but significantly different only in lines A1. A5. A9 and A2. A6. A10. and marginally in line A3. A7. A11. The middle row (row 2) was taken as an average parallel row measured at the distances of 6H. 9H. 12H and 15H from the southern hedge (SH). We again observe in 1994 (Figs. 262 & 263) unimportant differences within the rows and between rows 2 and 3. Row 1 was different from rows 2 and 3 but significantly different only in lines A1, A5. A9 and A2. A6. A10. and marginally in other lines. The transect lines 1, 2, 3 & 4 shown in Figs. 261 and 263 confirm the above observation.

(iii) Mean hourly wind speeds

Figs. 264-267 & 268-271 present results of hourly wind speeds for the same periods of July 1993 (93P7) and 1994 (94P2) respectively. For comparison purposes the results of the wind speeds in the control were also plotted in each graph along side the AF ones. The wind speeds were recorded with cup anemometers in row 1 (Figs. 264 & 268), row 2 (Figs. 265 & 269) and row 3 (Figs. 266 & 270). We can see from Figs. 264-271 that the winds attained their maximum values at 17h00 and their minima at 22h00 local time, in both years.

As in our previous explanations the wind speeds recorded in the open were also diurnally always the highest in comparison to the wind speeds recorded by positions A1. A2. A3 and A4 in row 1 (Figs. 264 & 268). Positions A5, A6, A7 and A8 in row 2 recorded higher wind speeds than those recorded in row 1, although they were still lower than those

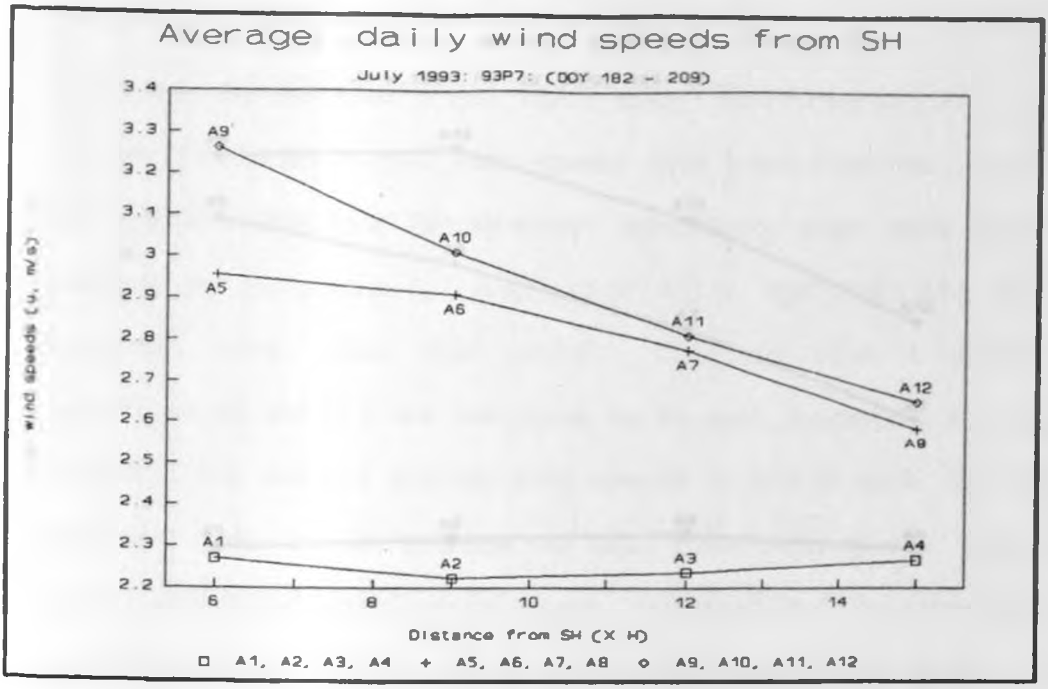


Fig. 260. Intercomparison of mean daily wind speeds in row 1, 2 & 3 at 2.4 m height in AF as function of the distance from SH for July 1993 (DOY 182-209) during windy season at Matanya.

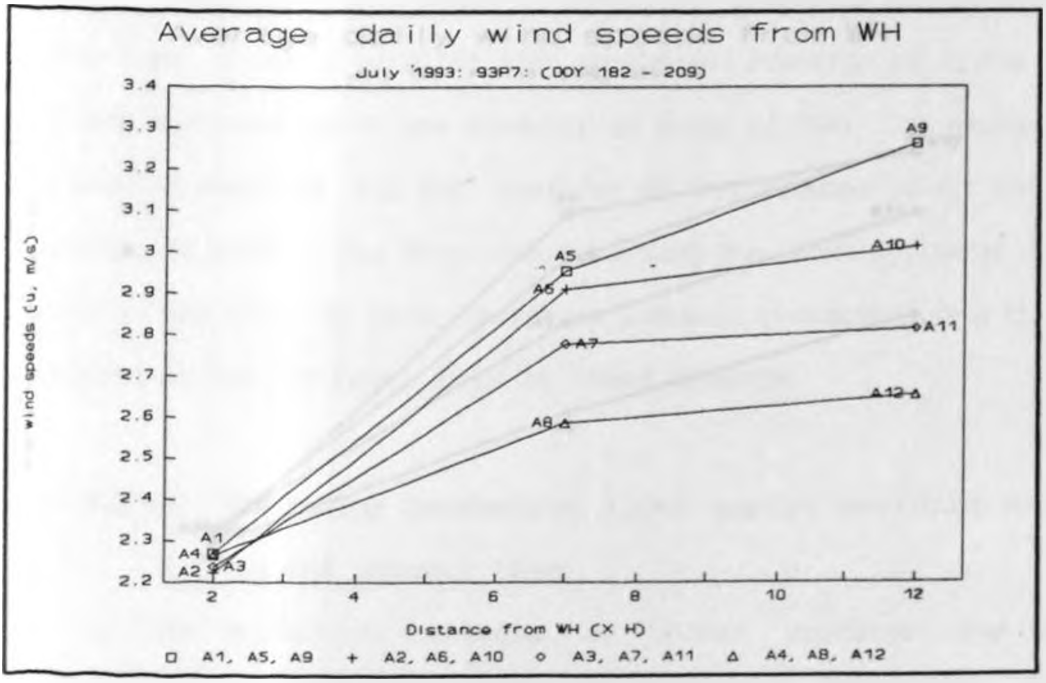


Fig. 261. Intercomparison of mean daily wind speeds in lines 1, 2, 3 & 4 at 2.4 m height in AF as function of the distance from SH for July 1993 (DOY 182-209) during windy season at Matanya.

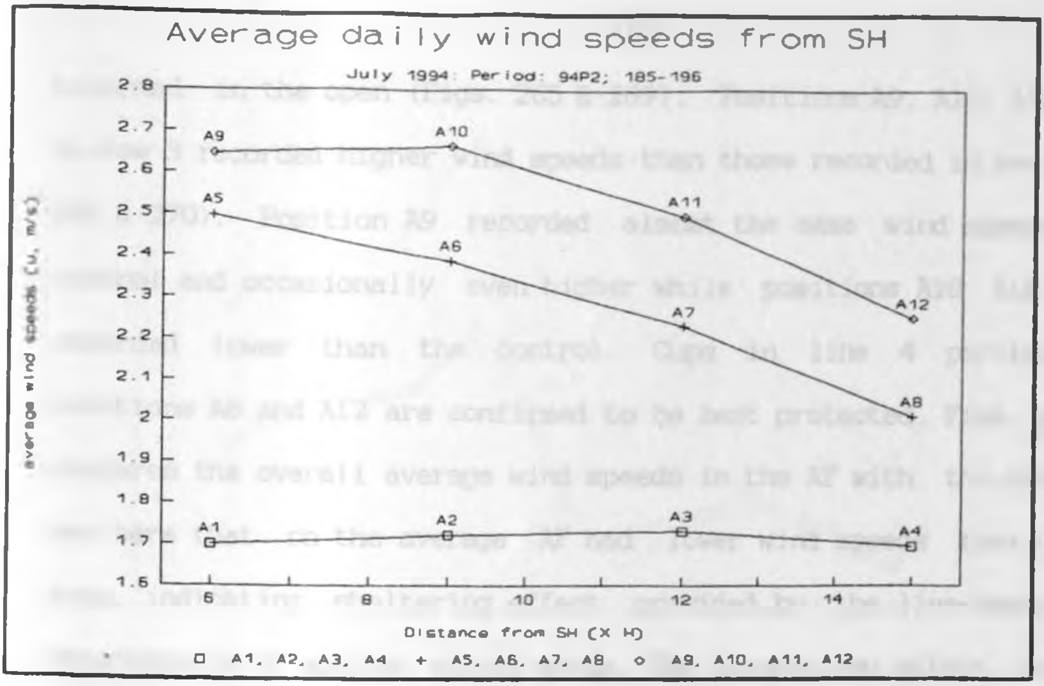


Fig. 262. Intercomparison of mean daily wind speeds in rows 1, 2 & 3 at 2.2 height in AF as a function of the distance from SH for July 1994 (DOY 185-196) during windy season at Matanya.

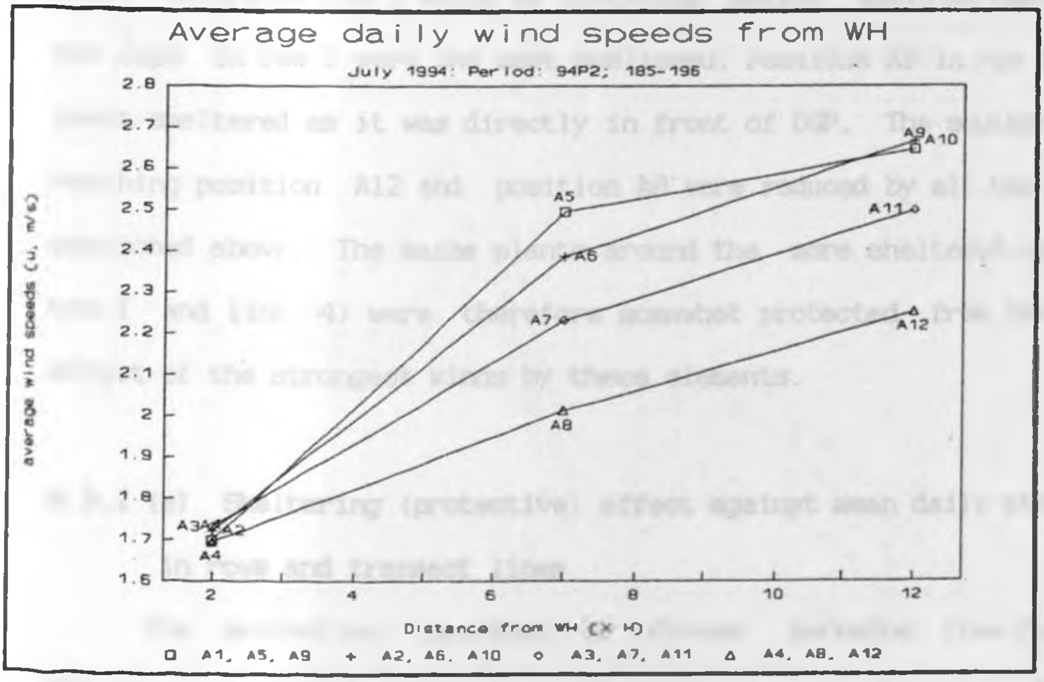


Fig. 263. Intercomparison of mean daily wind speeds in lines 1, 2, 3 & 4 at 2.2 m height in AF as function of the distance from SH for July 1994 (DOY 185-196) during windy season at Matanya.

recorded in the open (Figs. 265 & 269). Positions A9, A10, A11 and A12 in row 3 recorded higher wind speeds than those recorded in row 2 (Figs. 266 & 270). Position A9 recorded almost the same wind speeds as the control and occasionally even higher while positions A10, A11 and A12 recorded lower than the control. Cups in line 4 particularly in positions A8 and A12 are confirmed to be best protected. Figs. 267 & 271 compares the overall average wind speeds in the AF with the control. We see here that on the average AF had lower wind speeds than the open area, indicating sheltering effect provided by the live-fence to the intercrop in AF against strong winds. The channelling effect occasioned by the wide deliberate gap (DGP) (see Fig. 10) was the main cause of the high windspeeds which affected rows 2 and 3 in the AF as observed above, but the reduction of shelter of WH must have played a role as well, otherwise row 2 would be protected better. Again we observe that the cups in row 1 were the most sheltered. Position A9 in row 3 was the least sheltered as it was directly in front of DGP. The southerly winds reaching position A12 and position A8 were reduced by all the elements mentioned above. The maize plants around the more sheltered cups (i.e. row 1 and line 4) were therefore somewhat protected from the direct effect of the strongest winds by these elements.

4.3.2 (e) Sheltering (protective) effect against mean daily wind speeds in rows and transect lines

The protection provided by *Coleus barbatus* live-fence and *Grevillea robusta* trees against the strong seasonal southerly winds, with south-easterly and south-westerly components, was the main reason for wind measurements at Matanya and forms the core results in this

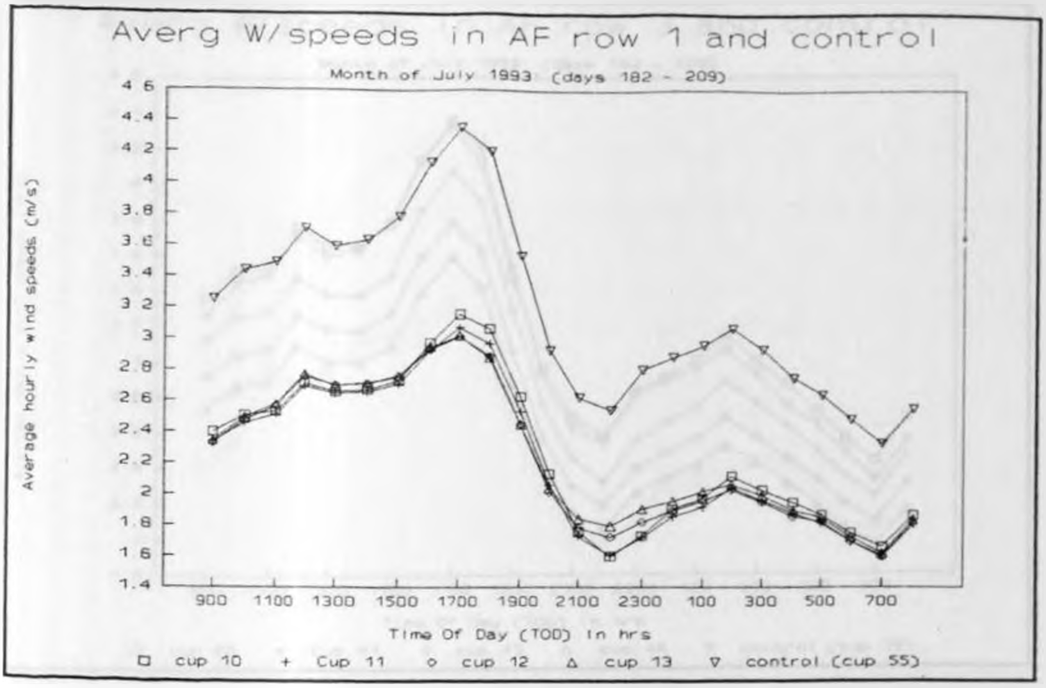


Fig. 264. Intercomparison of hourly wind speeds recorded by cup anemometers (cups 10, 11, 12 & 13) in row 1 and control at 2.4 m height in AF for July 1993 (DOY 182-209) during windy season at Matanya.

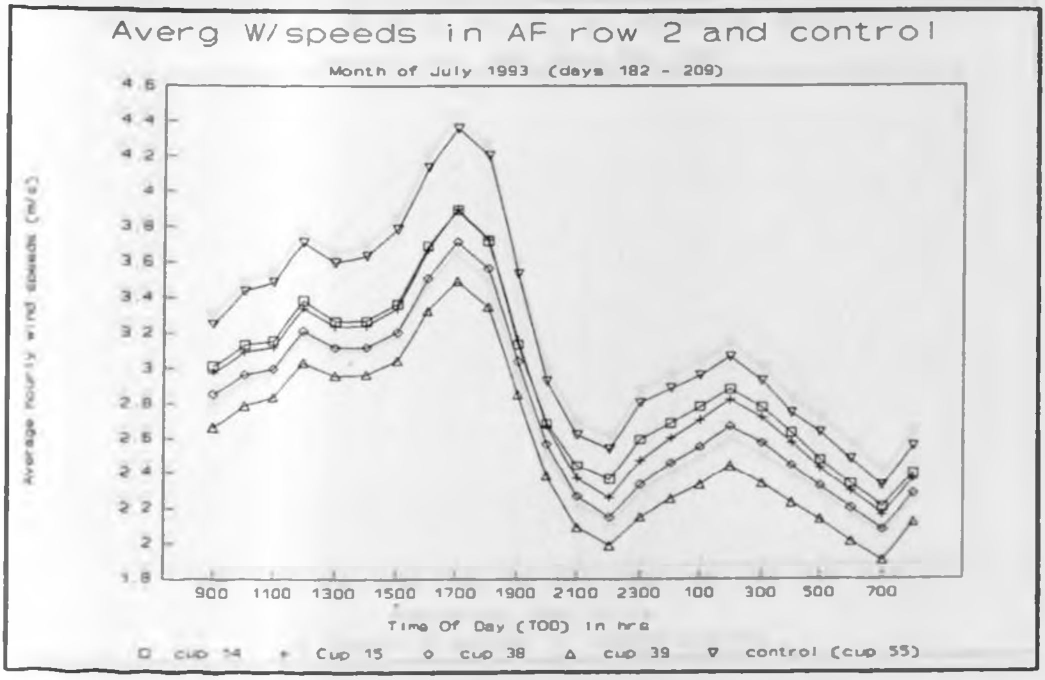


Fig. 265 Intercomparison of hourly wind speeds recorded by cup anemometers (cups 14, 15, 38 & 39) in row 2 and control at 2.4 m height in AF for July 1993 (DOY 182-209) during windy season at Matanya.

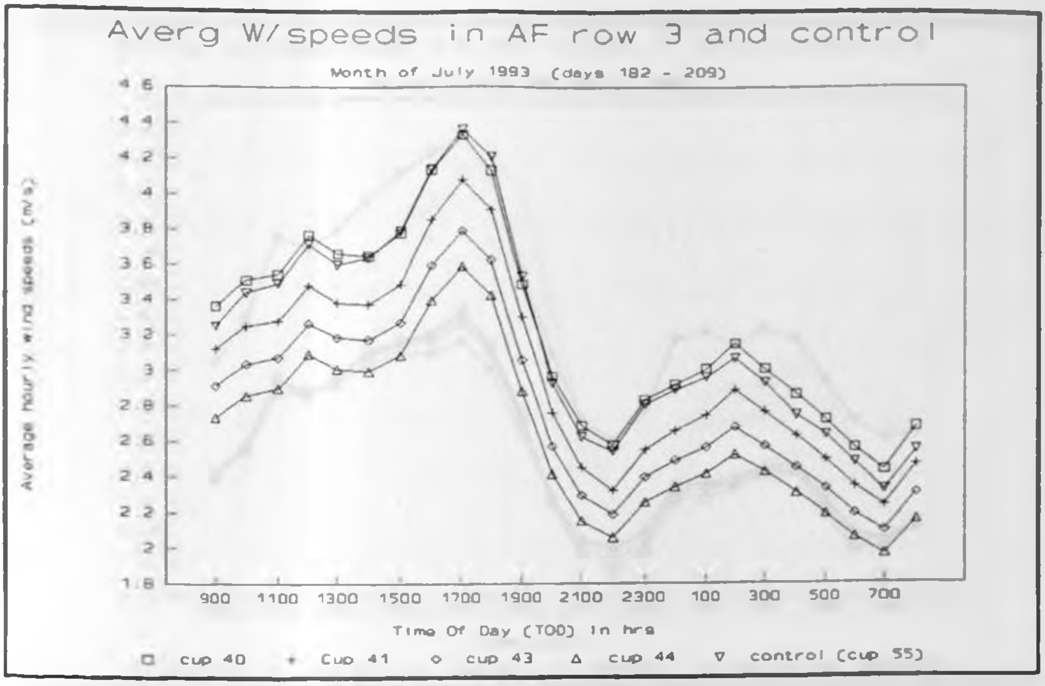


Fig. 266. Intercomparison of hourly wind speeds recorded by cup anemometers (cups 40, 41, 43 & 44) in rows 3 and the control at 2.4 m height in AF for July (DOY 182-209) during windy season at Matanya.

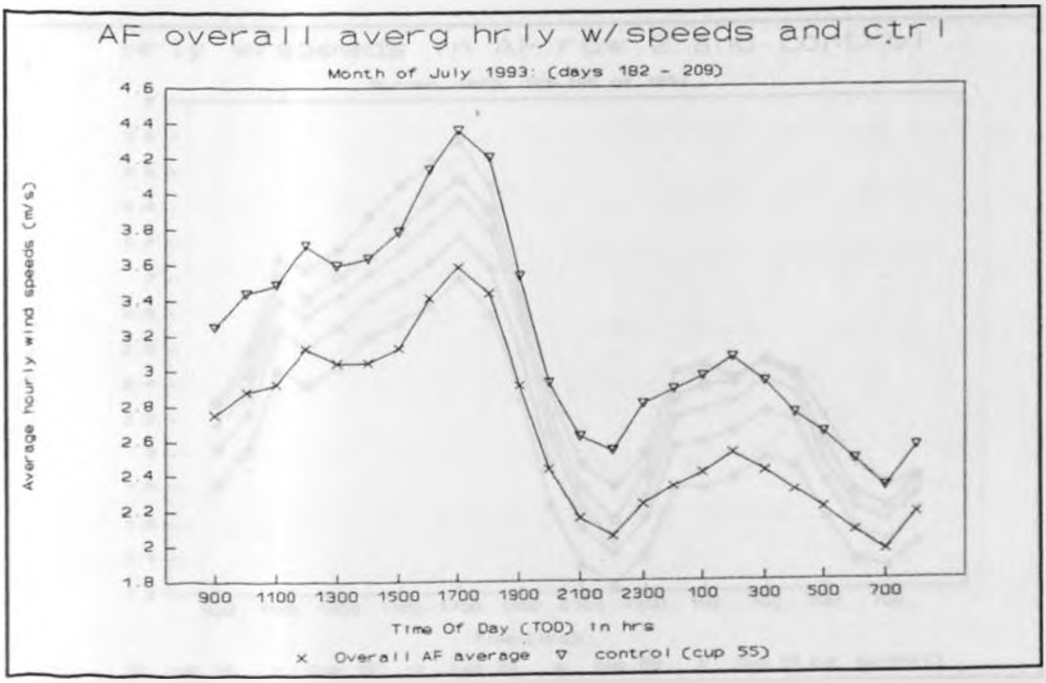


Fig. 267. Comparison of overall average hourly wind speeds in AF with control for July 1993 (DOY 182-209) during windy season at Matanya.

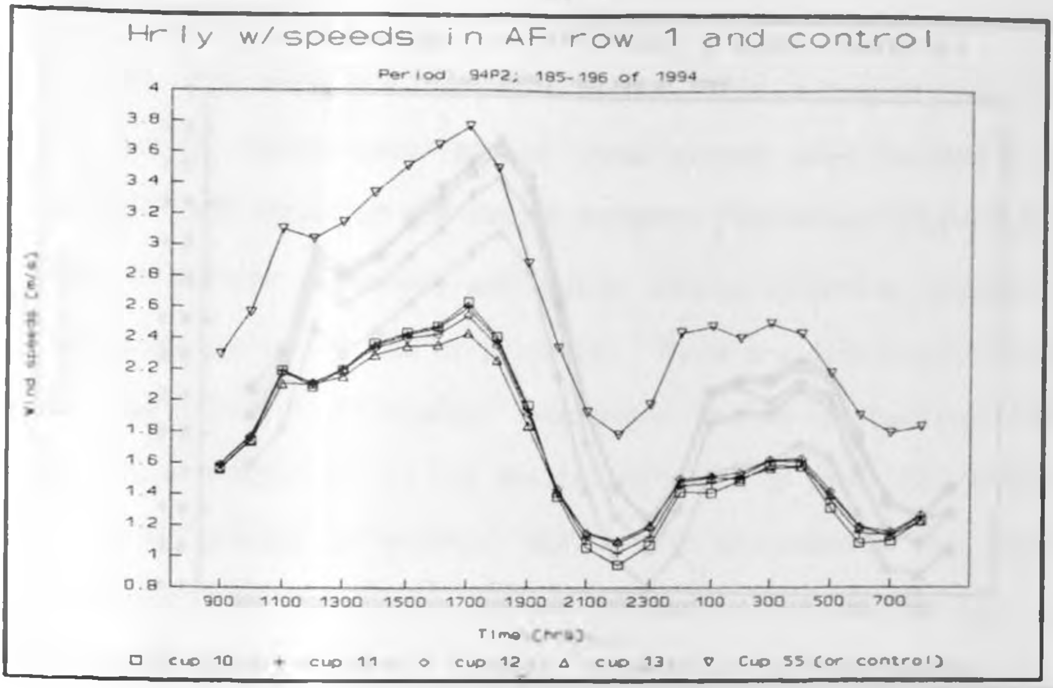


Fig. 268. Intercomparison of hourly wind speeds recorded by cup anemometers (cups 10, 11, 12 & 13) row 1 and control at 2.2 m height in AF for July 1994 (DOY 185-196) during windy season at Matanya.

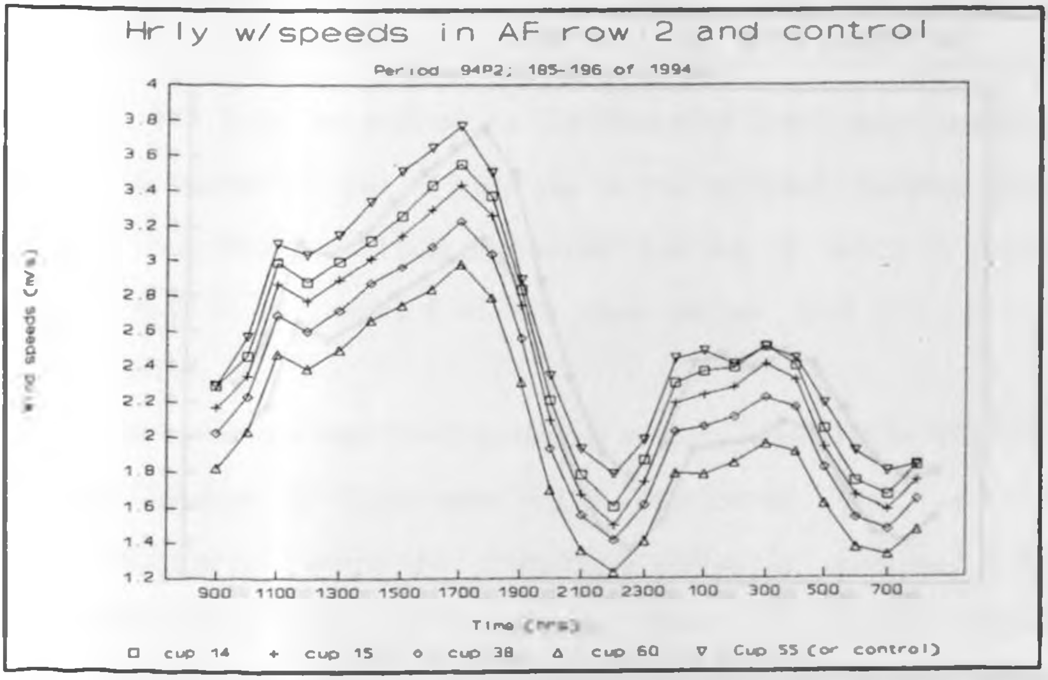


Fig. 269. Intercomparison of hourly wind speeds recorded by cup anemometers (cups 14, 15, 38 & 60) in row 2 and control at 2.2 height in AF for July 1994 (DOY 185-196) during windy season at Matanya.

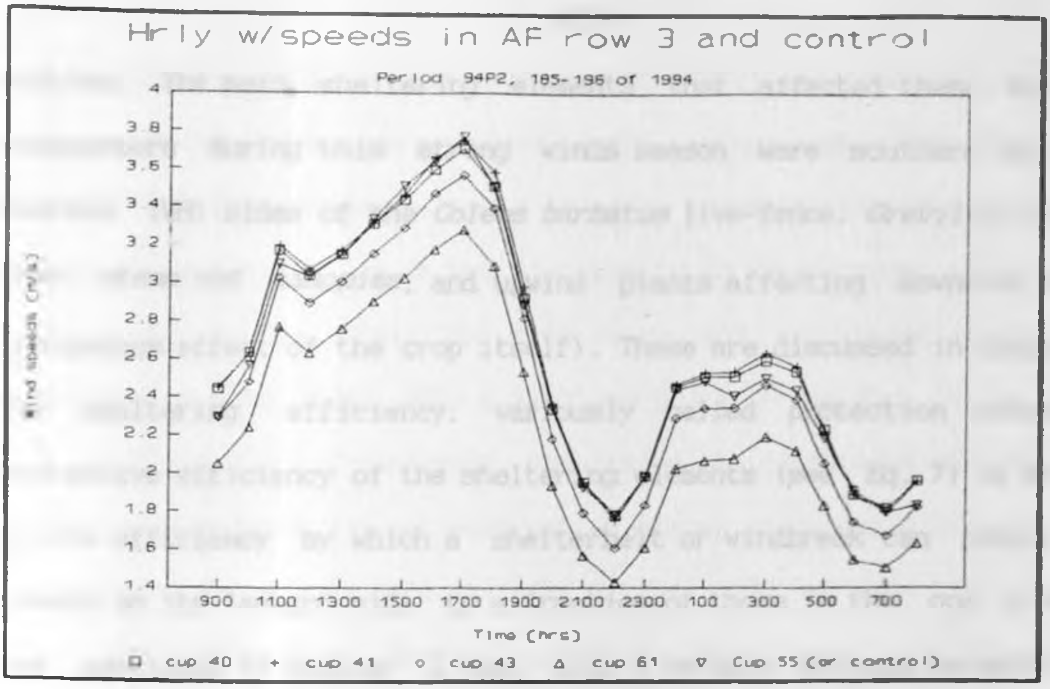


Fig. 270. Intercomparison of hourly wind speeds recorded by cup anemometers (cups 40, 41, 43 & 61) in row 3 and control at 2.2 m height in AF for July 1994 (DOY 185-196) during windy season at Matanya.

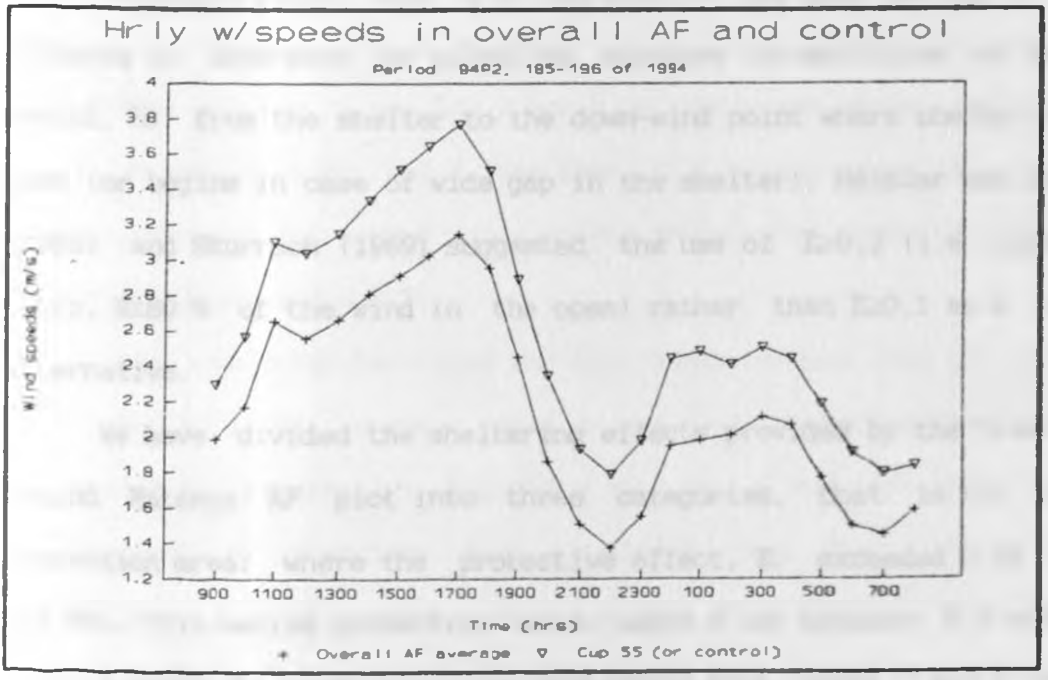


Fig. 271. Intercomparison of overall AF average of hourly wind speeds with control for July 1994 (DOY 185-194) during windy season at Matanya.

section. The main sheltering elements that affected these WAU cup anemometers during this strong winds season were southern (SH) and western (WH) sides of the *Coleus barbatus* live-fence. *Grevillea robusta tree stems and canopies*, and upwind plants affecting downwind plants (roughness effect of the crop itself). These are discussed in chapter 3. The sheltering efficiency, variously called protection effect or protective efficiency of the sheltering elements (see Eq. 7) is defined as the efficiency by which a shelterbelt or windbreak can reduce wind speeds on its leeward side to a fraction of those in the open area. It was mentioned in chapter 2 that till a certain minimum permeability, relatively denser windbreaks are more efficient as windbreak than the less dense ones.

Jensen (1954) and Bean *et al.* (1975) suggested the use of $E \geq 0.1$ (i.e. reduction ratio, $R \leq 90$ % of the wind in the open see eq. 7) as a criteria to determine the effective distance (in multiples of shelter height, H) from the shelter to the down-wind point where shelter effect ends (or begins in case of wide gap in the shelter). Heisler and Dewalle (1988) and Sturrock (1969) suggested the use of $E \geq 0.2$ (i.e. reduction ratio, $R \leq 80$ % of the wind in the open) rather than $E \geq 0.1$ as a better alternative.

We have divided the sheltering effects provided by the live-fence around Matanya AF plot into three categories, that is (i) strong protection area: where the protective effect, E, exceeded 0.35 (i.e. $E \geq 0.35$), (ii) medium protection area: where E lay between 0.2 and 0.35 (i.e. $0.2 \leq E \leq 0.35$), and (iii) low protection area: where $E \leq 0.2$. We are below quantifying significance of protection as quantitatively already handled in previous sections.

(i) Experimental periods in June 1993 (93P4) and 1994 (94P1)

On the protection provided by the western hedge (WH) (Fig. 10) we learn here that transect line 4 (cups in positions A4. A8 & A12) had the highest protection as it was also remote to SH and might also have been protected by the *Grevillea* tree stems and the upwind maize plants (plants in AFL1. AFM2. AFL2 & AFM3 and buffer - see Fig. 10) in AF.

Figs. 272 & 274 present results of the protective effects of the *Coleus live-fence* against destructive strong winds which occurred during experimental periods 93P4 and 94P1 of June 1993 and June 1994 (see Table A6). We observe here very high protection provided by the live-fence. with protective efficiencies, E. higher than 0.35 (E≥ 0.35) as recorded by the cup anemometers in row 1 in June 1994 (Fig. 274). The positions A9, A10, A11 and A12 in row 3 situated in the upper part of AF recorded the lowest protection in AF, especially in June 1993 (Fig. 272 & 273) which extended to include positions in row 2 except A8. Only position A4 in line 4 and row 1 had E>0.2 had high protection while positions A8 & A12 (in 1993 & 1994) had E less than 0.2 in both years indicating low protection against strong winds in the pruned AFM1 where they are located (Figs. 273 & 275).

We can infer here that for the month of June 1994 the positions. A1, A2, A3 & A4, in row 1 were in the well protected zone (Fig. 275, position A2 marginally). Positions A5, A6, A7 and A9, A10 & A11 were influenced by turbulent flow resulting from the DGP and other turbulence provoking plant elements during June. 1993 and 1994. They all read close to the same wind speeds as cup 55 in the open (Figs. 273 & 275). It should be noted that cups can pick up only partly the turbulent components, which means that damage may occur in AF for winds speeds not

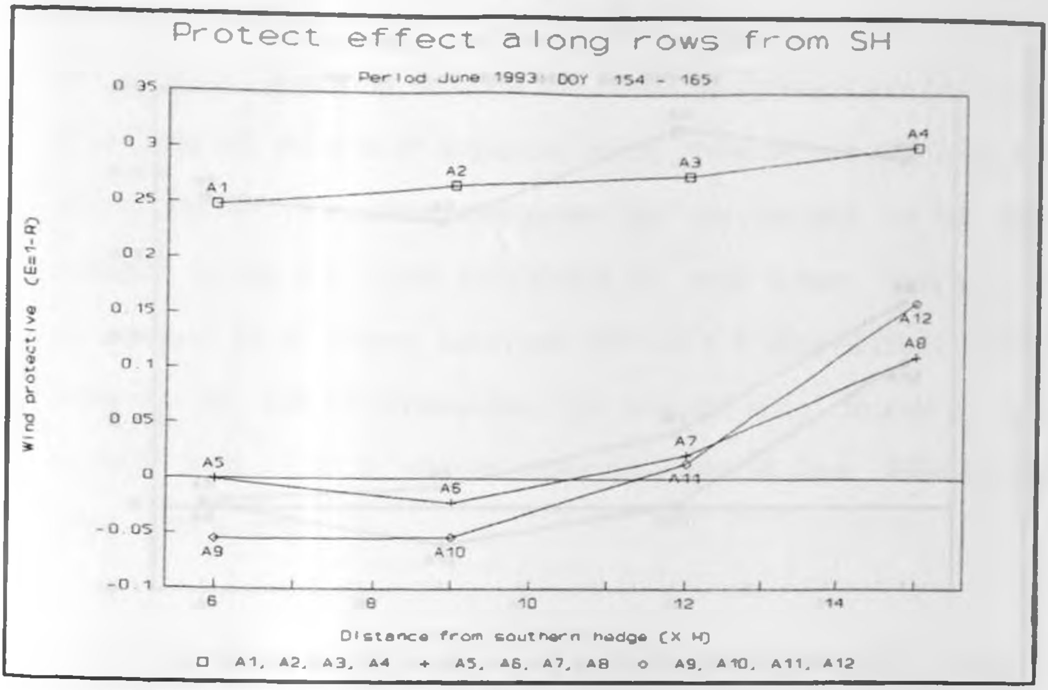


Fig. 272. Intercomparison of Grevillea robusta trees and Coleus barbatus live-fence protective effect, E, for rows 1, 2 & 3 as function of distance from WH for June (DOY 154-165) 1993.

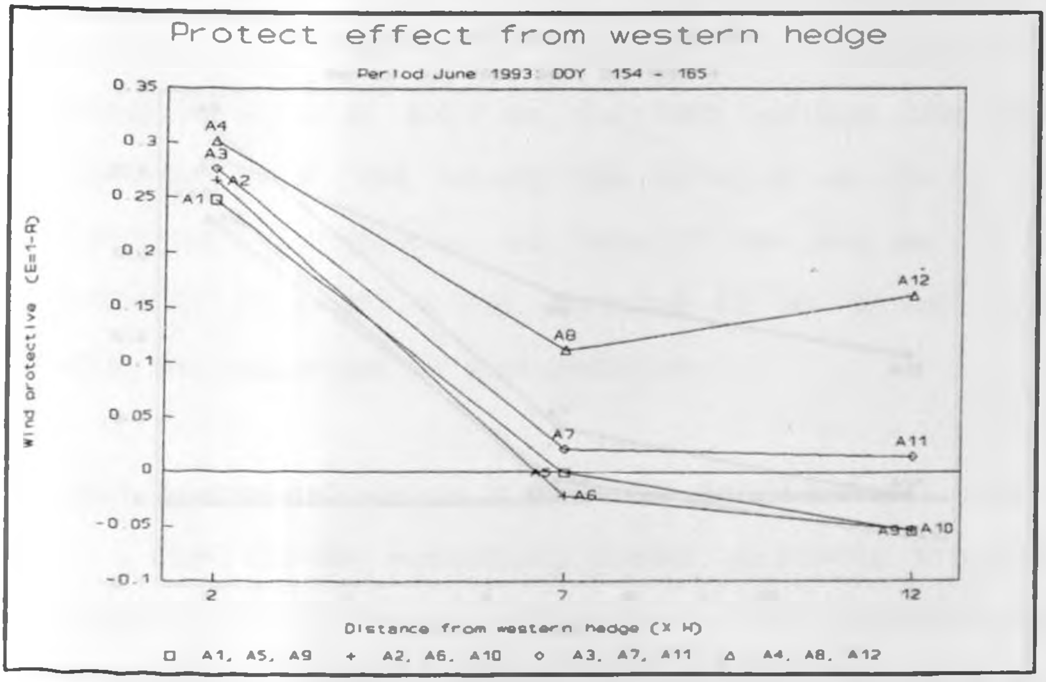


Fig. 273. Intercomparison of Grevillea robusta trees and Coleus barbatus live-fence protective effect, E, for lines 1, 2, 3 & 4 as function of distance from WH for June (DOY 154-165) 1993.

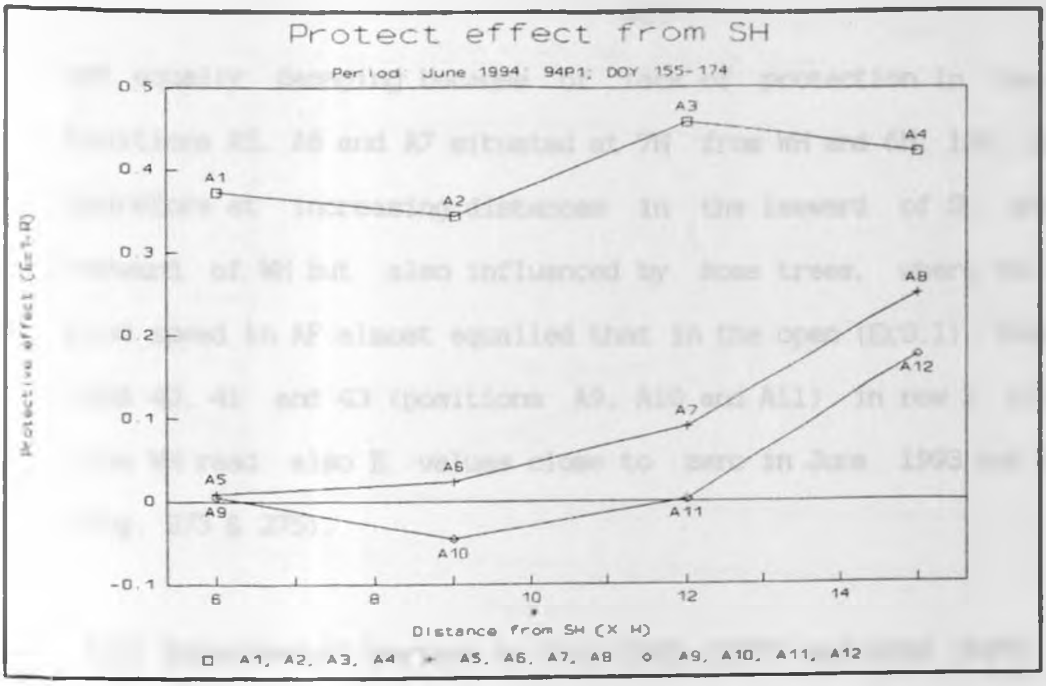


Fig. 274. Intercomparison of Grevillea robusta trees and Coleus barbatus live-fence protective effect, E, for rows 1, 2 & 3 as function of distance from SH for June (DOY 155-174) 1994.

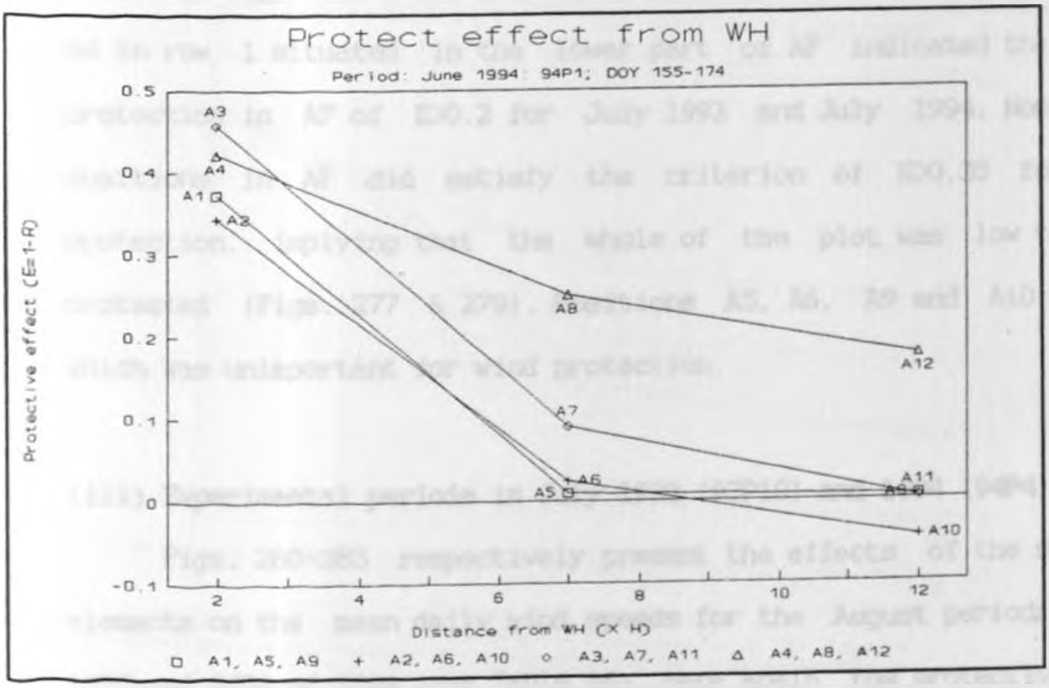


Fig. 275. Intercomparison of Grevillea robusta trees and Coleus barbatus live-fence protective effect, E, for lines 1, 2, 3 & 4 as function of distance from WH for June (155-174) 1994.

yet equally damaging because of lack of protection in the control. Positions A5, A6 and A7 situated at 7H from WH and 6H, 12H, 18H from SH therefore at increasing distances in the leeward of SH and equally leeward of WH but also influenced by some trees, where the resulting wind speed in AF almost equalled that in the open ($E\leq0.1$). Similarly, cups 40, 41 and 43 (positions A9, A10 and A11) in row 3 situated 12H from WH read also E values close to zero in June 1993 and June 1994 (Fig. 273 & 275).

(ii) Experimental periods in July 1993 (93P7) and 1994 (94P2)

Figs. 276 & 277 and 278 & 279 present the same way results on the effect of mean daily wind speed protective effects in rows 1, 2 & 3 during the month of July 1993 and 1994 which are mirror images of wind speeds in Figs. 260 & 261 and 262 & 263. Again positions A1, A2, A3 and A4 in row 1 situated in the lower part of AF indicated the highest protection in AF of $E>0.2$ for July 1993 and July 1994. None of the positions in AF did satisfy the criterion of $E>0.35$ for strong protection, implying that the whole of the plot was low to medium protected (Figs. 277 & 279). Positions A5, A6, A9 and A10 had $E\leq0.1$ which was unimportant for wind protection.

(iii) Experimental periods in July 1993 (93P10) and 1994 (94P4)

Figs. 280-283 respectively present the effects of the sheltering elements on the mean daily wind speeds for the August periods 93P10 of 1993 and 94P4 of 1994 (see Table A6). Here again the protective effect, E, was very high in row 1 in both years with $E\geq0.35$ in 1993 and $E\geq0.35$ in 1994. This implied relatively high wind reduction by the protective elements in the lower half of AF. All positions had $E\leq0.35$ in 1993 which

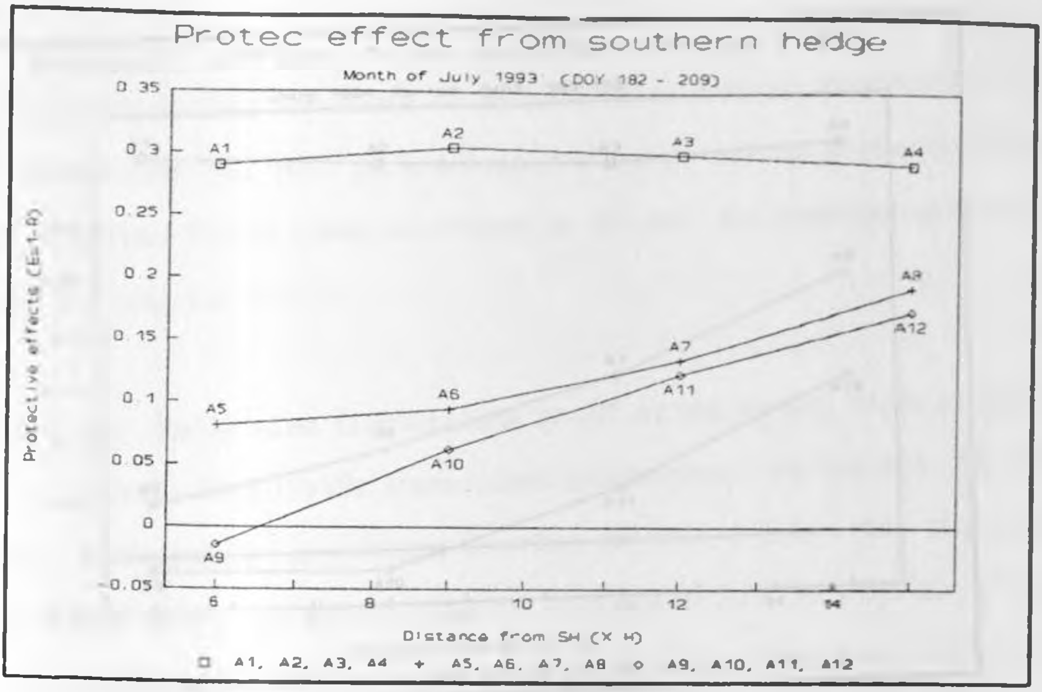


Fig. 276. Intercomparison of Grevillea robusta trees and Celus barbatus live-fence protective effect, E, for rows 1, 2 & 3 as function of distance of distance from SH for July (182-209) 1993.

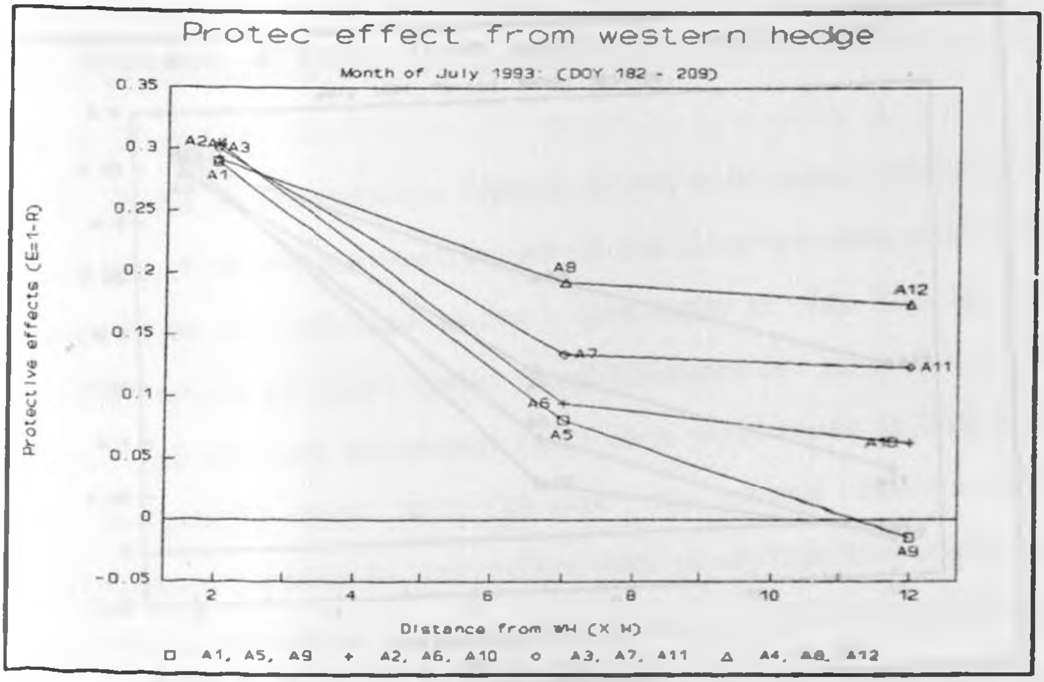


Fig. 277. Intercomparison of Grevillea robusta trees and Coleus barbatus live-fence protective effect, E, for lines, 1, 2, 3 & 4 for July (DOY 182-209) 1993.

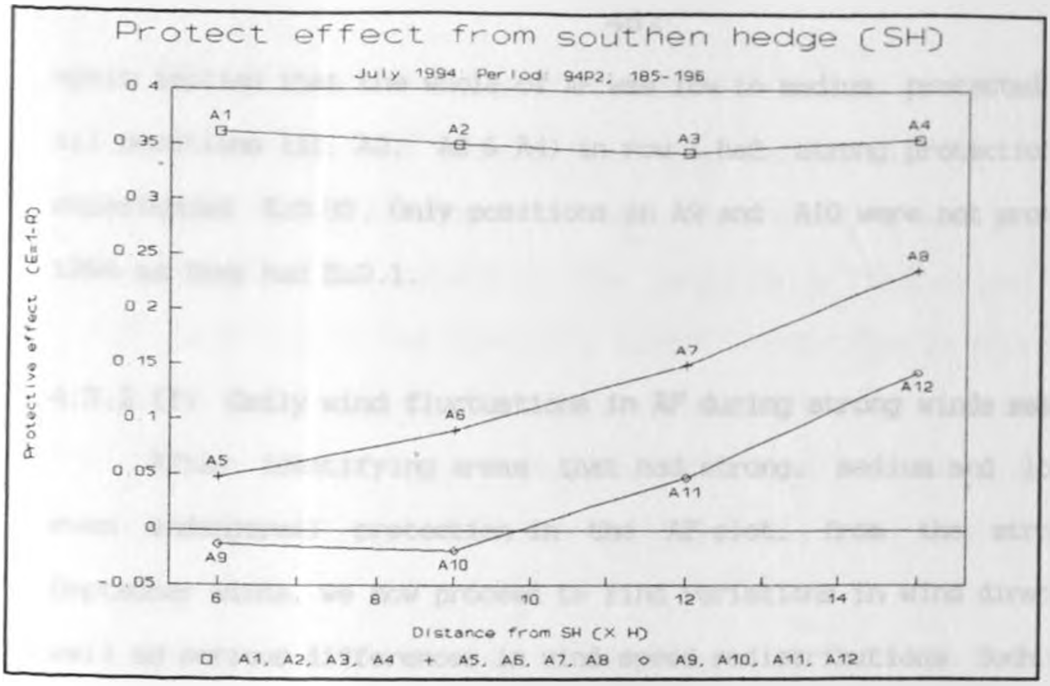


Fig. 278. Intercomparison of Grevillea robusta trees and Coleus barbatus live-fence protective effect, E, for rows 1, 2 & 3 as function of distance from SH for July (DOY 185-196) 1994.

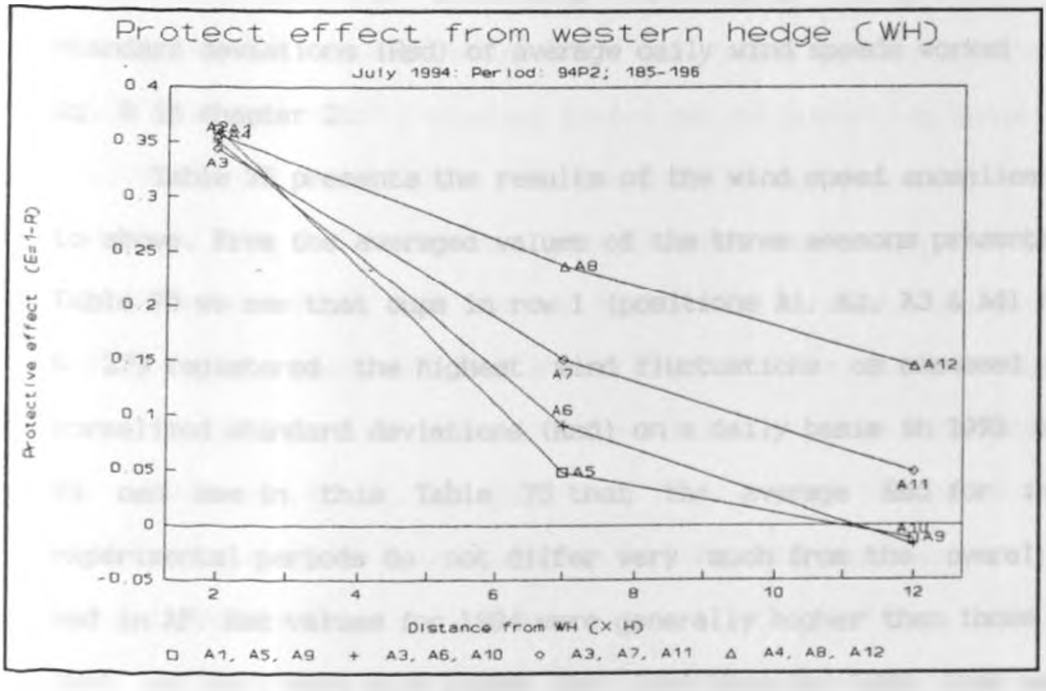


Fig. 279. Intercomparison of Grevillea robusta trees and Coleus barbatus live-fence protective effect, E, for lines 1-4 as function of distance from WH for July (185-196) 1994.

again implied that the whole of AF was low to medium protected. In 1994 all positions (A1, A2, A3 & A4) in row 1 had strong protection as they experienced E≥0.35. Only positions in A9 and A10 were not protected in 1994 as they had E≤0.1.

4.3.2 (f) Daily wind fluctuations in AF during strong winds season

After identifying areas that had strong, medium and low (no or even endangered) protection in the AF plot, from the strong June-September winds, we now proceed to find variations in wind directions as well as serious differences in wind speed redistributions. Such variable winds appreciably move protective and other plant parts differently, that are in turn influencing such values. Just ordinarily turbulence does not affect these averages. This was done to confirm, or otherwise, these observations by presenting our findings using wind normalized standard deviations (Rsd) of average daily wind speeds worked out using Eq. 8 in chapter 2.

Table 75 presents the results of the wind speed anomalies referred to above. From the averaged values of the three seasons presented in Table 75 we see that cups in row 1 (positions A1, A2, A3 & A4) Figs. 278 & 279 registered the highest wind fluctuations as assessed from the normalized standard deviations (Rsd) on a daily basis in 1993 and 1994. We can see in this Table 75 that the average Rsd for individual experimental periods do not differ very much from the overall average Rsd in AF. Rsd values for 1994 were generally higher than those for 1993 just as the E were also higher for 1994 than for 1993. This was due to the influence of stronger winds in 1994 than 1993 and also the increasing density with time of sheltering elements due to growth. The average Rsd values for cups row 1 were the highest in the plot. The Rsd for positions A3 and A4 (cups 12 and 13) were 0.32 and 0.35 in 1993, and 0.58 and 0.64 in 1994 respectively. This implied that for the AF plot the highest daily fluctuations were often found around row 1, with positions A3 and A4 registering even larger daily fluctuations. In row 2 positions A7 and A8 had relatively higher fluctuations in this row (i.e. Rsd of 0.12 for position A7 and 0.19 for position A8 in 1993 and 0.17 for position A7 and 0.42 for position A8 in 1994). In row 3 position A12 had the highest Rsd in both years although still lower than those in row 1.

The southerly flow met the SH, where the DGP was located, most regularly at right angle. This induced strong streamlined flow similar to that in the open area up to 12H along row 3 and 9H along row 2. This affected the cups at these distance as we have already mentioned, with Rsd≤0.1.

The daily relationship of fluctuations differs little, in the sense that for nearly constant direction no protection means constant relationships between daily fluctuations in the open and in the AF and therefore low Rsd's. However, many things mechanically influence daily average wind speeds with trends (increasing biomass, changing biomass influence wind speed and wind angle) that increase the Rsd-values.

The positions A7, A3 and A4 have many changing influences because of influence of SH, WH, gaps and trees. Such changes even include differences in maize height because of long (changing) wind paths before the air reaches these positions.

Aerodynamic features of flow around live-fence, Grevillea tree stems and canopies could induce fluctuating air movement and formation of turbulent eddies down-stream of these obstacles which then might have been picked up by the cup anemometers, thus registering relative higher

Table 75. Normalized standard deviations for average daily wind speeds for six representative periods during strong winds season in 1993 and 1994.

YEAR	1993	"Positions of WAU cup anemometers in the AF plot												
		row 1				row 2				row 3				
period	DOY	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	avg
93P4	155-174	0.24	0.26	0.35	0.39	0.08	0.04	0.08	0.17	0.05	0.03	0.08	0.21	0.14
93P7	185-196	0.16	0.18	0.19	0.18	0.02	0.03	0.07	0.11	-0.02	0.02	0.05	0.06	0.08
93P10	196-215	0.34	0.39	0.43	0.48	0.20	0.15	0.23	0.29	0.05	0.11	0.19	0.20	0.22
	average	0.24	0.28	0.32	0.35	0.10	0.08	0.12	0.19	0.03	0.05	0.11	0.16	0.15
YEAR	1994	row 1				row 2				row 3				
period	DOY	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	avg
94P1	155-174	0.47	0.44	0.67	0.66	0.05	0.05	0.09	0.81	0.08	-0.01	0.00	0.17	0.25
94P2	185-196	0.38	0.42	0.46	0.53	0.04	0.06	0.15	0.23	0.02	-0.01	0.03	0.10	0.17
94P3	196-215	0.44	0.49	0.54	0.62	0.07	0.10	0.17	0.27	0.04	0.01	0.03	0.09	0.21
94P4	216-235	0.56	0.62	0.65	0.73	0.17	0.20	0.28	0.39	0.12	0.10	0.14	0.19	0.30
	average	0.47	0.49	0.58	0.64	0.08	0.10	0.17	0.42	0.06	0.02	0.05	0.14	0.23

anomalies (as assessed via Rsd). This benefitted the plants by excluding lodging and respirational losses from strong destructive flow that was channelled into the plot through DGP. The maize in the areas with larger Rsd grew taller and had higher biomass yields. This gave high correlation between high Rsd-values, strong protection and high biomass yields.

4.3.2 (g) Shaded Piches with cup anemometers at Matanya: Comparison of shaded Piche with WAU electrical cup anemometers.

We present in Tables 77 and 78 the comparisons of the weekly wind speeds derived from daily evaporation data from shaded Piche evaporimeters with weekly wind speeds from WAU electrical cup anemometers at Matanya for June-August 1993 and 1994 respectively. This covered only the time of overlap of the strong winds (June-September) season with Long Rains (LR) crop season (April-August). WAU electrical cup anemometers were paired with shaded Piches on the same masts but on the opposite sides of the masts at the same heights. The main aim of comparing shaded Piches with the more accurate WAU electrical cup anemometers was to test the adaptability of shaded Piches as auxiliary anemometers for interpolation and extrapolation purposes in inhomogeneous agroforestry conditions (Kainkwa, 1991; Kainkwa and Stigter, 1994).

In this section we refer to some of the findings from Kainkwa (1991) and Kainkwa and Stigter (1994) on their work in Lyamungu and Setchet, Tanzania, which we find pertinent under Matanya conditions. Kainkwa (1991) compared the evaporation from shaded Piches with the square-root of average wind speeds for Lyamungu and Setchet as given in Eq. 24.

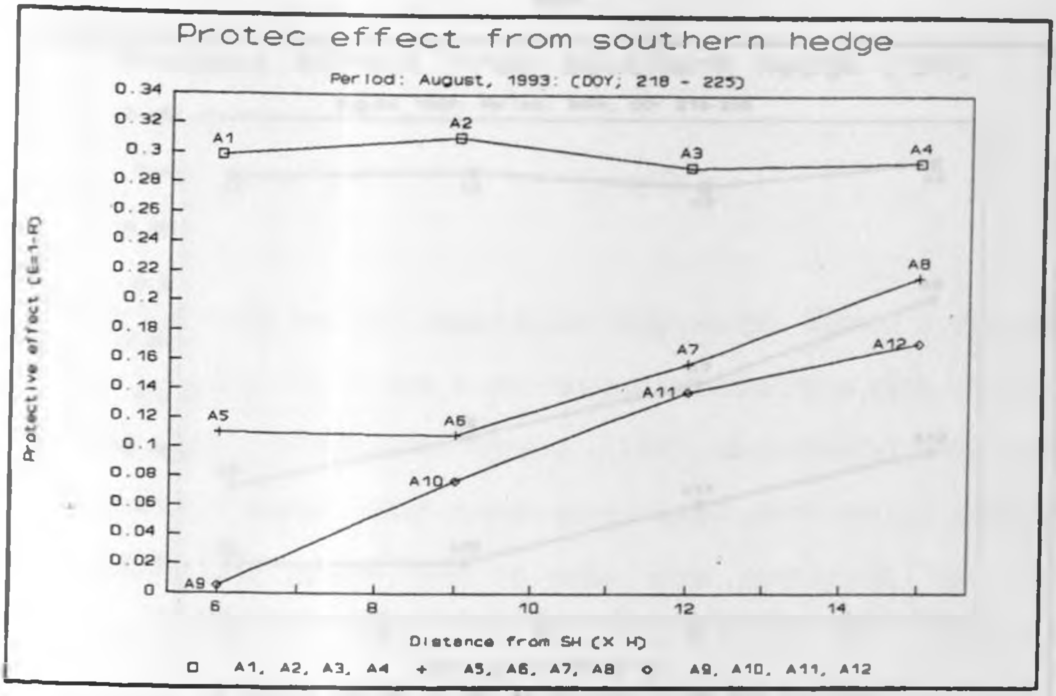


Fig. 280. Intercomparison of Grevillea robusta trees and Coleus barbatus live-fence protective effect, E, for rws 1-3 as function of distance from SH for August (229-236) 1993.

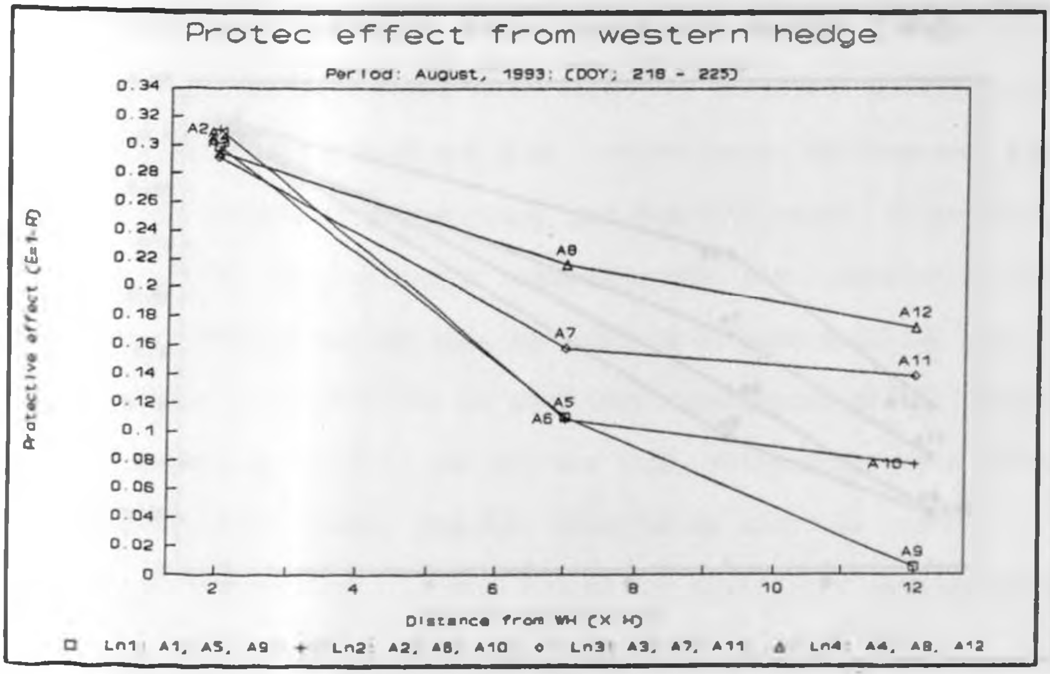


Fig. 281. Intercomparison of Grevillea robusta trees and Coleus barbatus live-fence protective effect, E, for lines 1-4 as fuction of distance from WH for August (229-236) 1993.

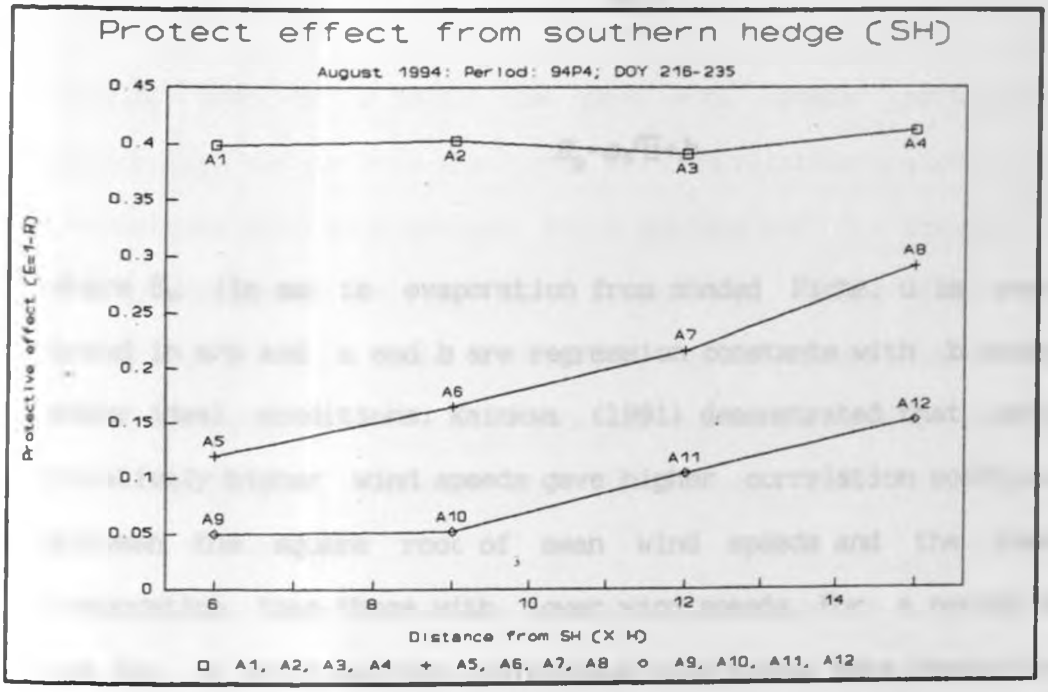


Fig. 282. Intercomparison of Grevillea robusta trees and Coleus barbatus live-fence protective effect, E, for rows 1-3 for August (DOY 216-235) 1994

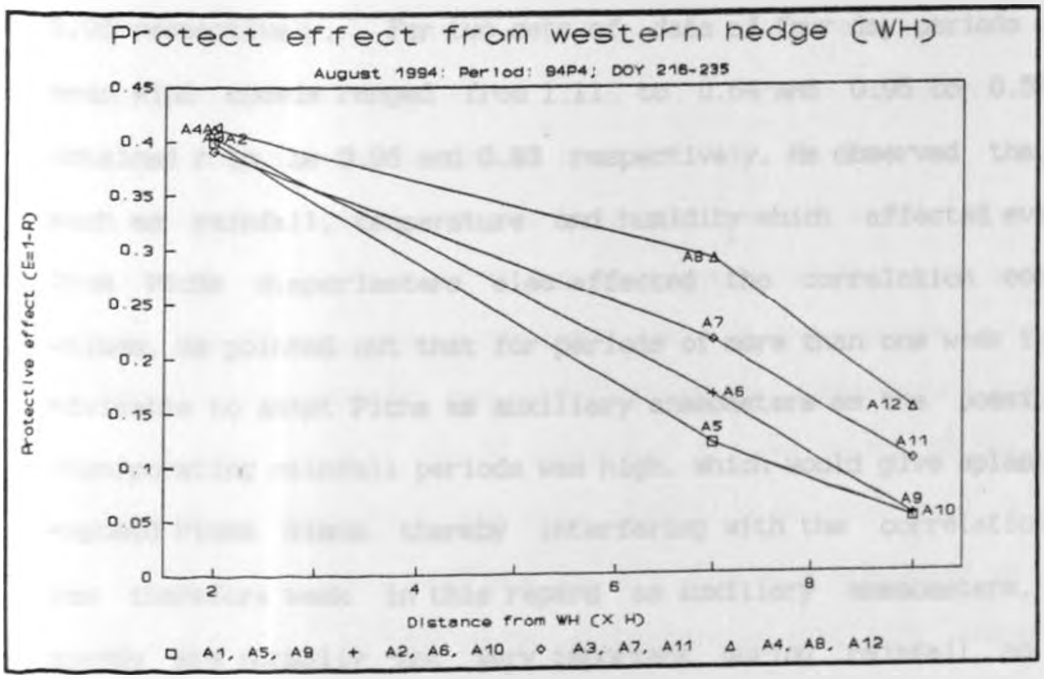


Fig. 283. Intercomparison of Grevillea robusta trees and Coleus barbatus live-fence protective effect, E, for lines 1-4 as function of distance from WH for August (DOY 216-235) 1994.

$$E_p = a\sqrt{u} + b \qquad (24)$$

where E_p (in mm) is evaporation from shaded Piche, u is average wind speed in m/s and a and b are regression constants with b close to zero under ideal conditions. Kainkwa (1991) demonstrated that periods with relatively higher wind speeds gave higher correlation coefficients (r) between the square root of mean wind speeds and the shaded Piche evaporation than those with lower wind speeds. For a period of nearly one day, in which maximum and minimum wind speeds were respectively 1.36 and 0.79 m/s he obtained the correlation coefficient of 0.98. For two periods of about two days in which the ranges from maximum to minimum wind speed were very comparable to above case he obtained r of 0.99 and 0.95 respectively. For two sets of data of four day periods in which mean wind speeds ranged from 1.11 to 0.64 and 0.95 to 0.53 m/s he obtained r to be 0.96 and 0.83 respectively. He observed that factors such as rainfall, temperature and humidity which affected evaporation from Piche evaporimeters also affected the correlation coefficient values. He pointed out that for periods of more than one week it was not advisable to adapt Piche as auxiliary anemometers as the possibility of incorporating rainfall periods was high, which would give splash on the exposed Piche discs, thereby interfering with the correlations. Piche was therefore weak in this regard as auxiliary anemometers, but wind speeds are normally not very important during rainfall, so periods between such events can be used. High atmospheric humidities, as a result of low wind speeds approaching zero (very calm conditions especially at night), lead to very low evaporation from the Piche.

slowing down to a halt. The zero wind speeds correspond to zero evaporation values from the Piche. At high relative humidities and small temperature gradients between Piche surface and the air the zero wind speed correspond to the zero evaporation values from the Piche. Inclusion of this point increased r-values, except in the open area (control) where very little decrease was observed for 1993 data. The same observation was also made by Kainkwa (1991) for Lyamungu and Setchet in Tanzania.

In determining airflow at point X relative to a reference point, r, say in the open (or at a point in AF), the interest is on ratio, R(x), of u(x) to u(r). We assume here that the square root of mean wind speed relation of Eq. 24 holds. If u(x) is known, the ratio, R'(x), of the square of piche evaporation (mm) data at X to the square of the same at r, that is $(E_p(x))^2$ to $(E_p(r))^2$ can be used to estimate the wind at a point X relative to that at r, if a and b can be worked out. Basically this is true for simultaneously measured data.

R(x) was correlated with R'(x) for average weekly wind and piche evaporation data with cups 55 and 38 (position A7 in row 2) as reference points. Cup 55 was used on the basis that it was exposed to appreciably different air movements and conditions of air temperature and humidity from the cups in AF. Cup 38 (position A7) was taken on the basis of similarity in exposure to the same conditions as other cups in AF.

The weekly data in AF and in the open were subjected to a number of manipulations to test piche atmometers as auxiliary anemometers in agroforestry situations. These are reported here as case 1 till case 8. The results are given in Table 76 for 24 weeks (i.e. June-August) for pooled data of LR93 and LR94.

Case 1: $R(x) = u(x)/u(r)$ was correlated with $R'(x) = (E_p(x))^2/(E_p(r))^2$ taking cup 55 as reference for all cups in AF.

Case 2: $R(x) = u(x)/u(r)$ was correlated with $R'(x) = (E_p(x))^2/(E_p(r))^2$ taking cup 38 (position A7 in row 2) as reference for all cups in AF.

Case 3: case 1 was repeated with row 2 left out.

Case 4 case 2 was repeated with row 2 left out.

Case 5: case 3 was repeated for odd numbered weeks.

Case 6: case 3 was repeated for even numbered weeks.

Case 7: case 4 was repeated for odd numbered weeks.

Case 8: case 4 was repeated for even numbered weeks.

We see in Table 76 that reasonably high correlation coefficients (r) were obtained for the correlation of R(x) with R'(x), for cup 55 used as reference (r>0.830, except case 1) without point (0,0), and very high r values (r>0.990) after point (0,0) was added. The r's associated with cup 38 as reference (identical exposure) were always higher than 0.990, even when the zero point was not added as data point. This is despite the fact that weekly average periods included varying air temperatures and air humidities from week to week. These factors affect evaporation from piche evaporimeters as found by Kainkwa (1991).

We can see in Table 76 that for all the 8 cases the relative wind reduction ratios (R(x)) are highly correlated with the piche evaporation reduction ratios (R'(x)) during the strong winds overlap period, with higher correlation values obtained for cup 38 (position A7) than for cup 55 in the open.

In case 1, taking cup 55 as reference, the averages of all cups gave correlation coefficient (r) between R(x) and R'(x) as 0.762. For the same averages and cup 38 as reference (case 2) r was 0.920. When

Table 76. Regression coefficients of comparison of weekly wind speeds for 1993 and 1994 recorded by WAU electrical anemometers during overlap period with those derived from Piche atmometers. a is the slope of the regression line and b is the intercept. EY is the standard error of Y estimate. EX is the standard error of X coefficient. r is the correlation coefficient. N is number of weeks in the period the June-august. Italics values are regression coefficients where point (0,0) was added as a measuring point. δr is the per cent increase/ decrease in r when point (0,0) is added. Cup 55 in the open and cup 38 (position A7) in AF were taken as reference anemometers.

b	EY	r	a	EX	δr%
Case 1: Cup 55 as reference all rows included					
0.39	0.03	0.762	0.53	0.14	
0.02	*0.03*	*0.991*	*0.97*	*0.04*	+30.1
Case 2: Cup 38 as reference all rows included					
0.11	0.01	0.920	0.86	0.12	
0.00	*0.02*	*0.998*	*0.99*	*0.02*	+8.5
Case 3: Cup 55 in the open as reference – row 2 excluded For all twenty four weeks (N=24) rows 1 & 3					
0.38	0.02	0.832	0.57	0.12	
0.01	*0.03*	*0.993*	*0.98*	*0.03*	+19.4
Case 4: cup 38 in AF as reference – row 2 excluded For all twenty four weeks (N=24) row 1 & 3.					
0.10	0.01	0.951	0.87	0.09	
0.00	*0.01*	*0.999*	*0.99*	*0.01*	+5.0
Case 5: case 3 but for odd weeks (wk1, wk3, ..., wk23) N=12					
0.44	0.02	0.845	0.45	0.40	
0.01	*0.03*	*0.996*	*0.98*	*0.04*	+17.9
Case 6: case 3 but for even weeks (wk2, wk4, ..., wk24) N=12					
0.27	0.02	0.849	0.66	0.21	
0.01	*0.03*	*0.997*	*0.99*	*0.04*	+17.4
Case 7: case 4 but for odd weeks (wk1, wk3, ... wk23) N=12					
0.22	0.05	0.986	0.72	0.06	
0.00	*0.01*	*1.000*	*0.99*	*0.07*	+1.4
Case 8: case 4 but for even weeks (wk2, wk4, ... wk24) N=12					
–0.03	0.01	0.960	1.04	0.15	
–0.00	*0.01*	*0.999*	*1.00*	*0.01*	+4.1

point (0,0) was added, r for case 1 increased by +30.1% to 0.991 while that for case 2 increased by +8.5% to 0.998.

In cases 3 and 4, row 2 was omitted and the correlation of R(x) with R'(x) obtained for rows 1 and 3 as explained above. The correlation coefficient of R(x) with R'(x) for cup 55 as reference before point

(0,0) was added increased as compared to case 1. r for cup 55 as reference was now 0.832 which increased by +19.4% to 0.993 when point (0,0) was added. In case 4 also there was a slight increase compared to case 2 and small increase of +5.0% was obtained when point (0,0) was added.

In cases 5 and 7 odd numbered weeks (wk1, wk3, ..., wk23) were used to correlate R(x) with R'(x) as explained above. The r values for cup 55 as reference again increased slightly (r = 0.845) compared to case 3. When point (0,0) was added r again leapt by +17.9% to 0.996. For case 7 cup 38 as reference r was 0.986 which marginally increased by +1.4% to 1.00. In fact for cup 38 there was no need to add point (0,0) as r values were even very high without inclusion of the zero point.

In cases 6 and 8 even numbered weeks (wk2, wk4, ..., wk24) were used to correlate R(x) with R'(x) again this is explained above. Again r for cup 55 as reference was lower than r for cup 38 as reference (case 8). The r values for cup 55 as reference again increased by +17.4% from 0.849 to 0.997. Again for case 8 there was a slight increase in r by +4.1% when point (0,0) was added.

We find in case 5 and 7 for cup 55 as reference that r increased slightly when a sample size was reduced, say by using only odd or even numbered weeks. In such cases the intercepts decreased markedly while the gradient increased to approach 1 fairly fast with addition of point (0,0). The results in Table 76 are indicative of very high correlations between shaded piche evaporation and wind speeds, which makes the shaded piche a good instrument for use in anemometry from which to extrapolate and interpolate wind speeds, especially under strong wind conditions in semi-arid agroforestry systems. Under conditions of a shaded Piche, evaporation from this atmometer is solely a function of air movement.

temperatures and humidity and there is little influence of related and other environmental radiation (Ibrahim *et al.*, 1989). The correlations were more stable for cup 38 than in the open area position. The largest shift in r values obtained by including point (0,0) was +8.5%. This was less than half of the smallest shift for the open area position of +17.4%.

The regression coefficients in Table 76 obtained by regressing observed wind speed reduction ratios (R(x)) on the piche evaporation reduction ratios (R'(x)) were used to calculate wind reduction ratios as in Eq. 25.

$$R(x) = a * R'(x) + b \qquad (25)$$

where a and b are regression constants and $R'(x) = (E_p(x))^2/(E_p(r))^2$ gives the evaporation reduction ratios for piches in positions A5, A6, A7 & A8 in row 2. R(x) are the calculated wind reduction ratios and a and b are constants for cases 1 till 8 in Table 76. Once R(x) is known we then use $R(x)=u(x)/u(r)$ to calculate weekly wind speeds for each cup, where u(r), the wind speed of the reference cup (cup 55 or cup 38), is known, u(x) can be calculated.

Tables 77 and 78 present the results of wind speeds and wind reduction ratios for cup anemometers in row 2 (positions A5, A6, A7 and A8) calculated using the above approach. The measured wind speeds and the associated wind reduction ratios for cup 55 as reference are presented in Table 77(i) and (ii). Appendix Tables A9 & A10 give the same, but for smaller samples taken as odd and even numbered weeks, whose regression coefficients were as presented in Table 76. The overall picture we see in these Tables is that calculated values were very close to the measured values given in Table 77(ii). It is interesting to note here that differences between the calculated and measured wind speeds were mostly less than 5%, even in what appeared as the worst case (i.e. case 1 without point (0.0)). Table 76 (iii) shows that the largest per cent difference, of 4.4%, between the calculated and the measured wind speeds in case 1, without point (0,0), was obtained for position [illegible] in row 2. The smallest difference was obtained for position A7 (cup 38) also in row 2. The second smallest difference, of +1.48% for position A8 (cup 39), widened to +5.10% on inclusion of the zero point. Only in a few cases such as case 3 (appendix Table A9 (i)) did the difference become negative. Fairly large differences, of 6.64% and 6.62% for cups 14 and 15 as shown for case 5 in Table A9, were obtained for odd numbered weeks. Again the second smallest difference for cup 39 widened to 5.28 on addition of the zero point. In fact all through the odd numbered weeks the difference became bigger by including point (0,0). The results for even numbered weeks however generally decreased after point (0,0) was added to the data. The largest difference and therefore the worst case was obtained in case 6 for position A6 (cup 15) followed by position A5 (cup 14). However, inclusion of point (0,0) reduced the difference between measured and calculated wind speeds.

Tables 77 and 78 also show that the method of using a reference point in an open area was for a sufficient sample inferior to using one of the positions in the AF as reference which has similar micro-climatic conditions of air temperature and humidity. As we can see in Table 76, in case 1 till case 8, the reference taken in the open was just as good for smaller samples and becomes worse for larger samples.

Table 77. Cup 55 as reference. (i) wind reduction ratios from measured wind speeds (ii) measured wind speeds (iii) case 1-0: calculated wind speeds with zero excluded. (iv) case 1 -0: wind reduction ratios from calculated wind speeds with zero point excluded: (v) case 1 +0: wind reduction ratios from calculated wind speeds with zero point included: and (vi) case 1 +0: calculated wind speeds with zero point included: a and b are coefficients given in Table 76. Note that (1) is average wind speeds of the 24 weeks and (2) is standard deviations (3) is per cent difference of the average of the calculated from the average of measured wind speeds. x is missing data.

(i)				(ii)				(iii)				(iv)			
wind speed reduction ratios from measured wind speeds Cup55 as refence				Measured wind speeds				calculated wind speeds point (0,0) not included case 1 -0				Calculated reduction rat point (0,0) not included case a=0.53 b=0.39			
cup14	cup15	cup38	cup39	cup14	cup15	cup38	cup39	cup14	cup15	cup38	cup39	cup14	cup15	cup38	cup39
0.98	1.02	0.97	0.89	2.13	2.22	2.11	1.93	2.00	2.04	2.00	1.84	0.92	0.94	0.92	0.85
0.93	0.95	0.90	0.81	1.83	1.87	1.78	1.59	1.71	1.81	1.72	1.59	0.87	0.92	0.87	0.81
0.93	0.96	0.90	0.81	2.58	2.66	2.50	2.24	2.26	2.28	2.40	2.21	0.81	0.82	0.86	0.80
1.01	1.02	0.96	0.89	3.01	3.03	2.84	2.65	2.75	2.76	2.66	2.66	0.93	0.93	0.90	0.90
0.91	0.90	0.87	0.81	2.89	2.85	2.75	2.58	2.74	2.68	2.68	2.56	0.86	0.84	0.84	0.81
0.93	0.91	0.88	0.82	2.78	2.72	2.61	2.43	2.68	2.52	2.52	2.45	0.90	0.85	0.85	0.82
0.92	0.90	0.86	0.80	3.08	3.02	2.88	2.68	3.06	2.85	2.89	2.80	0.91	0.85	0.86	0.84
0.91	0.90	0.85	0.79	2.95	2.92	2.76	2.57	2.60	2.58	2.77	2.54	0.80	0.80	0.85	0.78
0.90	0.91	0.86	0.80	3.14	3.17	2.98	2.79	3.16	3.16	2.91	2.95	0.91	0.91	0.84	0.85
0.89	0.89	0.84	0.78	2.69	2.70	2.55	2.36	2.65	2.66	2.52	2.44	0.87	0.88	0.83	0.80
0.85	0.86	0.82	0.76	2.78	2.81	2.66	2.47	2.76	2.59	2.71	2.54	0.85	0.80	0.83	0.78
0.84	0.85	0.81	0.76	3.10	3.13	2.98	2.80	3.07	3.04	3.01	2.88	0.83	0.83	0.82	0.78
0.94	0.95	0.85	0.00	1.73	1.75	1.57	*	1.36	1.60	1.55	1.50	0.74	0.87	0.84	0.81
1.00	0.98	0.86	0.00	1.46	1.42	1.25	*	1.26	1.35	1.22	1.06	0.87	0.93	0.84	0.73
1.00	0.98	0.89	0.00	2.36	2.31	2.10	*	2.44	2.18	2.06	1.65	1.03	0.92	0.87	0.70
0.96	0.92	0.85	0.77	2.74	2.62	2.44	2.21	2.84	3.00	2.42	2.39	1.00	1.05	0.85	0.84
0.95	0.90	0.85	0.76	1.92	1.84	1.74	1.55	2.03	1.91	1.77	1.76	1.00	0.94	0.87	0.87
0.96	0.91	0.86	0.77	2.70	2.58	2.42	2.16	2.65	2.54	2.46	2.47	0.94	0.90	0.87	0.87
0.95	0.90	0.85	0.77	2.48	2.37	2.22	2.01	2.28	2.36	2.22	2.10	0.87	0.90	0.85	0.80
0.93	0.88	0.82	0.74	2.46	2.33	2.18	1.97	2.25	2.04	2.21	2.07	0.85	0.77	0.84	0.78
0.87	0.83	0.78	0.70	2.68	2.55	2.40	2.17	2.52	2.39	2.45	2.27	0.82	0.77	0.79	0.73
0.86	0.82	0.77	0.70	2.20	2.08	1.95	1.78	2.10	2.09	2.01	1.92	0.82	0.82	0.79	0.75
0.86	0.83	0.78	0.71	2.96	2.83	2.67	2.43	2.82	2.82	2.72	2.47	0.82	0.82	0.80	0.72
0.84	0.81	0.76	0.69	3.12	2.99	2.82	2.57	3.05	2.91	2.93	2.90	0.82	0.78	0.79	0.78
				(1) 2.57	2.53	2.38	2.28	(1) 2	2.42	2.37	2.25				
				(2) 0.47	0.46	0.46	0.36	(2) 0	0.46	0.46	0.48				
				* - missing data											
								(3) 4	4.27	0.67	1.48				

Table 77. continued.

(v)					(vi)			
Calculated reduction ratios					calculated wind speeds			
point (0,0) included					point (0,0) included			
case 1 +0		a=0.97	b=0.02		case 1 +0		a=0.97b=0.02	
cup14	cup15	cup38	cup39		cup14	cup15	cup38	cup39
0.99	1.02	0.99	0.85		2.15	2.22	2.15	1.85
0.90	0.99	0.90	0.78		1.77	1.95	1.78	1.54
0.79	0.81	0.88	0.76		2.21	2.24	2.46	2.12
1.00	1.01	0.95	0.95		2.98	2.99	2.82	2.81
0.88	0.85	0.85	0.78		2.80	2.70	2.71	2.49
0.95	0.86	0.86	0.81		2.84	2.55	2.55	2.42
0.98	0.86	0.89	0.84		3.28	2.89	2.96	2.80
0.77	0.76	0.87	0.74		2.50	2.47	2.83	2.39
0.97	0.97	0.84	0.86		3.37	3.38	2.91	2.99
0.90	0.91	0.82	0.78		2.73	2.76	2.50	2.36
0.86	0.76	0.83	0.73		2.79	2.49	2.70	2.39
0.83	0.82	0.80	0.74		3.06	3.01	2.95	2.71
0.66	0.90	0.84	0.79		1.22	1.66	1.55	1.46
0.89	1.01	0.84	0.64		1.29	1.47	1.22	0.93
1.20	1.00	0.90	0.58		2.83	2.35	2.13	1.37
1.13	1.23	0.86	0.84		3.22	3.52	2.44	2.39
1.14	1.02	0.90	0.89		2.31	2.08	1.82	1.81
1.02	0.95	0.90	0.91		2.89	2.68	2.54	2.56
0.89	0.95	0.86	0.77		2.35	2.49	2.25	2.01
0.86	0.71	0.84	0.74		2.28	1.89	2.21	1.95
0.80	0.72	0.76	0.65		2.47	2.23	2.34	2.01
0.82	0.81	0.75	0.69		2.07	2.07	1.91	1.75
0.81	0.81	0.76	0.63		2.79	2.79	2.61	2.15
0.81	0.74	0.75	0.74		3.01	2.75	2.78	2.74
				(1)	2.55	2.48	2.38	2.17
				(2)	0.56	0.49	0.45	0.51
				(3)	0.86	1.86	0.09	5.10

Table 78. Cup 38 as reference. (i) case 2-0: calculated wind speeds with with zero excluded. (ii) case 2 -0: calculated wind speeds with point excluded. (iii) case 2 +0: wind reduction ratios calculated (iii) case 2 +0: wind reduction ratios from calculated wind speeds with zero point included: (iv) case 2 +0: calculated wind speeds with zero point included:

(i)				(ii)			
calculated reduction ratios				calculated wind speeds			
point (0,0) not included				point (0,0) not included			
case 2 -0	a=0.86 b=0.11			case 2 -0	a=0.86 b=0.11		
cup 38 as refence				cup 38 as refence			
cup14	cup15	cup38	cup39	cup14	cup15	cup38	cup39
0.97	1.00	0.97	0.85	2.05	2.11	2.05	1.79
0.97	1.05	0.97	0.85	1.72	1.88	1.73	1.52
0.88	0.89	0.97	0.85	2.21	2.24	2.43	2.12
1.02	1.02	0.97	0.97	2.90	2.91	2.76	2.75
1.00	0.97	0.97	0.90	2.75	2.66	2.67	2.47
1.07	0.97	0.97	0.93	2.80	2.53	2.53	2.42
1.06	0.95	0.97	0.92	3.07	2.74	2.80	2.66
0.87	0.86	0.97	0.83	2.40	2.38	2.68	2.30
1.11	1.11	0.97	0.99	3.30	3.31	2.89	2.96
1.05	1.06	0.97	0.92	2.68	2.71	2.47	2.35
1.00	0.90	0.97	0.87	2.66	2.40	2.58	2.31
1.00	0.99	0.97	0.90	2.98	2.94	2.89	2.68
0.78	1.03	0.97	0.92	1.22	1.61	1.52	1.44
1.03	1.15	0.97	0.76	1.28	1.44	1.21	0.95
1.26	1.06	0.97	0.66	2.65	2.25	2.04	1.30
1.25	1.36	0.97	0.95	3.05	3.31	2.37	2.32
1.21	1.10	0.97	0.96	2.09	1.90	1.69	1.67
1.09	1.02	0.97	0.98	2.64	2.46	2.34	2.36
1.01	1.07	0.97	0.88	2.23	2.36	2.15	1.95
1.00	0.84	0.97	0.87	2.18	1.83	2.11	1.89
1.02	0.93	0.97	0.85	2.45	2.23	2.33	2.03
1.04	1.04	0.97	0.89	2.04	2.03	1.89	1.74
1.03	1.03	0.97	0.82	2.75	2.75	2.59	2.18
1.04	0.96	0.97	0.96	2.95	2.71	2.74	2.70
				(1) 2.46	2.40	2.31	2.12
				(2) 0.53	0.47	0.44	0.49
				(3) 4.37	5.07	3.00	7.04

(iii)				(iv)			
calculated reduction ratios				calculated wind speeds			
point (0,0) included				point (0,0) included			
case 2 +0	a=0.99 b=0.00			case 2 +0	a=0.99b=0.00		
cup 38 as refence				cup 38 as refence			
cup14	cup15	cup38	cup39	cup14	cup15	cup38	cup39
0.99	1.02	0.99	0.85	2.09	2.16	2.09	1.80
0.98	1.09	0.99	0.86	1.76	1.94	1.77	1.53
0.89	0.90	0.99	0.85	2.22	2.26	2.48	2.13
1.05	1.05	0.99	0.99	2.98	2.99	2.82	2.81
1.02	0.99	0.99	0.91	2.82	2.72	2.72	2.50
1.11	0.99	0.99	0.94	2.89	2.59	2.59	2.45
1.10	0.97	0.99	0.93	3.16	2.79	2.86	2.70
0.87	0.86	0.99	0.83	2.41	2.39	2.74	2.30
1.15	1.15	0.99	1.02	3.42	3.43	2.95	3.03
1.09	1.10	0.99	0.93	2.77	2.79	2.52	2.38
1.02	0.91	0.99	0.87	2.72	2.42	2.64	2.32
1.03	1.01	0.99	0.91	3.06	3.00	2.95	2.70
0.77	1.06	0.99	0.93	1.21	1.66	1.55	1.4
1.05	1.20	0.99	0.75	1.32	1.50	1.24	
1.32	1.10	0.99	0.63	2.76	2.30	2.08	
1.31	1.44	0.99	0.97	3.20	3.50	2.42	
1.26	1.13	0.99	0.98	2.19	1.97	1.72	1.7
1.13	1.05	0.99	1.00	2.73	2.53	2.39	2.4
1.03	1.10	0.99	0.88	2.29	2.44	2.19	1.9
1.02	0.84	0.99	0.87	2.23	1.83	2.16	1.9
1.05	0.94	0.99	0.85	2.51	2.27	2.38	2.0
1.07	1.07	0.99	0.90	2.10	2.09	1.93	1.7
1.06	1.06	0.99	0.81	2.83	2.83	2.64	2.1
1.08	0.98	0.99	0.97	3.04	2.76	2.80	2.
				(1) 2.53	2.47	2.36	2.
				(2) 0.56	0.50	0.45	0.
				(3) 1.64	2.63	1.00	6.

The closeness of measured and calculated wind speeds for both positions (cup 55 and cup 30) as references suggests that a under semi-arid environment like Matanya there was hardly any difference change in air temperatures and air humidities over such a short distance of about 80 m. Indications, however, show that taking one of the cups in NF (in this case cup 30) as a reference we could get calculated wind speeds very close to the measured wind speeds as compared to the earlier used method of taking a reference position in the open.

4.4 Results on radiation and *Grevillea robusta* shading in AF

4.4.1 General

Although agroforestry systems may be considered a feasible alternative in dry-land farming, competition between crop and trees for resources such as soil moisture, sunlight and nutrients affects seed and biomass yields of the crop component. The aim of quantifying the shade effects of two representative *Grevillea robusta* trees (UT1 & PT2) on the under-crop at Matanya was to identify sectors around the trees where their shades concentrate for most of the maize (and bean) crop growing season and to mathematically relate the yields in that sector(s) to radiation received there. This may enable us to better understand the role of tree shading in yield reduction or yield improvement in an agroforestry system. We hypothesize that in dry months under semi-arid conditions, such as in Matanya, tree shades may have beneficial (protective) effects for growing crops with respect to reducing excessive water loss through evaporation and decrease water stress. The *Grevillea* tree shades may protect the intercrop from too high radiation load and accompanying high temperatures leading to yield improvement in shaded areas. However, in wet months we suspect that shade may be too heavy and plants may not be able to receive all the PAR that it can use which may lead to growth impairment. We need to establish which of the two (yield reduction or yield improvement) was stronger in the case of Matanya AF. We started by first standardizing the radiometers by intercomparing them in the open.

4.4.2 Comparison of thirteen tube solarimeters and two Kipp solarimeters in the open in October, 1991

Figs. 284-286 show daily tube and Kipp solarimeter readings during the intercomparison period (i.e. 20/10/91-31/10/91) in the open. We can see from Figs. 284-286 that the tubes for 94, 188 and 376 cm from UT1 gave almost identical radiation readings with Tb & kp2. All solarimeters were giving similar readings within ±0.2% of the average. using the calibration constants of the manufacturers.

Figs. 287 & 288 present regression constants of Tb (Sr. Nr. 2087) and kp2 (Sr Nr. 2091) on kp1 (Sr. Nr. 3080) of the daily solar radiation data. Regression equations derived during calibration exercise for the solarimeters for use in open as standard and substandard (in case of Tb) were as follows: Tb on kp1 was Tb= -0.22+ 1.01*kp1 (r=99.96%); kp2 on kp1 was kp2= -0.31+1.01*kp1 (r=99.93%) while Tb on kp2 was Tb=0.10+1.00*kp2 (r=99.89%). The gradients of the two equations were the same but their intercepts differed by 28.2% (Fig. 287). That meant that kp1 responded to solar radiation at a lower initial value than both Tb and kp2 radiometers. Fig. 288 shows that Tb is directly related to kp2 by the ratio 1:0.998 ≈ 1:1. The Tb responded to solar radiation at a lower initial value than kp2. by 0.1 Mwm^{-2}. The Tb was fairly more sensitive to radiation in its off-set value but closer to kp2 than kp1.

The canopy of the tall UT1 tends to intercept PAR before it can reach the shorter maize/beans intercrop. This has negative yield implications. as long as other resources like water; nutrients are not limiting. However. the shade beneficial effect. that is a protective (for the intercrop) or complementary (tree yield) effect to the maize/beans intercrop may be expected to be high in the sector where tree shading was maximum because of limiting water and nutrients

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We have already seen in section 3.1 that maize total biomass harvesting was done row-by-row. The separation distance between maize rows was 94 cm. The maize yields obtained in the first row on either side of the tree rows were taken to correlate with light that was representatively measured in a straight line 94 cm from UT1. Similarly for the maize yields at 188 cm and the third and fourth rows at 282 and 376 cm respectively from the tree rows. The effect of radiation falling on a straight line passing 94 cm from the tree therefore were matched to the yields. The TSLs were installed at 94, 188 and 376 cm. Because radial yields could not be taken, the effect of radiation falling on a circle 94 cm from the tree was therefore correlated with the yields of the row passing at 94 cm as the best approximation of yields depending on shade.

4.4.3 Solar radiation received by intercrop under UT1 during SR91:

Effect of UT1 shade on daily radiation totals.

Variations of daily total radiation, that is at 94 cm from UT1 ((NE)1, (SE)1, (SW)1 and (NW)1), at 188 cm from UT1 ((NE)2, (SE)2, (SW)2 and (NW)2 and at 376 cm from UT1 ((NE)3, (SE)3, (SW)3 and (NW)3) are displayed in the Appendix Figs. A6-A26, for the periods of November and December 1991, April and May 1992 and October-November 1992. We observe from the variations in these figures that total radiation was affected by the UT1 canopy shade and its position with respect to the tree stem in different seasons, superimposed on the seasonal and daily fluctuations of incoming solar radiation.

We here below deal in detail with the effect of radiation totals on the maize under the UT1 canopy and PT2 canopy using the radiation received by maize plants at 94, 188 and 376 cm as fraction of the radiation in the open, herein referred to as fractional radiation.

4.4.3 (a) Fractional radiation received by the inter-crop in November

Reifsnyder (1989) contends that transmission of solar radiation through tree canopies in the middle latitudes is not linear when looked at as function of crown closure or tree density but near linear (or nearly linear) in the tropics. He found that a stand with 50% crown closure transmitted less than 20% of the incident solar radiation, a rather open stand with only 10% crown closure reduced radiation reaching the ground by about 25%. From these findings he concluded that sparse stands would offer considerable protection from excessive radiation loads. On the other hand a crown closure of only 1/3, a rather open stand, would reduce radiation by 2/3 (to be precise roughly 60%) which might result in too little radiation for some crops.

The solar radiation which was recorded by the tube solarimeter in the open (Tb) is equal to that which fell on the top of the *Grevillea* canopy. Total solar radiation transmission (penetration) to the under-crop was taken to be the sum of radiation which missed the trees completely to reach the ground (or intercrop) and that which passed through the tree canopies according to Eq. 13. The total fraction was the radiation read by the tube solarimeters (TSLs) under the tree

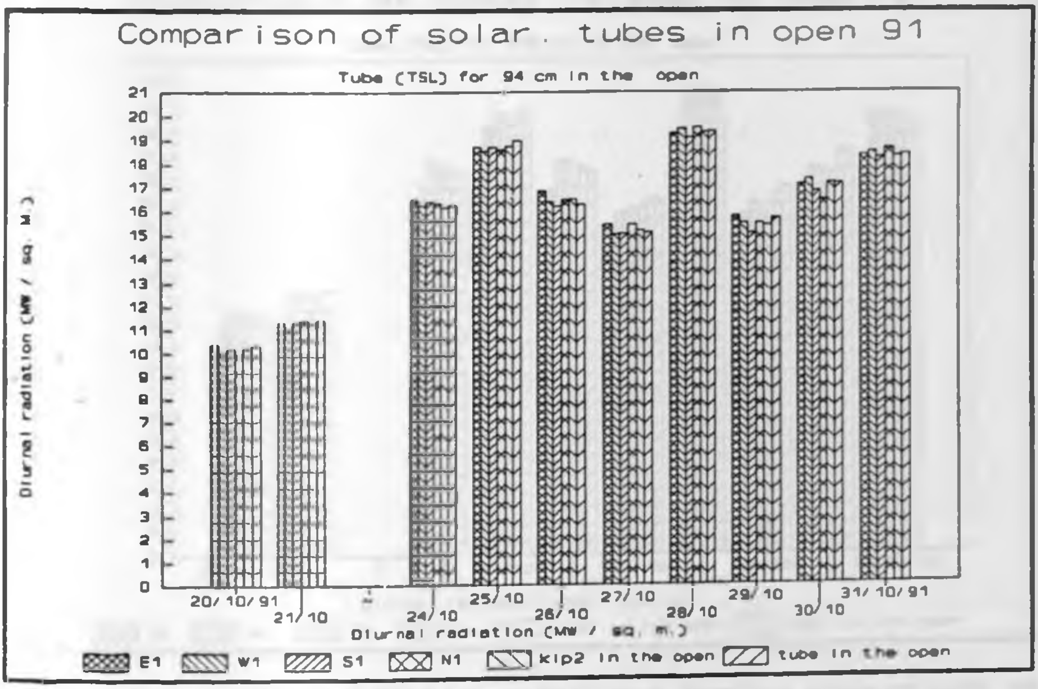


Fig. 284. Solar radiation readings during comparison of TSLs in the open in October 1991 for TSLs to be installed at 94 cm from experimental *Grevillea robusta* tree.

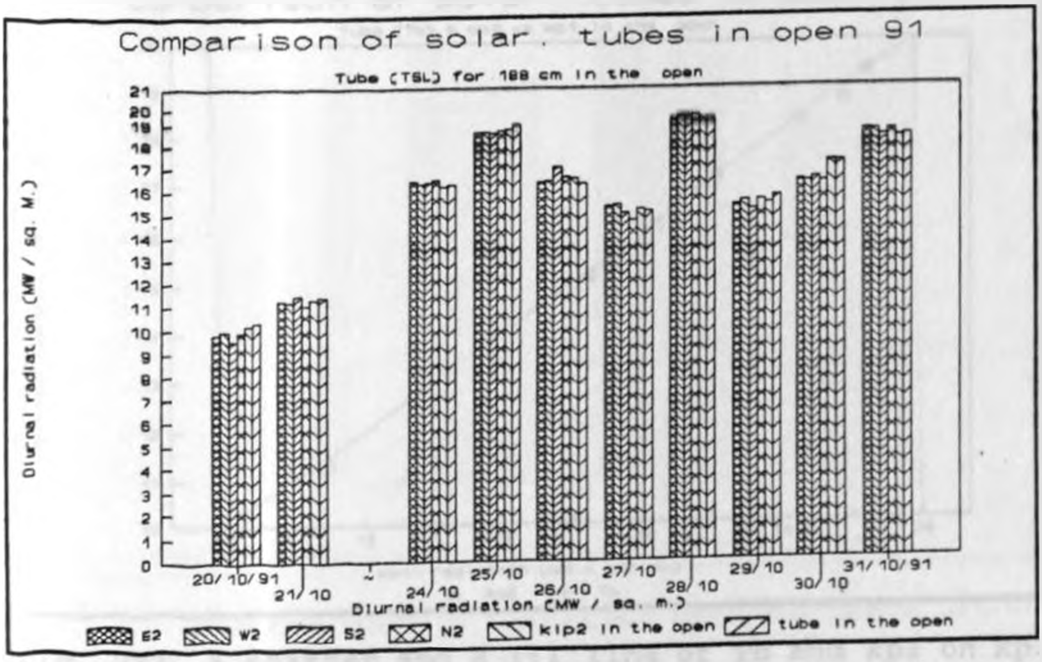


Fig. 285. Solar radiation readings during comparison of TSLs in the open in October 1991 for TSLs to be installed at 188 cm from experimental *Grevillea robusta* tree.

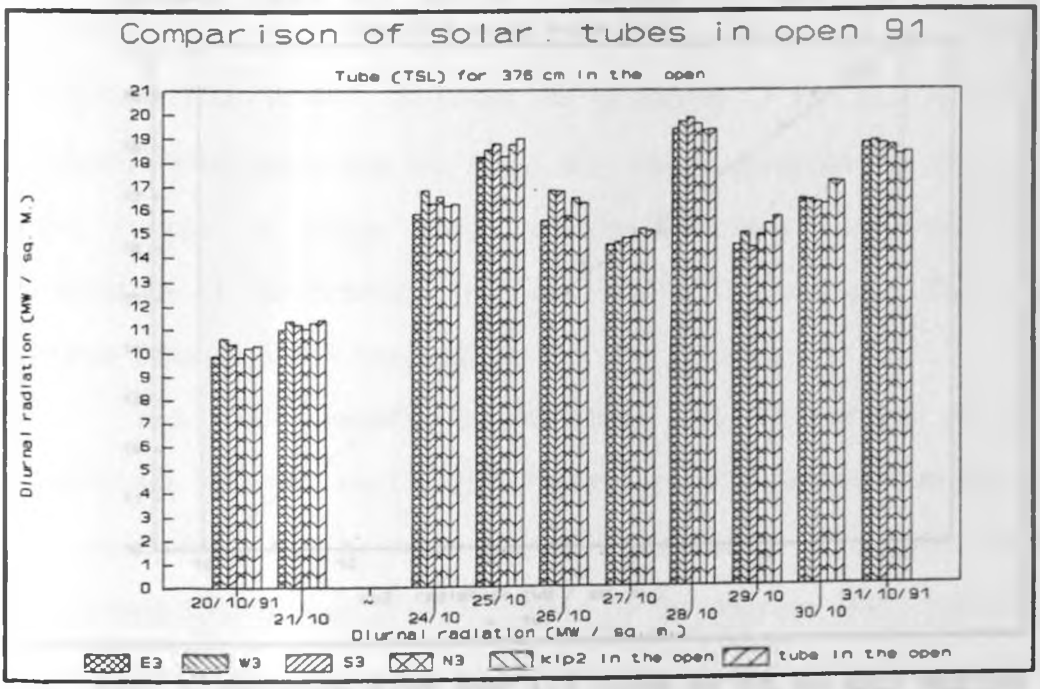


Fig. 286. Solar radiation readings during comparison of TSLs in the open in October 1991 for TSLs to be installed at 376 cm from experimental *Grevillea robusta* tree.

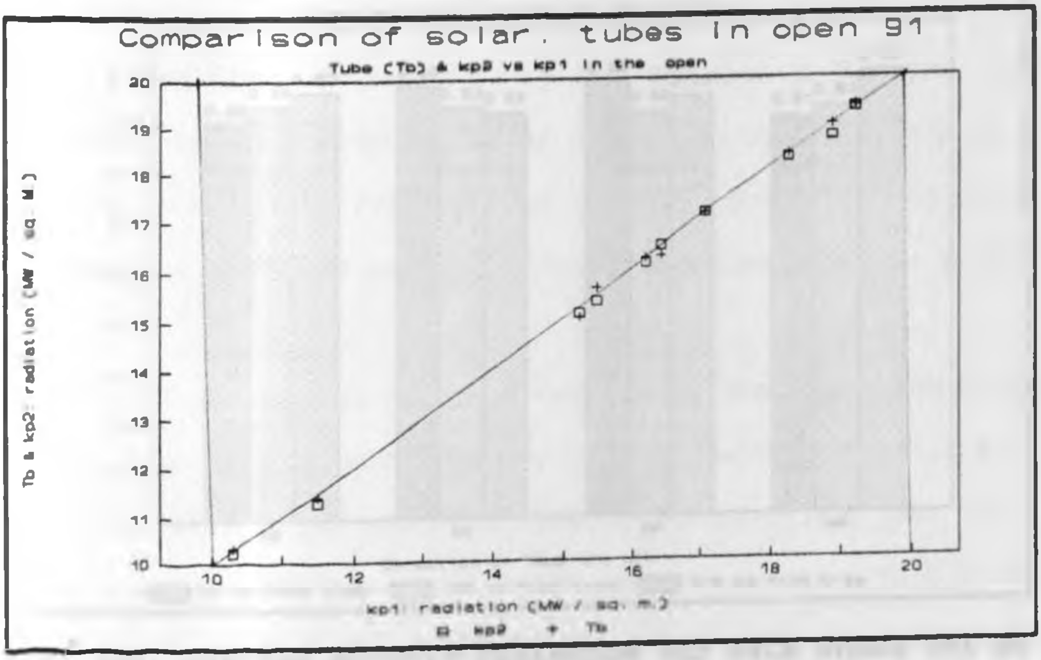


Fig. 287. A scatter and a 1:1 line of Tb and kp2 on kp1 during comparison in the open in October 1991.

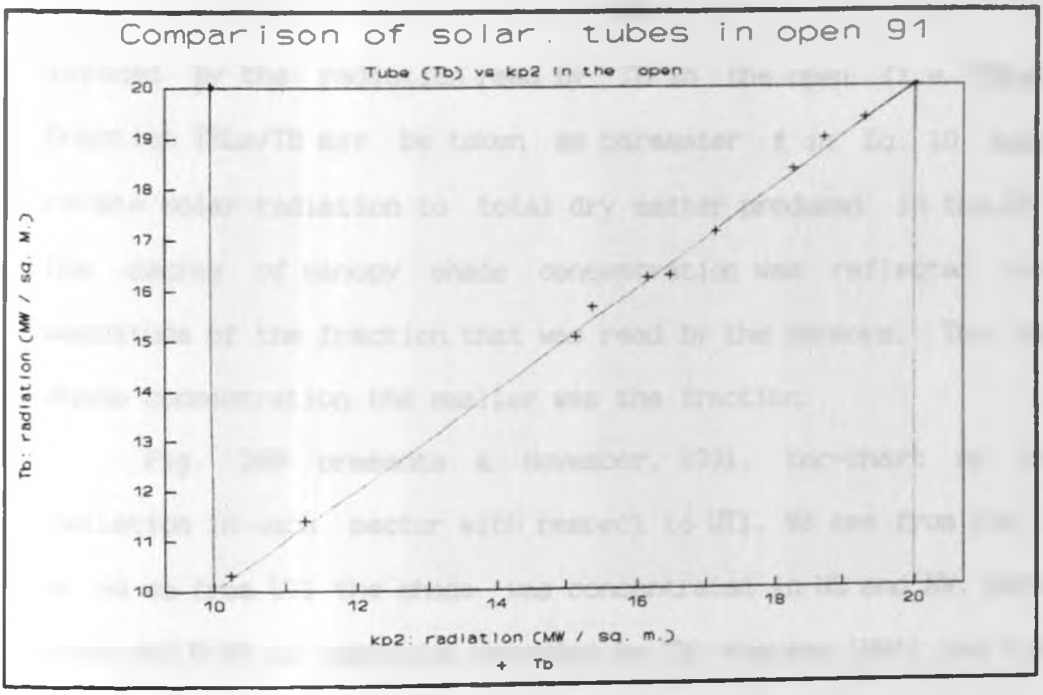


Fig. 288. A scatter plot and 1:1 line of Tb on kp2 during comparison in the open in October 1991.

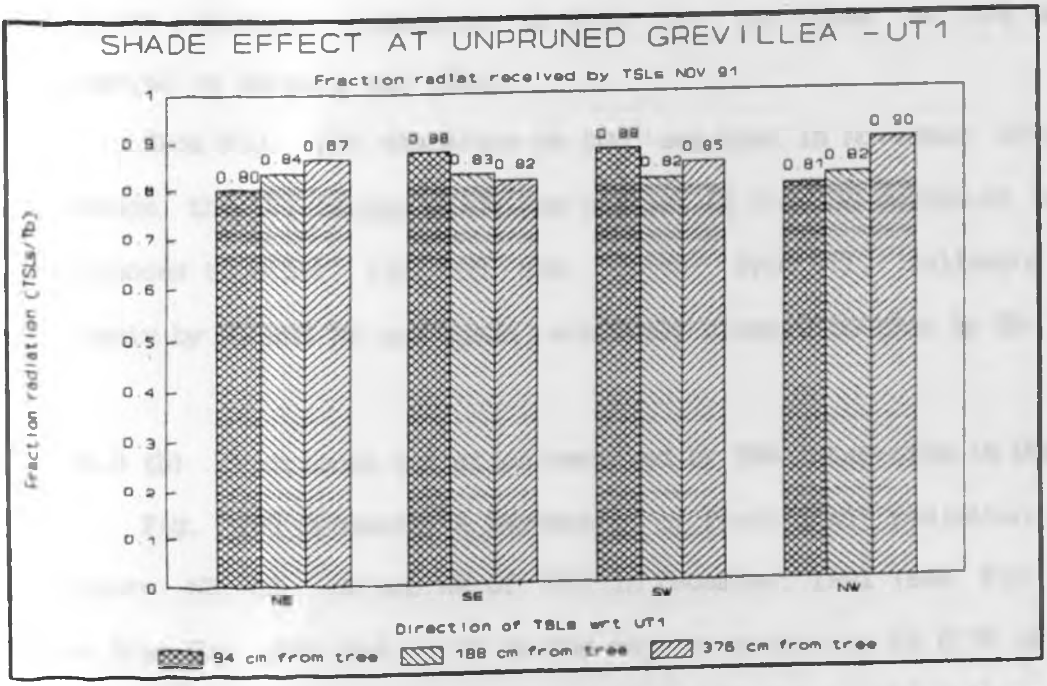


Fig. 289. Average monthly radiation for TSLs under UT1 as fractions of radiation read with Tb in the open area (fractional radiation) during November 1991.

divided by the radiation read by Tb in the open (i.e. TSLs/Tb). The fraction TSLs/Tb may be taken as parameter **f** in Eq. 10 and used to relate solar radiation to total dry matter produced in the AF system. The degree of canopy shade concentration was reflected in relative magnitude of the fraction that was read by the sensors. The higher the shade concentration the smaller was the fraction.

Fig. 289 presents a November. 1991. bar-chart of fractional radiation in each sector with respect to UT1. We see from Fig. 289 that at 94 cm from UT1 the shade was concentrated in NE and NW. Sector (NE)1 received 0.80 of radiation recorded by Tb. whereas (NW)1 had 0.81. while the other sections received 0.88. Maximum fractional radiation reduction to 0.82 for the tubes at 188 cm was observed in sectors (SW)2 and (NW)2. but here (SE)2 and (NE)2 remained also with 0.83 and 0.84. The highest radiation reduction to 0.82 for the tubes at 376 cm was observed in sectors and (SE)3.

From Fig. 289 therefore we can see that in November 1991 on the average the UT1 canopy shade was highest in the NE sector at the three distances together (94. 188 and 376 cm) from UT1. following rather closely by SE and NW and again relatively closely to that by SW.

4.4.3 (b) Fractional radiation received by the inter-crop in December

Fig. 290 presents a bar-chart of fractional radiation in four sectors: NE. SE. SW and NW of UT1 in December. 1991 (see Fig. 11). We see from Fig. 290 that at 94 cm the highest reduction to 0.76 of that in the open was in (NW)1 of UT1 which also had a similar reduction for (NW)2 at 188 cm. NE received 0.80 of radiation in the open through the canopy. Thus the canopy shade was concentrated mainly in area between NE and NW. SW Sector also received low radiation rates only at 188 cm. In

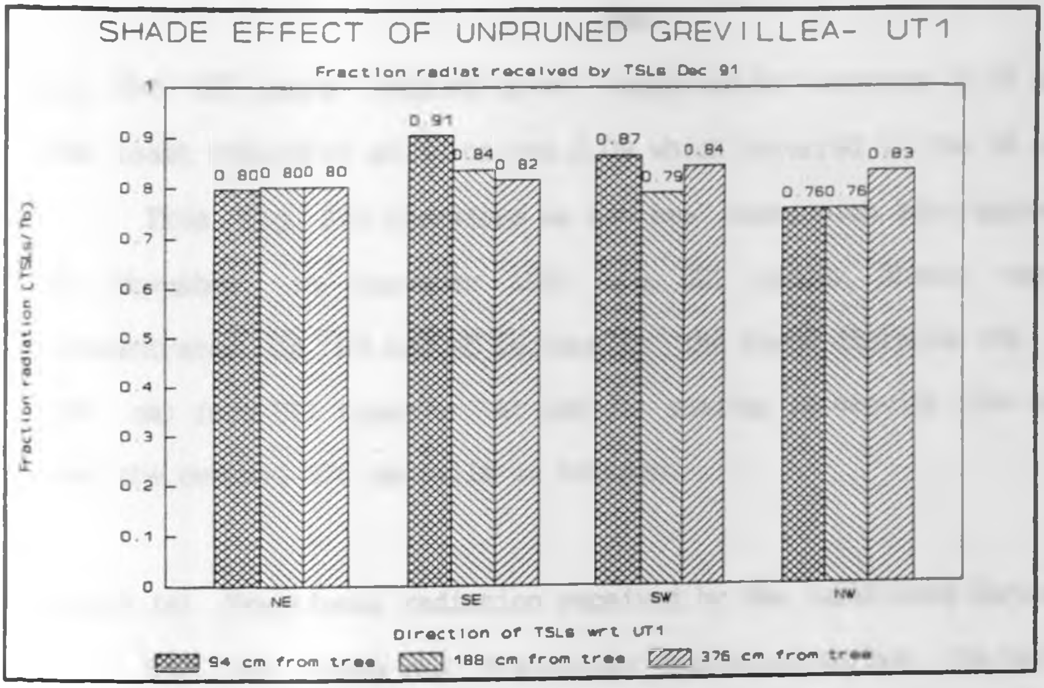


Fig. 290. Average monthly radiation for TSLs under UT1 as function of fractional radiation during December 1991.

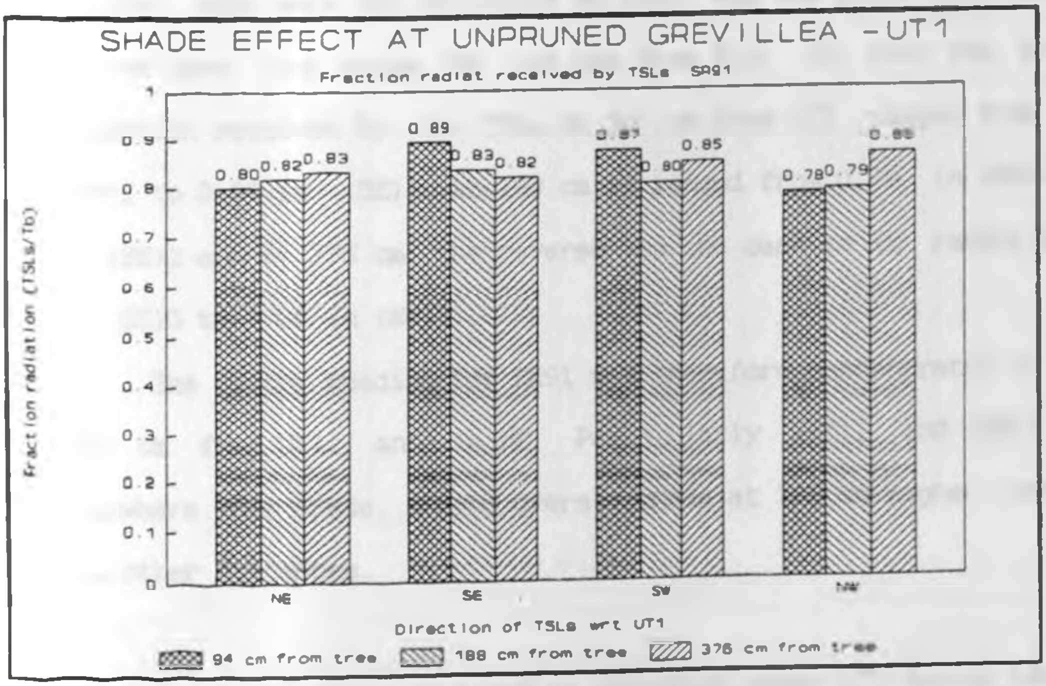


Fig. 291. Average fraction radiation of Short Rains 1991 (SR91) for TSLs under UT1.

all the UT1 canopy reduced solar radiation by between 0.09 and 0.24. The least reduction at 94 cm was 0.09 which occurred in the SE sector.

From Fig. 290 therefore we can see that, with more emphasis than in November, in December 1991 the UT1 canopy shade was rather concentrated in NW and NE sectors at the three distance (94, 188 and 376 cm) from UT1 together. At 188 cm shading is heavier than at 94 cm, and the overall 376 cm falls in between.

4.4.3 (c) Fractional radiation received by the inter-crop during SR91

Fig. 291 gives the fractional radiation during the maize crop growing period. The growing period does not cover January since the crop will have stopped growing as it will have reached maturity. At that stage radiation will have no effect on dry matter accumulation. The October data were not available as that was the month when calibration in the open took place. We can see from Fig. 291 that the fractional radiation received by the TSLs at 94 cm from UT1 ranged from 0.78 in (NW)1 to 0.89 in (SE)1. At 188 cm it ranged from 0.79 in (NW)2 to 0.83 in (SE)2 and at 376 cm the reverse was the case as it ranged from 0.82 in (SE)3 to 0.86 in (NW)3.

The canopy shading for SR91 was therefore concentrated in NW up to 188 cm from UT1, and in NE. Particularly (SE)1 and (SW)1 receive somewhere less shade, making overall shade at 188 cm higher than at the two other distances.

4.4.4 Solar radiation received by intercrop under UT1 during LR92

4.4.4 (a) Fractional radiation received by the inter-crop in April

Fig. 292 shows a bar-chart of fractional radiation in each sector of UT1 in April, 1992 (Fig. 11). We see from Fig. 292 that at 94 cm the

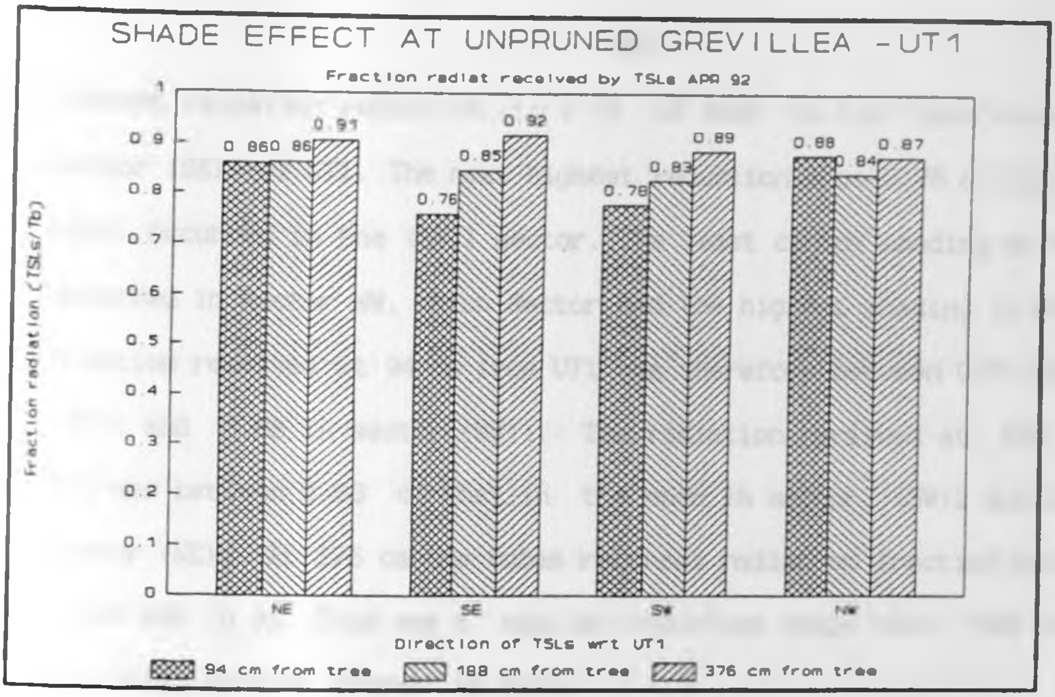


Fig. 292. Average monthly radiation for TSLs under UT1 as function of fractional radiation during April 1992.

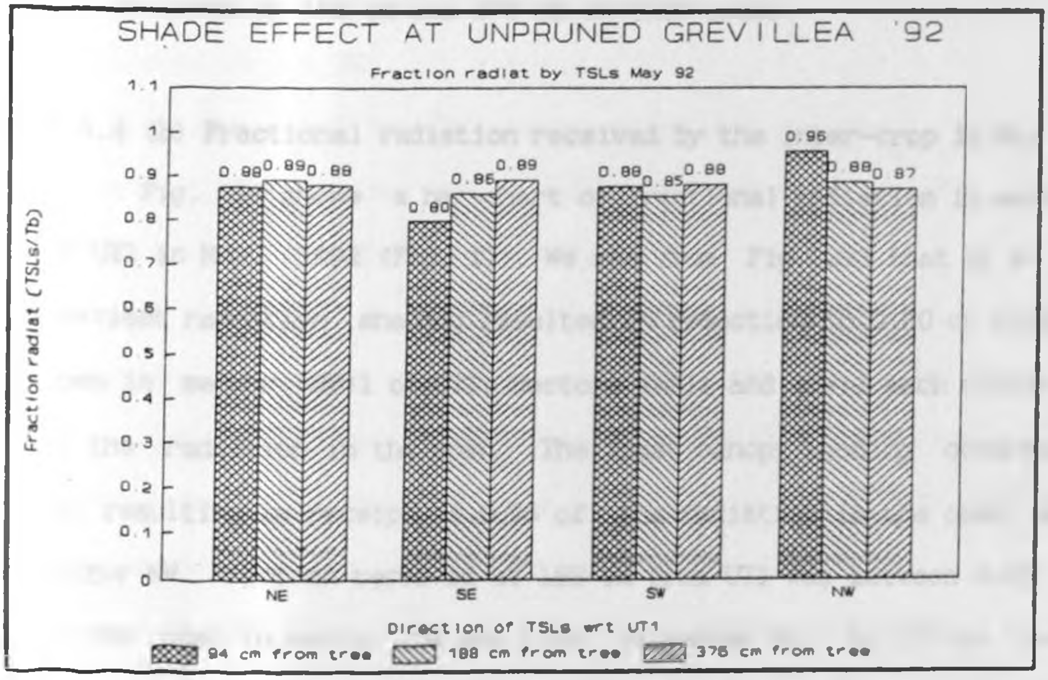


Fig. 293. Average monthly radiation for TSLs under UT1 as function of fractional radiation during May 1992.

highest radiation reduction to 0.76 of that in the open occurred in sector (SE)1 of UT1. The next highest reduction, to 0.78 of that in the open, occurred in the (SW)1 sector. The least canopy shading at 94 cm occurred in sector NW, which Sector had the highest shading in SR91. The fraction received at 94 cm from UT1 was therefore between 0.76 in sector (SE)1 and 0.88 in sector (NW)1. The radiation received at 188 cm from UT1 was between 0.83 of that in the open in sector (SW)2 and 0.86 in sector (NE)2. At 376 cm the tubes recorded radiation fraction between 0.87 and 0.92. This was a smaller reduction range than that recorded for this distance overall in SR91.

Thus the *Grevillea robusta* (UT1) canopy shade was heaviest in the area between SW and SE sectors (Fig. 292), and clearly heaviest at 94 cm, followed by 188 cm and 376 cm in that order.

4.4.4 (b) Fractional radiation received by the inter-crop in May

Fig. 293 shows a bar-chart of fractional radiation in each sector of UT1 in May, 1992 (Fig. 11). We see from Fig. 293 that at 94 cm the heaviest radiation shading resulted in reduction to 0.80 of that in the open in sector (SE)1 of UT1. Sectors (NE)1 and (SW)1 each received 0.88 of the radiation in the open. The least canopy shading occurred at 94 cm, resulting in receipt of 0.96 of the radiation in the open, again in sector NW. Fraction received at 188 cm from UT1 was between 0.85 of that in the open in sector SW and 0.89 in sector NE. At 376 cm the tubes recorded radiation between 0.87 and 0.89 in sectors NW and SE respectively.

In the month of May, 1992 the *Grevillea robusta* (UT1) canopy shade was overall heavier in the SE sector between 94 and 188 cm, followed by

SW (over all distances) (Fig. 293). Differences between distances were overall very small, with 188 cm getting a bit more shade than the other two distances.

4.4.4 (c) Fractional radiation received by the inter-crop in June

Fig. 294 presents the results of fractional radiation received in each sector of UT1 in June, 1992. We see from Fig. 294 that at 94 cm the heaviest radiation shading resulted in reduction to 0.81 of the radiation in the open in sector SE of UT1. The least canopy shading averred at 94 cm, resulting in receipt of 0.92 of the radiation in the open, again in sector NW. Fractional radiation received at 188 cm from UT1 was between 0.81 of that in the open in sector SE and 0.89 in sector NW. At 376 cm the tubes recorded radiation between 0.87 in NE and 0.91 in sectors SW and SE.

In June, 1992 the UT1 canopy shade was heavier in the SE and NE sectors at the distance of up to 188 cm from the tree (Fig. 294), with 188 cm getting somewhat some share.

4.4.4 (d) Fractional radiation received by the inter-crop during LR92

Fig. 295 gives the fractional radiation during the maize crop growing period in the LR92 season. We can see from Fig. 295 that the fractional radiation received by the TSLs was the lowest in sector SE at 94 cm from UT1. The fractional radiation received ranged from 0.79 in SE to 0.92 in NW sectors. At 188 cm it ranged with little change from 0.84 in both SE and SW to 0.87 in both NE and NW. At 376 cm again the reverse was the case as the fractional radiation of 0.90 in SE was the highest while lowest of 0.87 was recorded in NW, but differences were small again.

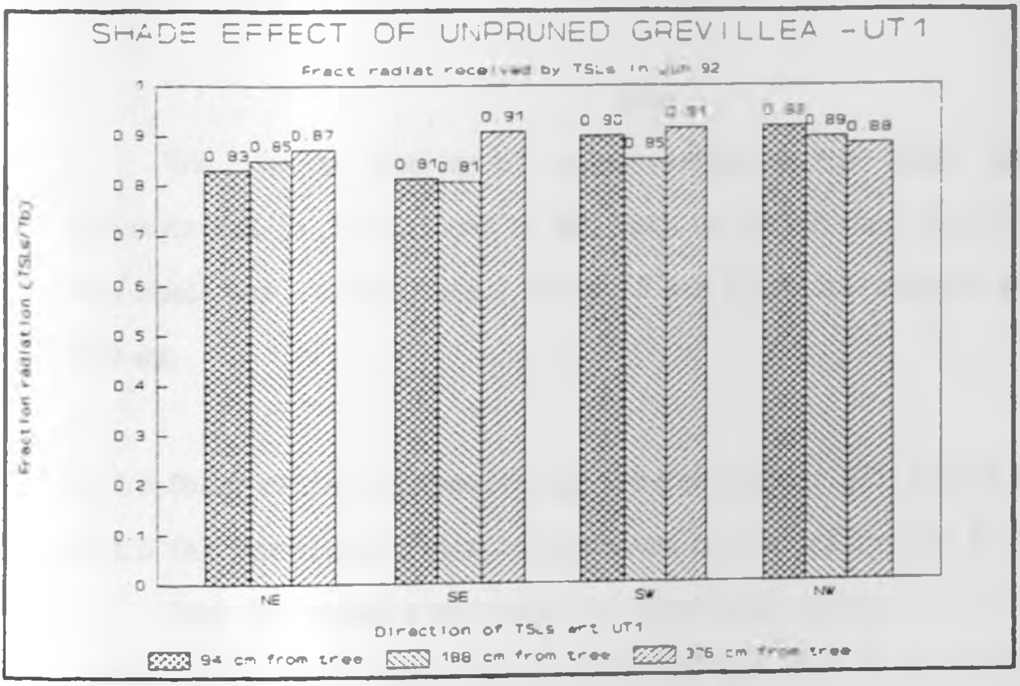


Fig. 294. Average monthly radiation for TSLs as function of fractional radiation under unpruned *Grevillea robusta* tree (UT1) during June 1992.

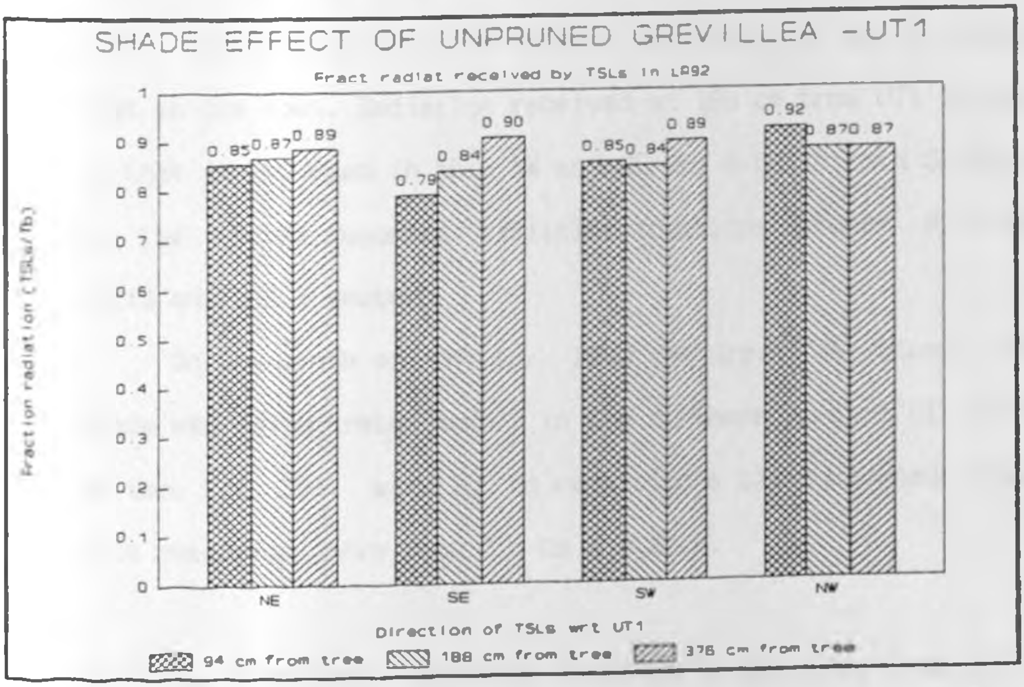


Fig.295. Average monthly radiation for TSLs as function of fractional radiation under unpruned *Grevillea robusta* tree (UT1) for the entire LR92.

The canopy shading of solar radiation for LR92 was therefore concentrated in SE followed by SW, both up to 188 cm from UT1. At 376 cm the shade was clearly less, while it was identical overall at 94 cm and 188 cm.

4.4.5 Solar radiation received by intercrop under UT1 during SR92

4.4.5 (a) Fractional radiation received by the inter-crop in October

Fig. 296 shows a bar-chart of fractional radiation in each sector of UT1 in October, 1992. We see from Fig. 296 that at 94 cm from UT1 the heaviest shading shifted to sector (NE)1 resulting in a receipt of 0.76 of the radiation in the open. Sectors (NW)1 and (SE)1 received 0.80 and 0.84 of the radiation in the open. The position of least canopy shading at 94 cm also shifted to SW which received 0.88 of that in the open. Radiation received at 188 cm from UT1 lay between 0.80 of that in the open in both NW and NE and 0.82 in both SE and SW. At 376 cm the tubes recorded radiation fractions between 0.84 and 0.89 in (NE)3 and (SW)3 sectors.

In the month of October, 1992 the *Grevillea robusta* (UT1) canopy shade was concentrated mainly in the northern part of UT1 between NE and NW (see Fig. 296), with 188 cm receiving a bit more shade than 94 cm but both comparably more than 376 cm distance.

4.4.5 (b) Fractional radiation received by the inter-crop in November

Fig. 297 shows a bar-chart of fractional radiation in the four sectors of UT1 in November, 1992. We can see from Fig. 297 that at 94 cm from UT1 the heaviest radiation shading was in the NE sector, which had 0.84 of its value in the open. Other sectors had much lighter canopy

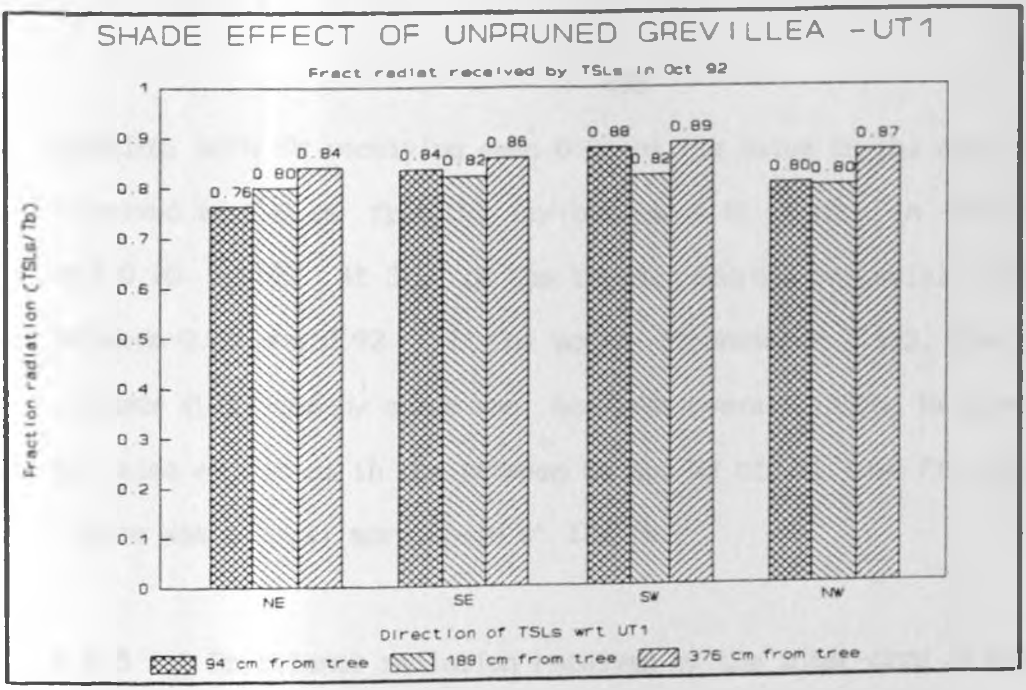


Fig. 296. Average monthly radiation for TSLs under UT1 as function of fractional radiation during October 1992

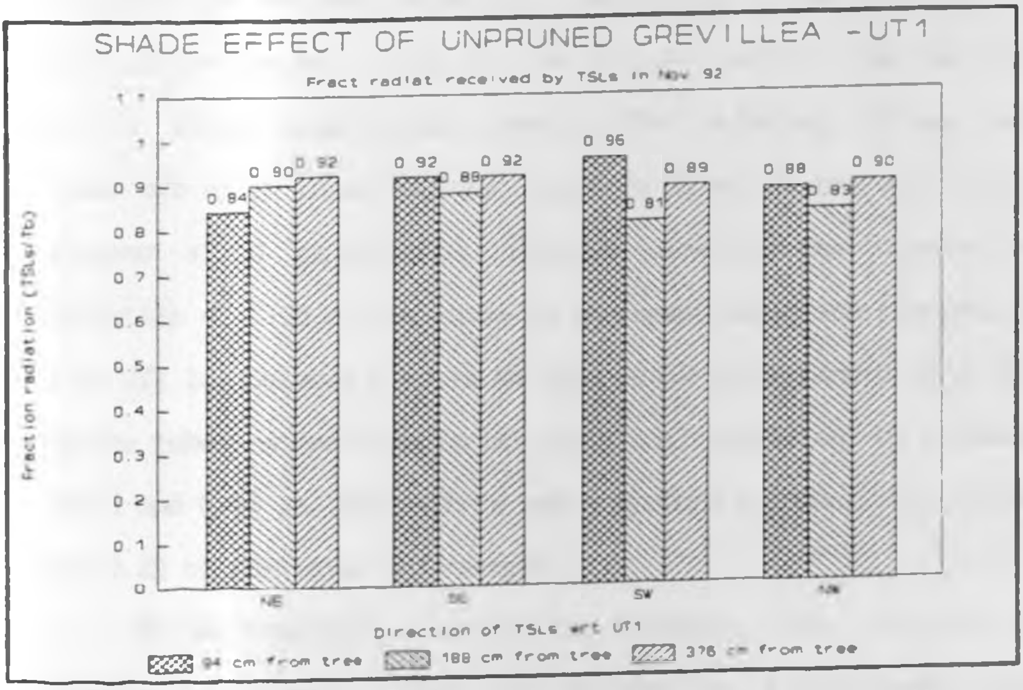


Fig. 297. Average monthly radiation for TSLs under UT1 as function of fractional radiation during November 1992.

shading, with SW receiving even 0.96 of its value in the open. Radiation received at 188 cm from UT1 lay between 0.81 of that in the open in SW and 0.90 in NE. At 376 cm the tubes recorded sectorial radiation of between 0.89 and 0.92. In the month of November, 1992, the *Grevillea robusta* (UT1) canopy shade was heaviest overall in the NW part of UT1, but also at 188 cm in the between SW and NW of UT1 (see Fig. 297). There was overall more shade at 188 cm.

4.4.5 (c) Fractional radiation received by the inter-crop in December

Fig. 298 displays a bar-chart of fractional radiation in the four sectors of UT1 in December, 1992. We can see from Fig. 298 that at 94 cm from UT1 the heaviest radiation shading was in the NE sector which had 0.83 of its amount in the open. We notice from Fig. 298 that the centre of UT1 canopy shading has moved to 188 cm NW and SW and extended to cover 376 cm in those sectors. Sectors SE and SW had very light canopy shading at 94 cm distance, with SW receiving the highest fractional radiation of 0.93 of its value in the open. Radiation received at 188 cm from UT1 lay between 0.80 in NW (and 0.82 in SW) and 0.92 in SE. At 376 cm the tubes recorded sectorial fractional radiation of between 0.78 in (SE)3 and 0.93 in (NE)3. There was therefore a reduction of between 0.07 and 0.22 of its value in the open.

We can therefore conclude for December, 1992, that the *Grevillea robusta* (UT1) canopy shade was heaviest in the northern and western parts of UT1 between 188 and 376 cm (see Fig. 298), which overall received close to the same shade.

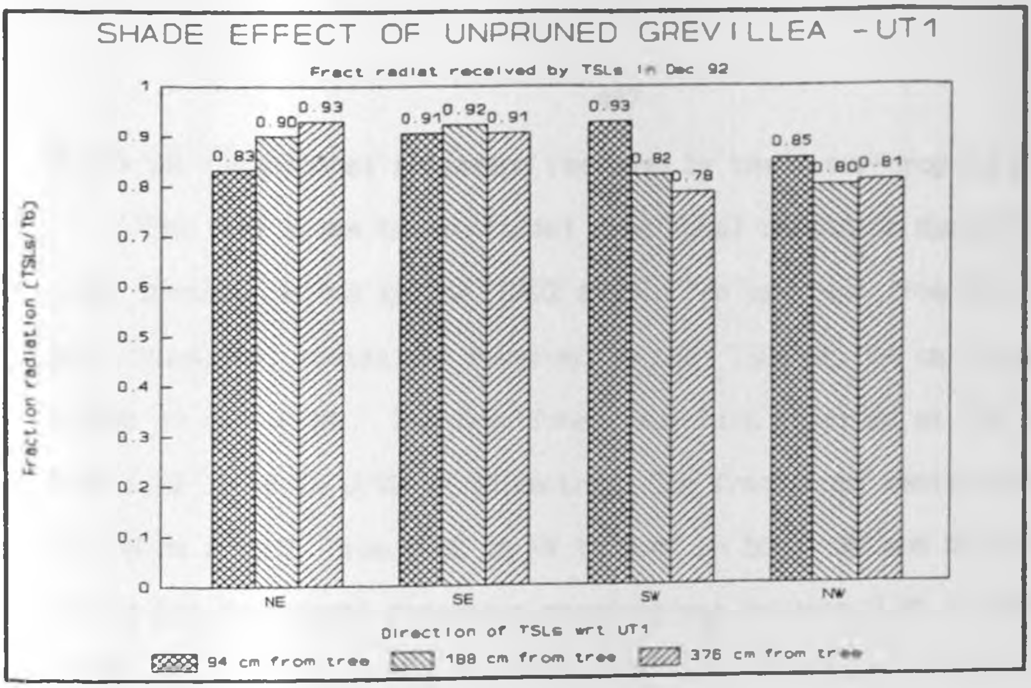


Fig. 298. Average monthly radiation for TSLs under UT1 as function of fractional radiation during December 1992.

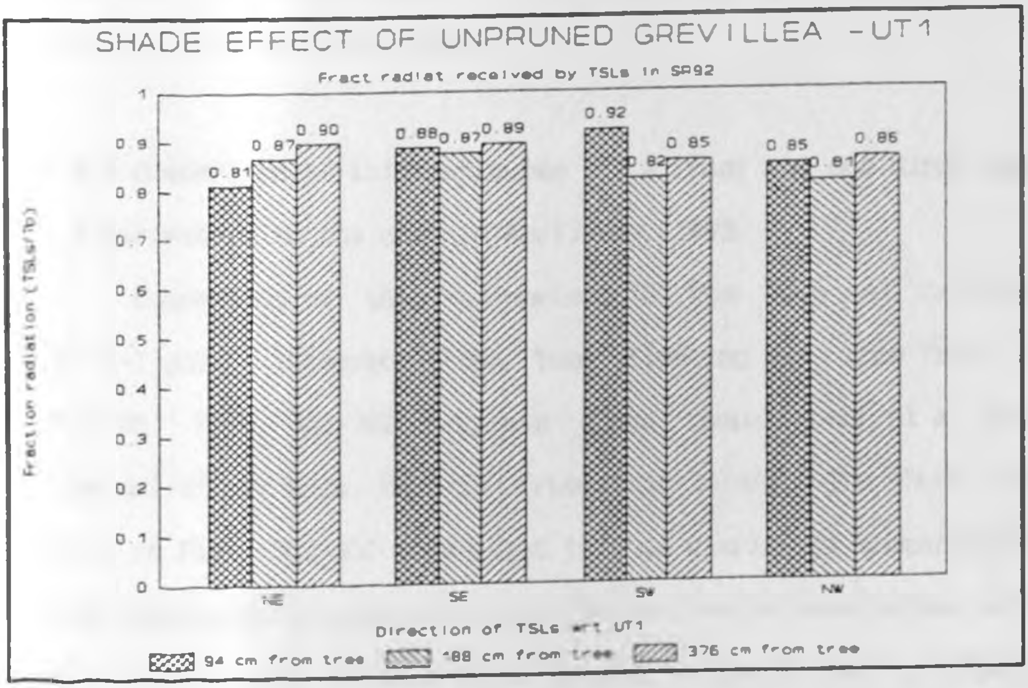


Fig. 299. Average monthly radiation for TSLs as function of fractional radiation under unpruned *Grevillea robusta* tree (UT1) for the entire SR92.

4.4.5 (d) Fractional radiation received by the inter-crop during SR92

Fig. 299 gives the sectorial fractional radiation during the maize crop growing period in the SR92 season. We can see from Fig. 299 that the fractional radiation received by the TSLs at 94 cm from UT1 was lowest in sector NE. The fractional radiation received at 94 cm ranged from 0.81 in NE to 0.92 in SW sectors. The fractional radiation received at 188 cm ranged from 0.81 in NW to 0.87 in both SE and NE sectors. At 376 cm the fractional radiation received was between 0.85 in SW and 0.90 in NE.

The canopy shading of solar radiation for SR92 was again heaviest between NE through NW and SW. with NW being most shaded overall among them. For the whole season. like in October and November. the 188 cm distance received more shade.

4.4.6 Comparison of thirteen tubes (Tb & TSLs) and one Kipps (kp2) solarimeters in the open in April-May. 1993

Comparison of the radiometers in the open and calibration of Delta-T solar integrators and tube flushing was done from 14/4/ to 31/5/93. Figs. 300-302 displays these comparisons at a short time interval of six days. that is from 19/4/-24/4/93. The short period data plots in Figs. 300-302 were meant to show clarity of comparisons. During this comparison we also calibrated Delta-T solar integrators and removed some tubes whose painted white sensing elements had cracked paint on their surfaces and were beginning to show erroneous readings when compared in the open to Kipp solarimeter. The thirteen tube (one Tb & twelve TSLs) and one Kipp (kp2) solarimeter (since kp1 had been removed and it could not be repaired) were installed at 50 cm above the ground in an open area. without trees nearby to cast shadows on them. As in

1991, calibration of the 12 TSLs consisted of 4 (E1, W1, S1 & N1) which were to be installed around the unpruned Grevillea robusta tree 1 (marked UT1) at 94 cm, 4 (E2, W2, S2 & N2) at 188 cm and 4 (E3, W3, S3 & N3) at 376 cm from the tree trunk (see Fig. 11). We can see from Figs. 300-302 that the tubes for 94, 188 and 376 cm from UT1 gave almost identical radiation readings with Tb & kp2 to within about ±0.1% on the average.

4.4.7 Fractional radiation received by the inter-crop in June, 1993

After calibration of the instruments in the open, as presented in section 4.4.5, the tube solarimeters (TSLs) were taken back and installed in AF under UT1 as in Fig. 11, while the Tb and kp2 were installed in the open as before.

Fig. 303 presents results of fractional radiation received above the maize crop under UT1 in the four sectors (see Fig. 11) during the middle of LR93, in June 1993, which was the only month of data for this LR93 season. We can see from Fig. 303 that UT1 canopy had grown thicker than it was in SR92, as there was generally quite substantial reduction (i.e. 16-39%) in solar radiation transmitted to the sensors. The cold and cloudy period in Kenya, when most non-precipitating clouds cover the sky thereby shielding the ground, begins in June and ends in September. This also might have contributed to low radiation reaching the sensors, but would affect even Tb and kp2 and the fraction would be unchanged. Hence leaving us with the first mentioned reason for reduced fraction. It means nevertheless that total solar radiation is an important input next to the fractions when correlations with biomass take place. The region of heaviest radiation canopy shading had moved further from tree stem and affected mainly the area around 188 cm and beyond.

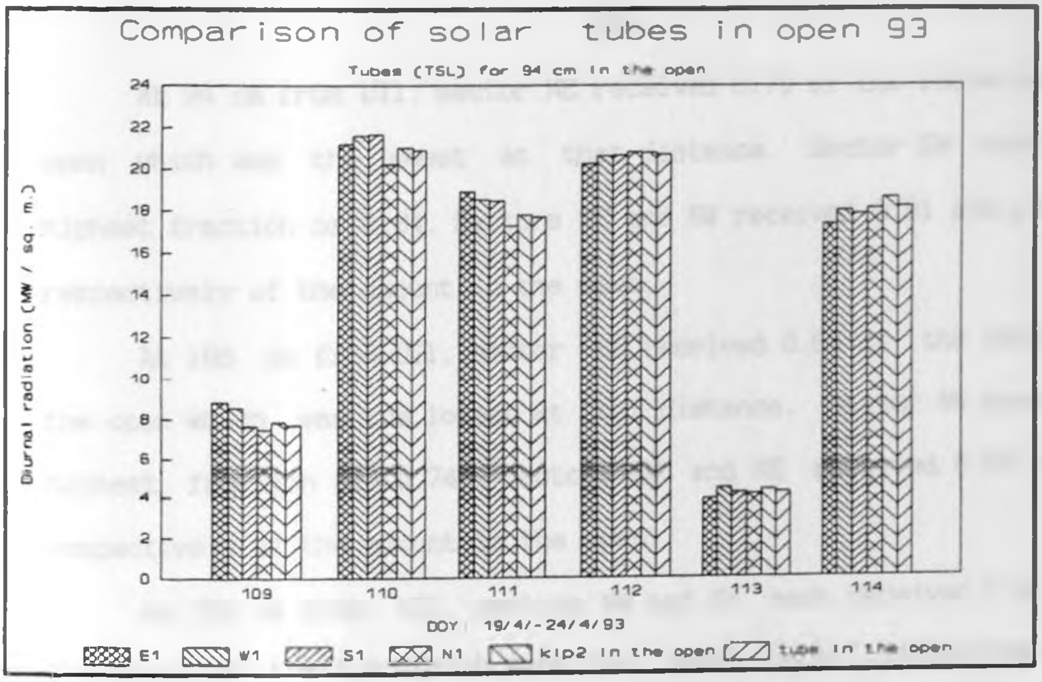


Fig. 300. Daily radiation totals for TSLs for 94 cm during part of comparison in the open: 19/4/-24/4/93.

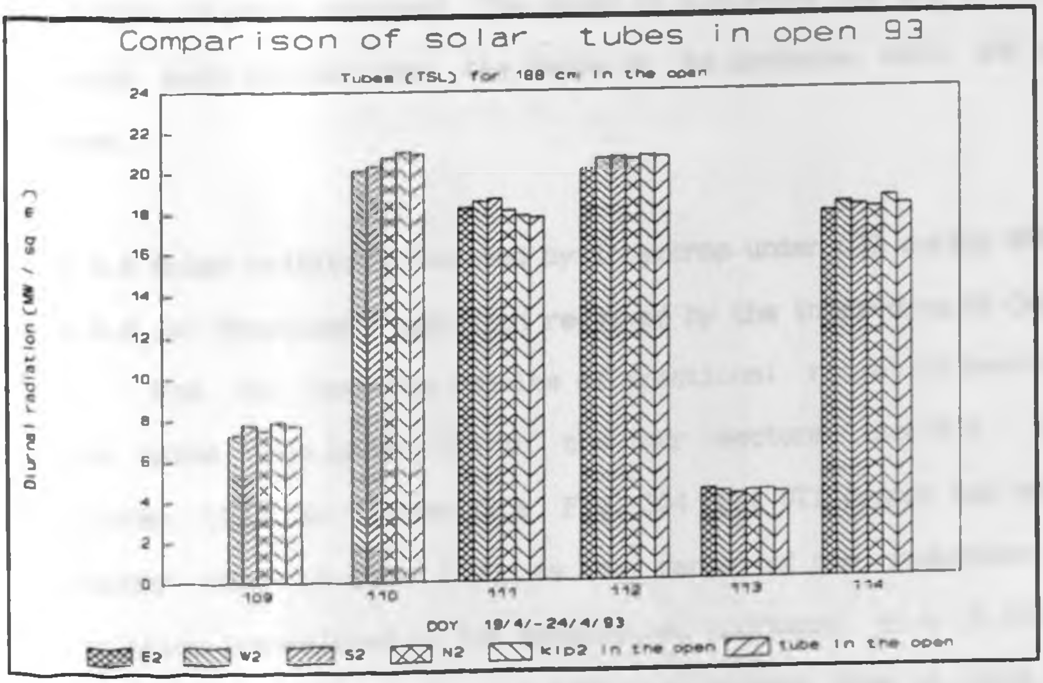


Fig. 301. Daily radiation totals for TSLs for 188 cm during part of comparison in the open: 19/4/-24/4/93.

At 94 cm from UT1, sector NE received 0.79 of the radiation in the open which was the lowest at that distance. Sector SW received the highest fraction of 0.84. Sectors SE and NW received 0.81 and 0.82 Figs. respectively of the amount in the open.

At 188 cm from UT1, sector SE received 0.63 of the radiation in the open which was the lowest at that distance. Sector NW received the highest fraction of 0.74. Sectors SW and NE received 0.69 and 0.68 respectively of the amount in the open.

At 376 cm from UT1, sectors NW and SW each received 0.61 of the radiation in the open which were the least overall indicating that the canopy shade at distance 376 cm was somewhat heavier west of UT1.

For June 1993 as a whole there are hardly any differences between sectors in shade received. The shade at distances 188 and 376 cm were again much heavier than the shade at 94 distance, with 376 cm having most.

4.4.8 Solar radiation received by intercrop under UT1 during SR93

4.4.8 (a) Fractional radiation received by the inter-crop in October

Fig. 304 presents results of fractional radiation received above the maize crop under UT1 in the four sectors (see Fig. 11) during October, 1993. We can see from Fig. 304 that UT1 canopy had grown even thicker than in June 1993 as the range of the reduction in solar radiation transmitted to the sensors had increased (i.e. 0.16-0.47). So the canopy shading in October 1993 was heavier than in June 1993. The region of heaviest canopy shading had now shifted to the northern and western part of UT1 to affect NE and NW sector, especially at 94 cm (where in fact all sectors are involved in the heaviest shade as SW and even SE have appreciable shade). At 188 cm distance from the tree stem,

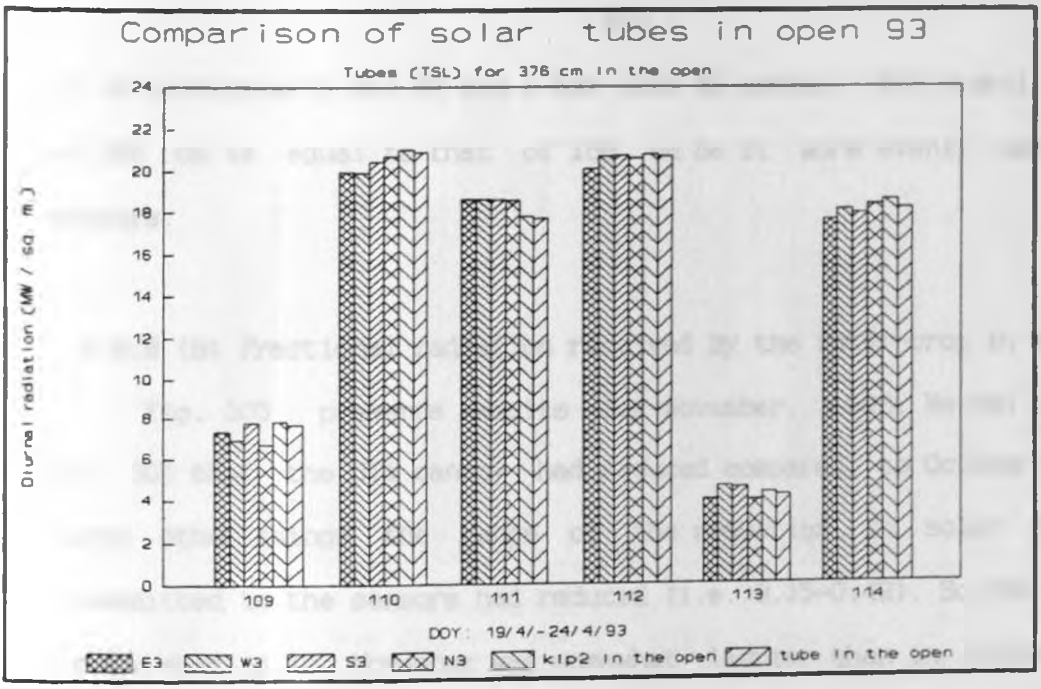


Fig. 302. Daily radiation totals for TSLs for 376 cm during part of comparison in the open: 19/4/-24/4/93.

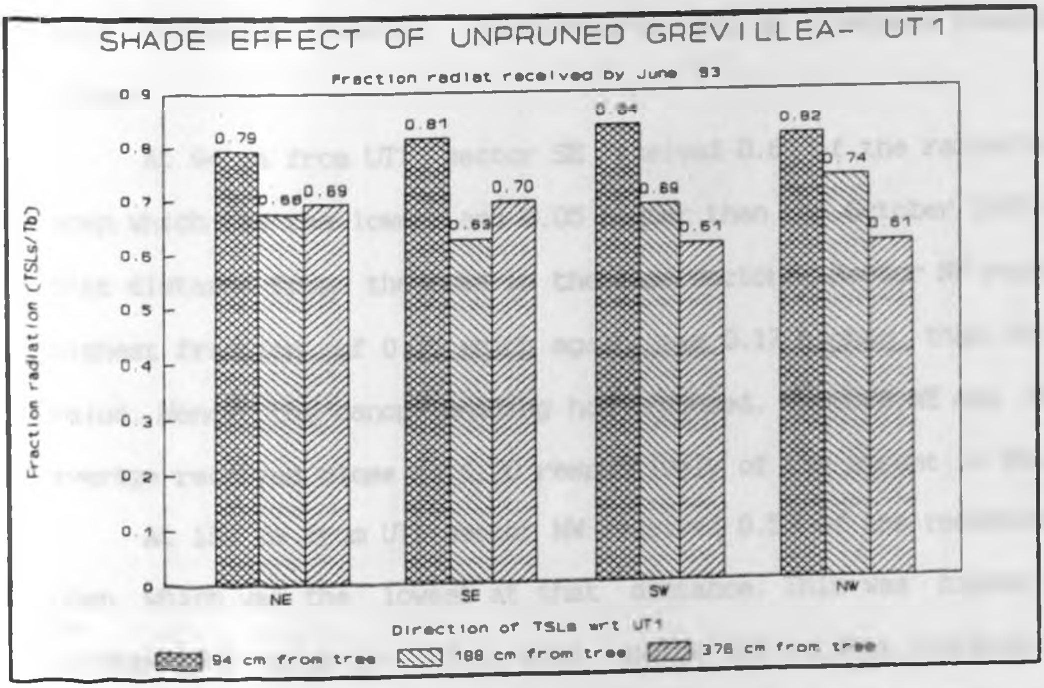


Fig. 303. Average radiation as a function of fractional radiation for TSLs under UT1 during LR93, June.

it is particularly the NW and a bit less NE sector. but overall shading at 396 cm is equal to that of 188 cm be it more evenly spread over sectors.

4.4.8 (b) Fractional radiation received by the inter-crop in November

Fig. 305 presents results for November, 1993. We can see from Fig. 305 that the UT1 canopy had reduced compared to October 1993 as among other things the range of the reduction in solar radiation transmitted to the sensors had reduced (i.e. 0.15-0.42). So the canopy shading in November was somewhat lighter than in October 1993. The region of heaviest canopy shading was still in the northern part of UT1 and affected most heavily the NE and NW sectors, and most serious at 188 cm distance from the tree stem, where the other sectors received more radiation. Overall, particularly 376 cm distance received less shade.

At 94 cm from UT1 sector SE received 0.68 of the radiation in the open which was the lowest and 0.05 higher than the October 1993 value at that distance from the tree in the same sector. Sector NW received the highest fraction of 0.75 which again was 0.17 higher than the October value. Hence the canopy shading had reduced. Sectors NE and SW on the average received close to 0.70 respectively of the amount in the open.

At 188 cm from UT1 sector NW received 0.58 of the radiation in the open which was the lowest at that distance. This was higher than the October 1993 value by 0.05 in that sector and at that distance from the tree. Sector SE received the highest fraction of 0.81 which was 0.03 lower than October 1993 value in that sector.

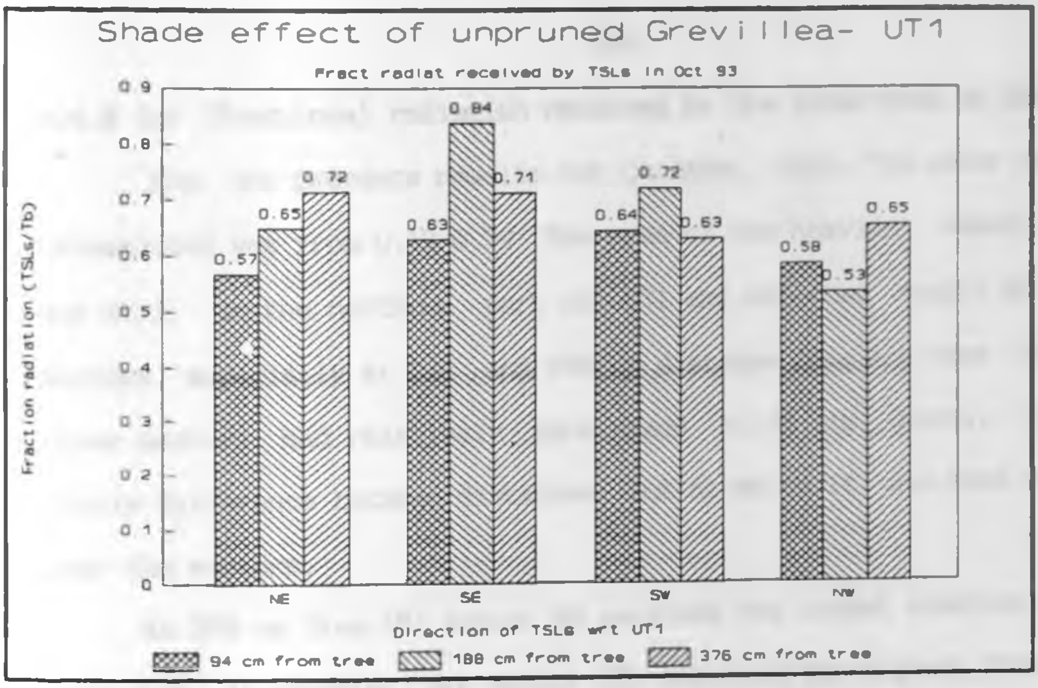


Fig. 304. Average monthly radiation as a function of fractional radiation for TSLs under UT1 during October 1993.

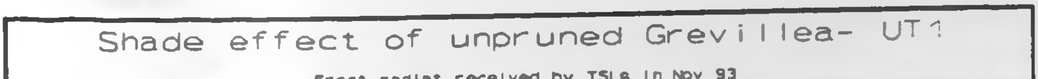


Fig. 305. Average monthly radiation as a function of fractional radiation for TSLs under UT1 during November 1993.

4.4.8 (c) Fractional radiation received by the inter-crop in December

Fig. 306 presents results for December, 1993. The solar radiation transmitted was from 0.19-0.39. The area of the heaviest canopy shading was still in the northern part of UT1 and affected mainly NW and NE sectors, especially at 188 and 376 cm distance from the tree stem. The other sectors had relatively more shade at 94 cm. Overall there was little difference between distances, but at 94 cm it was more uniformly over the sectors.

At 376 cm from UT1 sector NW received the lowest fraction of 0.64, less than in November, and sector SE received the highest fraction, of 0.76, appreciably less than in November. Sector SW received 0.75 while NE received 0.66 of the amount in the open, together also less than in November.

4.4.8 (d) Fractional radiation received by the inter-crop during SR93

Fig. 307 gives the sectorial fractional radiation during the maize crop growing period in the SR93 season. We can see from Fig. 307 that the fractional radiation received by the TSLs at 94 cm from UT1 was lowest in sector NE where 0.65 of radiation in the open was received and 0.69 in SW sectors. This was less than the fraction received in SR92 (see Fig. 299) which ranged from 0.81 in NE to 0.92 in SW sectors, indicating than that UT1 canopy had grown in thickness, thereby reducing the fractional radiation received at 94 cm by between 0.16 and 0.23 in these two sectors.

The fractional radiation received at 188 cm in SR93 ranged from 0.57 in NW to 0.82 in SE sectors. This was less than that received in SR92 (see Fig. 299) which ranged from 0.81 in NW to 0.87 in SE and NE sectors confirming that the UT1 canopy had grown in thickness thereby

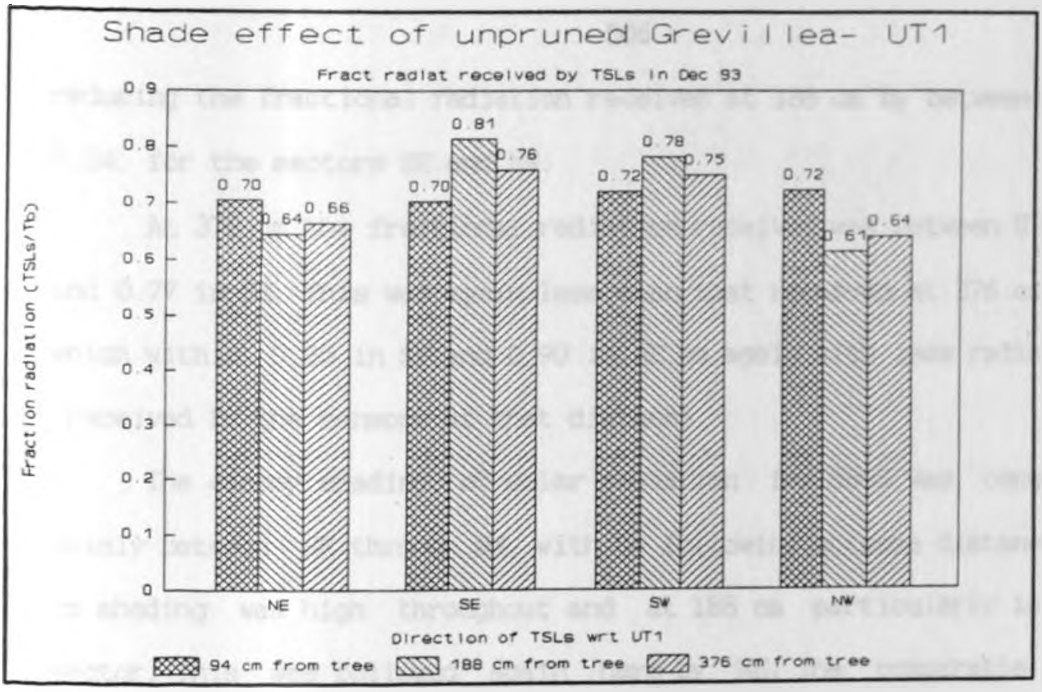


Fig. 306. Average monthly radiation as a function of fractional radiation for TSLs under UT1 during December 1993.

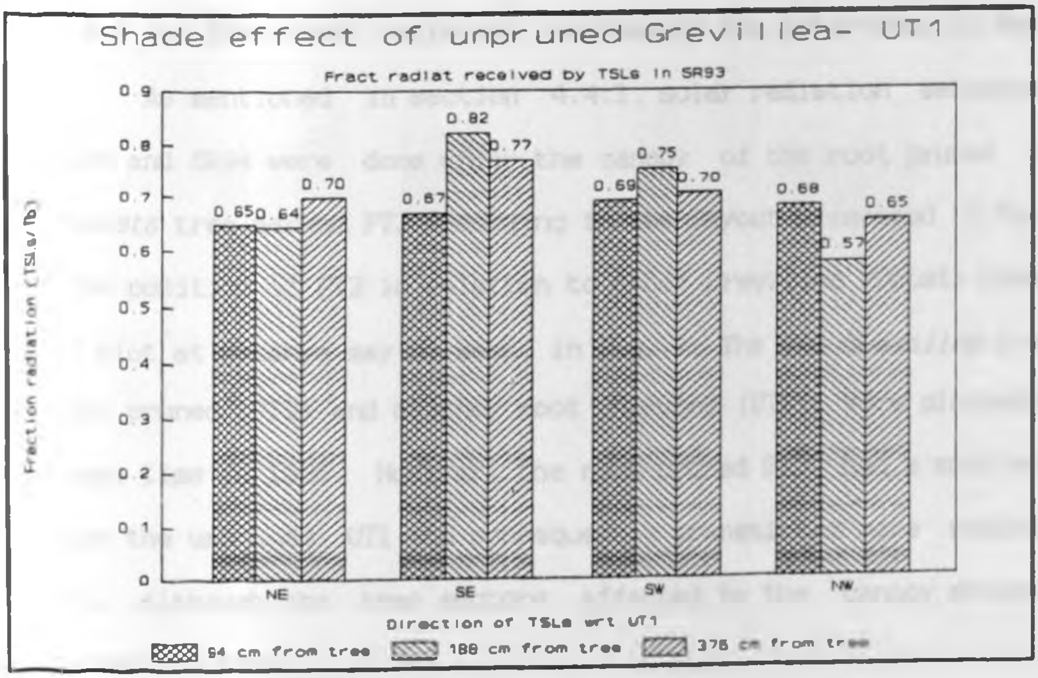


Fig. 307. Average radiation as a function of fractional radiation for TSLs under UT1 during SR93.

reducing the fractional radiation received at 188 cm by between 0.05 and 0.24. for the sectors SE and NW.

At 376 cm the fractional radiation received was between 0.65 in NW and 0.77 in SE. This was again less than that received at 376 cm in SR92 which within 0.85 in SW and 0.90 in NE so again with less radiation received by the sensors at that distance.

The canopy shading of solar radiation for SR93 was concentrated mainly between NE through NW, with SW following at some distance. At 94 cm shading was high throughout and at 188 cm particularly in the NW sector. This was followed again here by NE. The comparable overall shading at 376 cm was more evenly distributed over the sectors.

4.4.9 Solar radiation received by intercrop under PT2 during LR94

4.4.9 (a) Fractional radiation received by the inter-crop in May

As mentioned in section 4.4.1, solar radiation measurements for LR94 and SR94 were done under the canopy of the root pruned *Grevillea robusta* tree marked PT2 according to the layout presented in Fig. 11. The position of PT2 in relation to other *Grevillea robusta* trees in the AF plot at Matanya may be seen in Fig. 9. The two *Grevillea* trees. one root pruned (PT2) and another root unpruned (UT1), were planted at the same time in 1986. However, the root-pruned PT2 had a smaller canopy than the unpruned UT1 and consequently transmitted more radiation than UT1, although the tree sectors affected by the canopy shades are of course the same.

Fig. 308 presents results for May, 1994. Note that the data for April of that year were not available. We can see from Fig. 308 that the PT2 canopy had transmitted appreciably more fractional radiation than

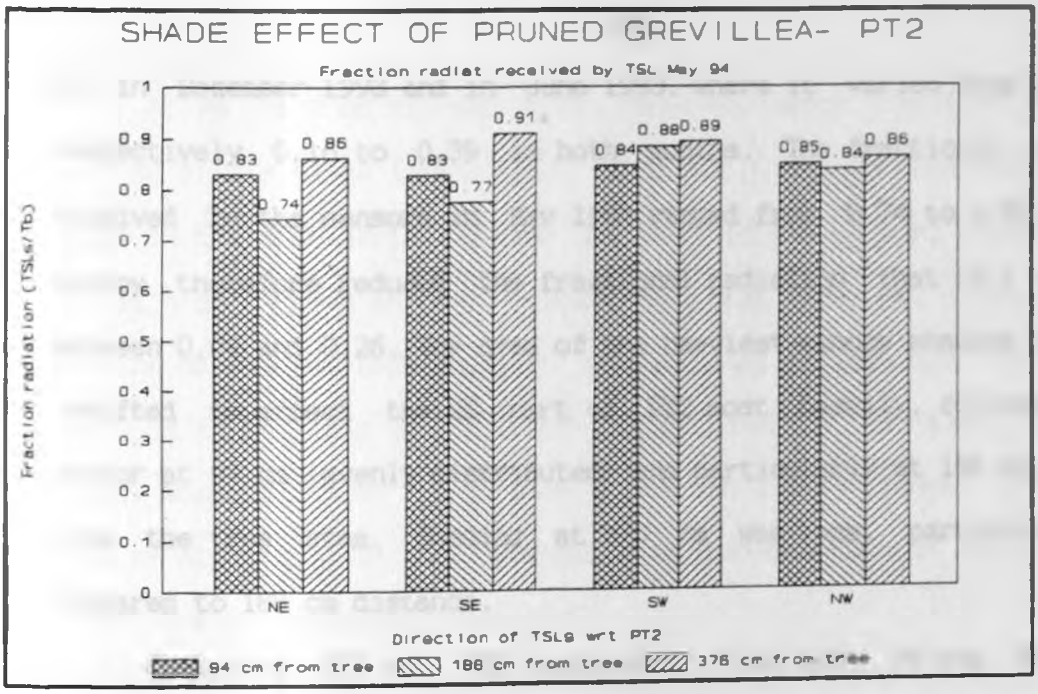


Fig. 308. Average monthly radiation as a function of fractional radiation for TSLs under PT2 during May 1994.

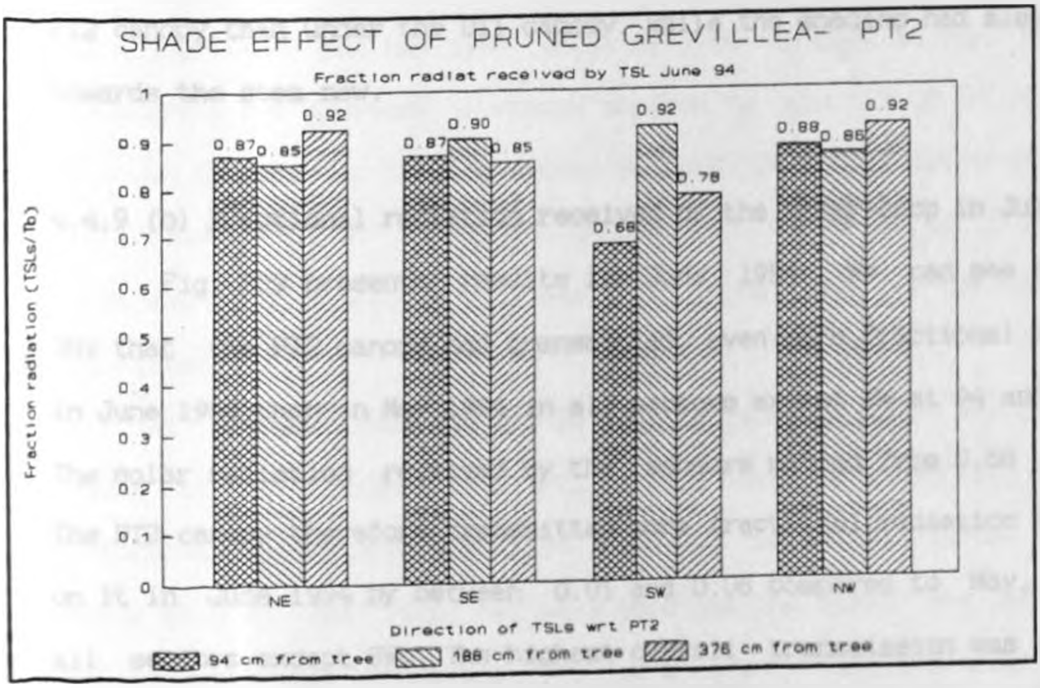


Fig. 309. Average monthly radiation as a function of fractional radiation for TSLs under PT2 during June 1994.

UT1 in December 1993 and in June 1993, where it varied from 0.19Figs. respectively 0.16 to 0.39 in both months. The fractional radiation received by the sensors in May 1994 ranged from 0.74 to 0.91. The PT2 canopy therefore reduced the fractional radiation that fell on it by between 0.09 and 0.26. The area of the heaviest canopy shading had shifted to affect the NE part of PT2 most heavily, followed by SE sector at 94 cm (evenly distributed) and particularly at 188 cm distance from the tree stem. Shading at 376 cm was less, particularly the compared to 188 cm distance.

Comparing UT1 and PT2 canopies we find that NW and NE are the sector of heaviest canopy shading by the UT1 in December and there was an even distribution in June 1993 while the heaviest shading had shifted in May 1994 to NE. Overall the shading the was much lighter under the PT2 canopy than under the UT1 canopy, while the shading had also shifted towards the stem now.

4.4.9 (b) Fractional radiation received by the inter-crop in June

Fig. 309 presents results for June, 1994. We can see from Fig. 309 that the PT2 canopy had transmitted even more fractional radiation in June 1994 than in May 1994 in all sectors except SW at 94 and 376 cm. The solar radiation received by the sensors ranged from 0.68 to 0.92. The PT2 canopy therefore transmitted more fractional radiation that fell on it in June 1994 by between 0.01 and 0.06 compared to May, 1994, in all sectors except SW. The highest overall transmission was in SE in June, 1994 compared to SW in May, 1994. For the heaviest overall shading for June was in the SW sector while it was NE in May. The shade becomes again relatively heavier towards the stem.

4.4.9 (c) Fractional radiation received by the inter-crop during LR94

Fig. 310 gives the sectorial fractional radiation during the maize crop growing period in the LR94 season. We can see from Fig. 310 that the fractional radiation received by the TSLs at 94 cm from PT2 was lowest in sector SW where 0.76 of radiation in the open was received. The fractional radiation received in LR94 at 94 cm ranged to 0.86 in the NW sector. This was more than the fraction received in SR93 (see Fig. 315) which ranged from 0.65 in NE to 0.69 in SW sectors indicating that the PT2 canopy was now thinner than the UT1 canopy and hence transmitted more fractional radiation at 94 cm. The fractional radiation received at 188 cm in LR94 ranged from 0.80 in NE to 0.90 in SW sectors. This was much more than that received in SR93 (see Fig. 306) which ranged from 0.57 in NW to 0.82 in SE sectors again indicating that the PT2 canopy was thinner than UT1 canopy and allowed in more fractional radiation at 188 cm.

At 376 cm the fractional radiation received was between 0.84 in SW and 0.89 in NE and NW. This again was more than that received at 376 cm in SR93 which was within 0.65 in NW and 0.77 in SE resulting in increase in fractional radiation received at 188 cm. The canopy shading of solar radiation for LR94 was heaviest in the SW, where 94 cm and 376 cm had their lowest fraction, followed by NE, where 188 cm has its lowest fraction. Overall most shade was received at 94 cm distance from the tree, followed by 188 cm.

4.4.10 Solar radiation received by intercrop under PT2 during SR94

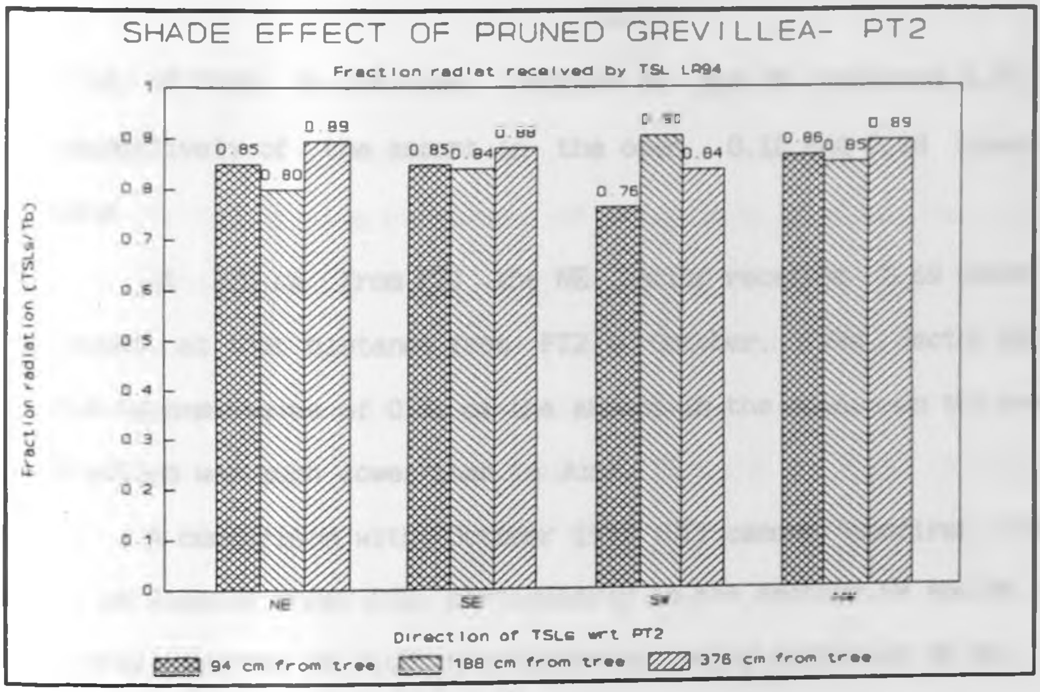
4.4.10 (a) Fractional radiation received by the inter-crop in October

As mentioned in section 4.4.8, solar radiation measurements for

LR94 and SR94 were done under the canopy of the root pruned *Grevillea robusta* tree marked PT2 according to the layout presented in Fig. 11. Fig. 311 presents results of fractional radiation received above the maize crop under PT2 in the four sectors during October. 1994. We can see from Fig. 311 that PT2 canopy had grown thicker as it had transmitted relatively less solar radiation in October 1994 than it did in June 1994. The range transmitted in October was between 0.64 in NW to 0.81 in the SW sectors. However the canopy shading was somewhat more overall distributed in October than in June 1994. There was a shift of the shaded area to the NW and NE sectors of PT2. particularly at 94 cm. but for the NW sector also at 188 cm and for the NE sector also at 376 cm distance.

At 94 cm from PT2. sector NW received the lowest fractional radiation of 0.64 of its value in the open. This was 0.24 lower than the June 1994 value in the same sector. Sector SE received the highest fraction at 94 cm of 0.78 which was 0.09 lower than that received in June 1994 in the same sector. Sectors SW and NE received fractional radiation of 0.74 and 0.68 respectively. which was 0.06 higher and 0.19 lower than for June 1994 respectively. Hence the canopy shading under PT2 in October. 1994 was heavier than in June 1994 by about 0.12 at 94 cm, on the average.

At 188 cm from PT2. sector NW received 0.70 of the radiation in the open which was the lowest at that distance in October. 1994 and again lower than the June 1994 value by 0.16 in that sector and at that distance from the tree. Sector SE received the highest fraction at 188 cm of 0.79 which was lower than the June 1994 value by 0.11 in that sector. There was therefore a net decrease in canopy shading by about



Fiog. 310. Average radiation as a function of fractional radiation for TSLs under PT2 during LR94.

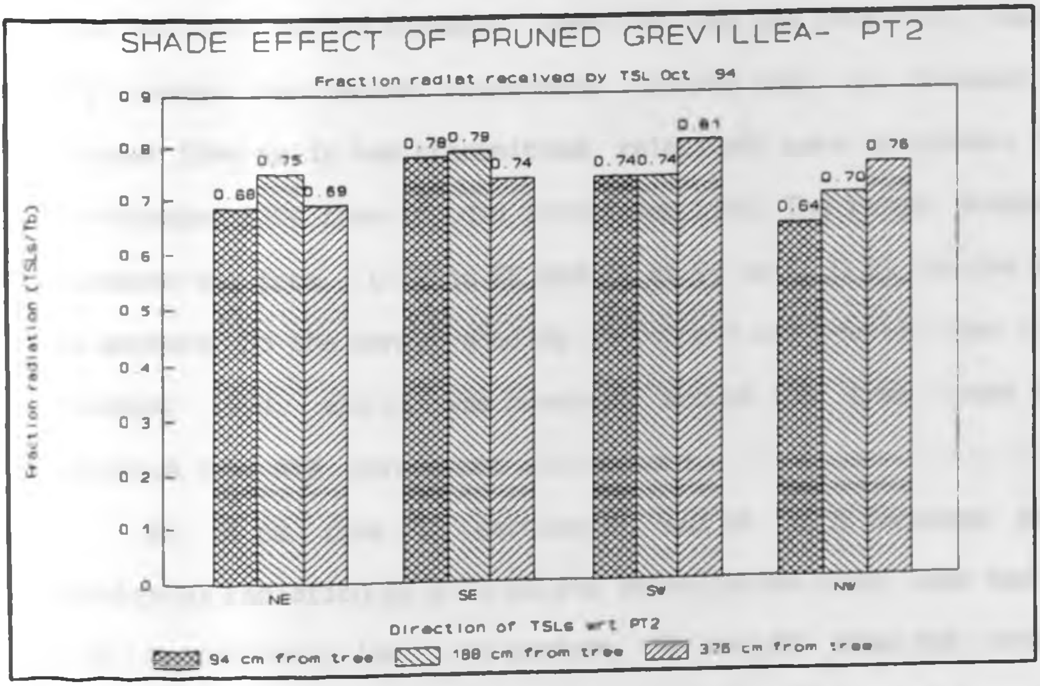


Fig. 311. Average monthly radiation as a function of fractional radiation for TSLs under PT2 during October 1994.

0.13 of that in the open. Sectors NE and SW received 0.75 and 0.74 respectively of the amount in the open, 0.10 and 0.18 lower than in June.

At 376 cm from PT2 the NE sector received 0.69 which was the lowest at that distance from PT2 in October, 1994. Sector SW received the highest value of 0.81 of the amount in the open. On the average the fraction was much lower than in June.

A comparison with October 1993 (UT1 canopy) confirms the shading to be lighter under PT2, particularly in the sectors SW and NW, with an overall average of 0.08, the difference being higher at 94 cm.

4.4.10 (b) Fractional radiation received by the inter-crop in November

Fig. 312 presents results of fractional radiation under PT2 in the four sectors during November, 1994. We can see from Fig. 312 that the PT2 canopy had become relatively thinner than in November 1994 in October 1994 as it had transmitted relatively more fractional radiation in November 1994 than it did in October 1994. The range transmitted in November was from 0.72 in SE and SW at 94 cm to 0.89 in the SW at 376 cm sectors. So the canopy shading in October was heavier than in November 1994, and it was heaviest around the tree trunk at 94 cm distance from PT2, throughout all sectors.

At 94 cm from PT2 sectors SE and SW each received the lowest fractional radiation of 0.72 of its value in the open. This was 0.06 and 0.02 respectively lower in sectors SE and SW than the October 1994 values in these sectors. Sector NE received the highest fraction at 94 cm of 0.74 which was 0.06 higher than that received in October 1994 in the same sector. Sector NW received fractional radiation of 0.73, 0.09 higher than the previous month. Hence the canopy shading under PT2 in

November. 1994 was a very little bit lighter than in October 1994 by about 0.05 on the average.

At 188 cm from PT2 sector NW received 0.78 of the radiation in the open which was the lowest at that distance in November. 1994 but more than the October 1994 value by 0.08 in that sector and at that distance from the tree. Sector SE received the highest fraction at 188 cm of 0.81 which was higher than the October 1994 value by 0.02 in that sector. Sectors NE and SW received 0.80 and 0.79 respectively of the amount in the open. both 0.05 higher than October. There was therefore a net decrease in canopy shading at 188 cm by about 0.05 of that in the open on the average.

At 376 cm from PT2 the NW sector received 0.81 which was the lowest at that distance from PT2 in November. 1994. Sector SE received the highest value of 0.89 of the amount in the open. All values were again higher than in October.

A comparison with November 1993 (UT1 canopy) gives the same average overall picture of 0.08 more fractional radiation received under PT2, here particularly, in the NE and NW sectors, but now with the least difference at 94 cm from stem.

4.4.10 (c) Fractional radiation received by the inter-crop in December

Fig. 313 presents results of fractional radiation under PT2 in the four sectors during December. 1994. We notice from Fig. 313 that the PT2 canopy had grown relatively thicker in December. 1994 than it was in November 1994 in the NE and SW sectors but had become thinner in SE and NW sectors. be it total shade increased overall. The range transmitted in December 1994 was from 0.49 in SW at 94 cm to 0.97 in the SE at 376 cm.

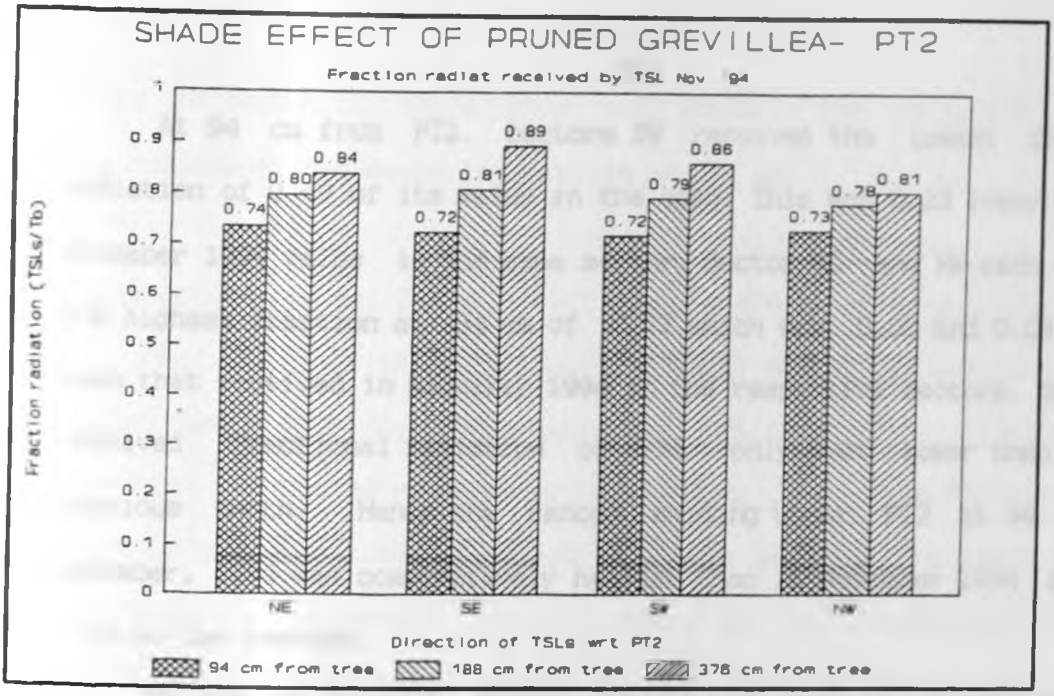


Fig. 312. Average monthly radiation as a function of fractional radiation for TSLs under PT2 during November 1994.

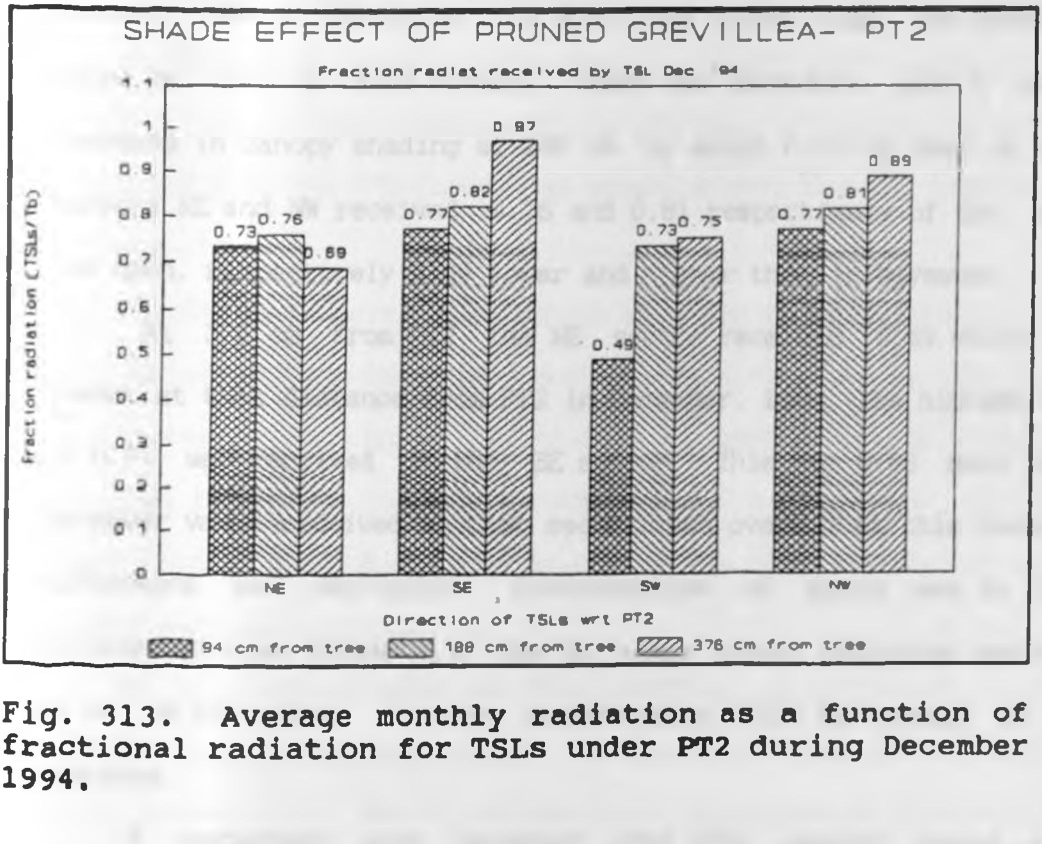


Fig. 313. Average monthly radiation as a function of fractional radiation for TSLs under PT2 during December 1994.

At 94 cm from PT2, sectors SW received the lowest fractional radiation of 0.49 of its value in the open. This was 0.23 lower than the November 1994 value in the same sector. Sector SE and NW each received the highest fraction at 94 cm of 0.77 which was 0.05 and 0.04 higher than that received in November 1994 in the respective sectors. Sector NE received fractional radiation of 0.73, only 0.01 lower than in the previous month. Hence the canopy shading under PT2 at 94 cm in December, 1994 was comparatively heavier than in November 1994 by about 0.04 on the average.

At 188 cm from PT2, sector SW received 0.73 of the radiation in the open which was the lowest at that distance in December, 1994 and lower than the November 1994 value by 0.06 in that sector and at that distance from the tree. Sector SE received the highest fraction in December 1994 at 188 cm of 0.82 which was higher than the November 1994 value by 0.01 in that sector. There was therefore only a meager net increase in canopy shading at 188 cm by about 0.01 of that in the open. Sectors NE and NW received 0.76 and 0.81 respectively of the amount in the open, respectively 0.09 lower and higher than in November.

At 376 cm from PT2 the NE sector received 0.69 which was the lowest at that distance from PT2 in December, 1994. The highest fraction of 0.97 was received in the SE sector. This was 0.08 more than the November value received in that sector, but overall at this distance the difference was negligible. Concentration of shade was in the SW, followed at some distance by the NE, while lowest radiation was received at 94 cm throughout with an exception in this NE sector at 376 cm distance.

A comparison with December 1993 (UT1 canopy) shows a 0.065 fractional radiation increase under PT2. There is appreciably less shade in the NW sector but appreciably more shade in the SW sector. Overall most additional radiation is received at 376 cm.

4.4.10 (d) Fractional radiation received by the inter-crop during SR94

Fig. 314 gives the sectorial fractional radiation received by the sensors under PT2 in SR94 season. We notice in Fig. 314 that the fractional radiation received by the TSLs at 94 cm from PT2 was lowest in sector SW where 0.65 of radiation in the open was received, ranging to 0.76 in the SE sector. This was less than the fraction received in LR94 (see Fig. 310) which ranged at this distance from 0.76 in SW to 0.86 in NW sectors, indicating that the PT2 canopy had grown much between the two seasons. This is true throughout the comparison of these two seasons but particularly heavy at 94 cm.

The fractional radiation received at 188 cm in SR94 ranged from 0.76 in NW to 0.81 in SE sectors. This was again less than that received in LR94 which ranged from 0.80 in NE to 0.90 in SW sectors again indicating that the PT2 canopy had grown between the two seasons at that distance.

At 376 cm the fractional radiation received was between 0.73 in NE and 0.86 in SE. This again was less than that received at 376 cm in LR94 which ranged from 0.84 in SW and 0.89 in both NE and NW, resulting in decreased fractional radiation received at 376 cm by the sensors. The overall canopy shading of solar radiation for SR94 was again heaviest in the SW, particularly at 94 cm.

We also confirm here that the canopy of the pruned PT2 as expected allowed in more radiation overall, to reach the sensors than the canopy of the unpruned UT1, as we may see from a comparison with SR93 (Fig. 307). The same intercomparison learns that particularly more radiation reached the NE and NW sectors under the root pruned tree, and particularly at distances 188 cm and 376 cm from the tree more radiation was received by the inter-crop under root pruned conditions. Thus, root pruning enhances radiation reaching the inter-crop, which may benefit from radiative enrichment as long as the increased radiation does not cause higher temperatures which are lethal to the plants, or increase evaporation significantly under dry conditions.

4.4.11 Shading effects of *Grevillea robusta* canopy on maize dry matter yield at Matanya

4.4.11 (a) General

We have hitherto presented the fractional radiation received by the intercrop under the *Grevillea robusta* trees (UT1 & PT2) with respect to that in the open. In the following sections we use this fractional radiation to relate radiation interception in the dominant sector(s) with the total maize biomass yields for the season studied. The maize biomass yields used have already been presented in section 4.1. We did not deal with bean yields as radiation intercepted by bean plants had been transmitted by the tree and maize plant canopies before reaching the beans. Hence tracking such radiation amounts was a complex matter that we did not have the capacity to deal with. Only with ceptometers this can these days be done with a reasonable speed.

The fractional radiation at TSL levels installed at a height of 2 m under UT1 and PT2 were used to relate total maize yield (i.e. total dry matter) produced to intercepted radiation by the maize crop after transmission through the tree canopy for the two plots in which these trees stood that were selected for radiation measurements. The fractional radiation may be taken as f in Eq. 10. We have already seen that according to Eq. 10 the total dry matter, DM, produced, when water is not limiting, depends on: the amount of dry matter formed per unit radiation intercepted (also known as conversion efficiency, e), the total PAR radiation (mean of daily totals), S, and duration of crop growth t. The two components of temporal radiation interception are therefore the duration of the crop cycle and the rate of leaf area development between emergence and attainment of an adequate value of leaf area index (total leaf area over total area of ground) to intercept most light. According to Keating and Carberry (1993) the leaf area index of 3 marks the lowest limit ($L\geq3$ Eq. 13) as an adequate value for crop interception of light.

By regressing maize total dry matter (biomass plus grain), in this case per row of 5 m in the treatments where the selected trees were and as a function of distance to the trees, produced on the total radiation for a crop season in the selected sectors, we obtain a gradient of the regression line which is a function of S, e and t and an intercept which depends on other factors like temperature, and evaporation. Net biomass accumulation (i.e. gross photosynthesis less respiration) under optimal growth conditions has been linearly related to cumulative light interception for a number of crops (Warren, 1969; Kiniry *et al.*, 1989; Sinclair and Horie, 1989). The slope of this relationship, the amount of DM produced per unit of intercepted solar radiation is also termed the crop radiation-use efficiency (RUE) (Keating and Carberry, 1993). For our purpose RUE is calculated using above-ground biomass and the fractional radiation intercepted by the maize crop. Consequently the daily increase in above-ground biomass (YLD) can be estimated using Eq.

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26 below

$$YLD=E*Rd+C \qquad (26)$$

where YLD is increase in above-ground biomass over time: E. the gradient of the line, is RUE; Rd is fractional radiation intercepted by maize crop and C is the intercept of the regression line.

The results in Figs. 315–325 relate total biomass to fractional radiation incident on the maize plants after transmission through UT1 or PT2 canopies, as a function of distance to the trees. We have already mentioned elsewhere in section 4.1 that harvesting of LR92 biomass was done in the area enclosed by PQRST and P'Q'R'S'T' in Fig. 9. The maize biomass on the eastern side of UT1 was not harvested for LR92. This gave us fewer points than expected for LR92 to relate to the radiation received by the maize plants, but did not affect accuracy.

4.4.11 (b) Maize dry matter yield estimated from solar radiation at Matanya for LR92-SR93

Figs. 315–317 present linear relations between final maize biomass yields per row in the AFM2 plot and fractional radiation transmitted by the UT1 canopy at 94, 188 and 376 cm. We observe in Fig. 315 that at 94 cm from the UT1 stem there was a rather low correlation coefficient (r=63.0%) between dry matter produced by the maize crop and radiation measured by the TSL, which was assumed equal to the radiation received by the maize canopy. High 'r' would mean that radiation falling on TSL was virtually the only determining factor for the maize crop to produce dry matter. Based on the criterion of low 'r' we may infer inefficient use of the captured radiation resource by the maize. We observe a wider scatter of the data at higher radiation, for SR92, than at lower values for SR93 and LR93 (Fig. 315). There was higher dry matter production at higher radiation in SR92, when we had enough rainfall, than in any other seasons. From Table 79 we see that the errors of estimate (err of YLD$_{est}$ = 1.69 t/ha and Rd coefficient = 6.44 t/ha) in yields are quite high, indicating high variability of biomass produced per unit of radiation resource captured. This was expected as dry matter production depends on many production factors (or resource capture ability of the crop), solar radiation being only one of them. Keating and Carberry (1993) believe that the issue of capture and use of resources in an intercropping system is essentially one of a managed degree of competition between component crops. We know that efficient use of resources is the major reason for intercropping.

We can see in Fig. 315 that calculated dry matter generally increased with increase in fractional radiation towards that observed in the open. Alternatively dry matter production decrease with decrease in fractional radiation until about 0.65 where it virtually stopped. Radiation below that ratio at 94 cm from the tree stem was found to be too little for maize to produce any dry matter. However, there was also a case of very low yields and relatively high radiation, were another factor must have been limiting.

We observe in Fig. 316 that at 188 cm from UT1: stem, the correlation coefficient (r=52.2%) decreased compared to 94 cm distance from the tree. We see in Table 79 that the errors of estimate (err of YLD$_{est}$ = 1.69 t/ha and Rd coefficient = 8.37 t/ha) in yields have remained (relatively) the same. The scatter was even wider here for SR92 than at 94 cm for higher radiation values. At 188 cm from the UT1 stem,

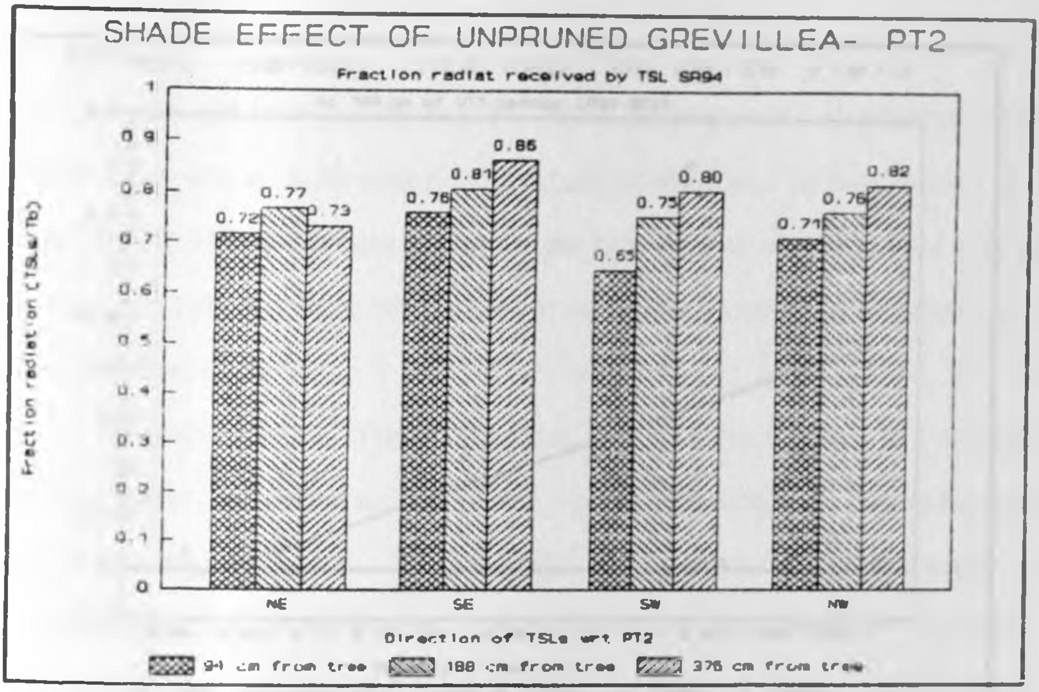

Fig. 314. Average radiation as a function of fractional radiation for TSLs under **PT2** during SR94.

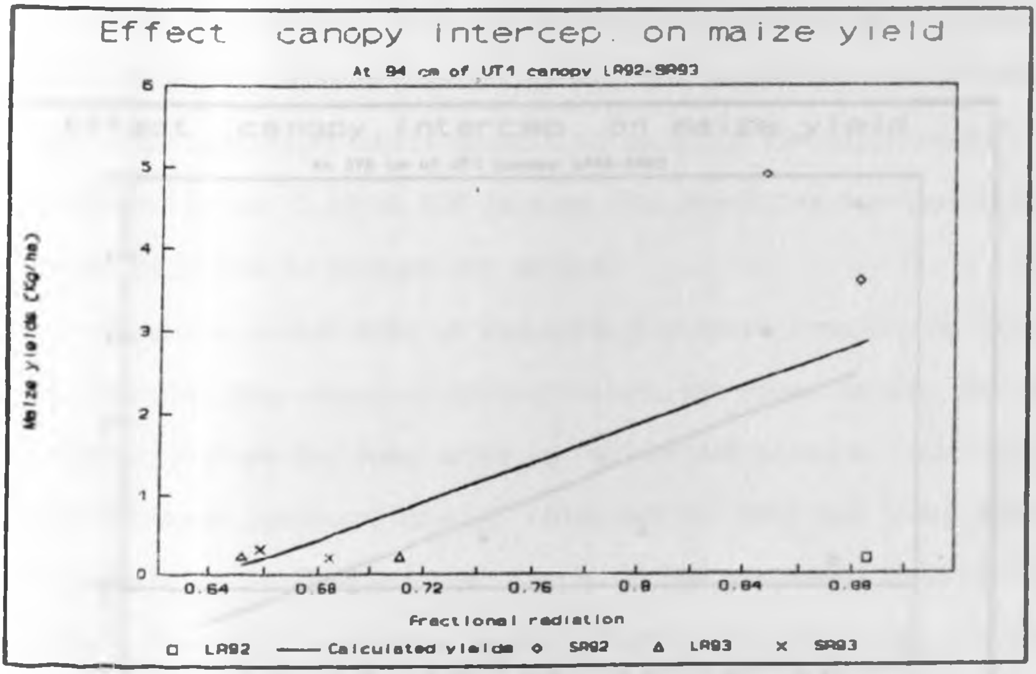

Fig. 315. The effect on maize dry matter yields of transmitted radiation through **UT1** canopy at 94 cm from the tree during LR92-SR93 seasons.

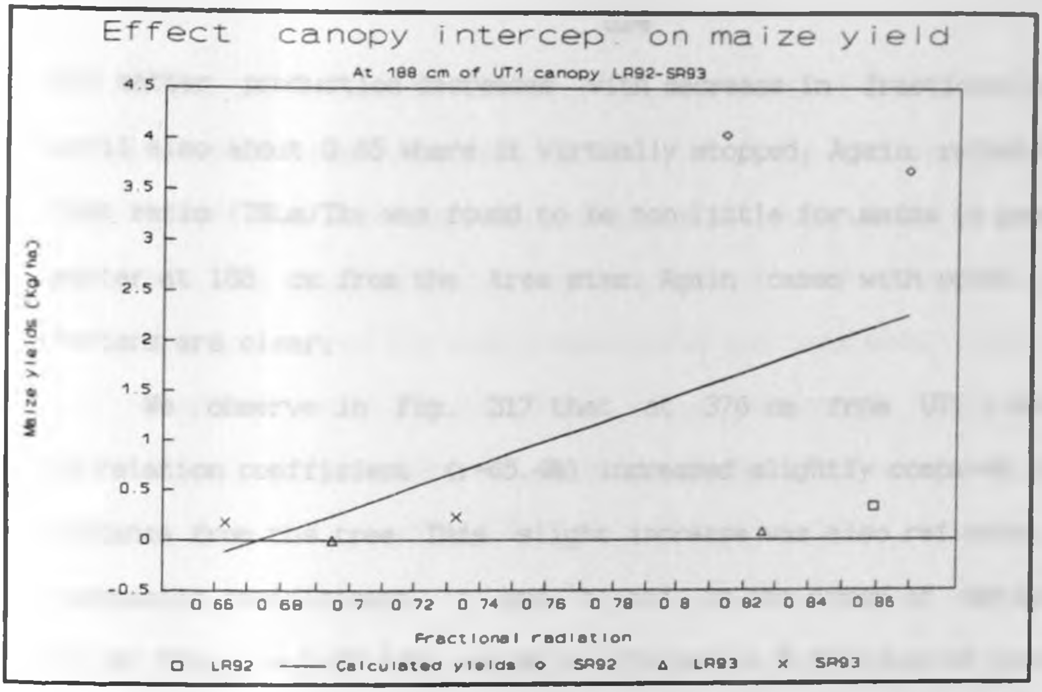

Fig. 316. The effect on maize dry matter yields of transmitted radiation through UT1 canopy at 188 cm from the tree during LR92-SR93 seasons.

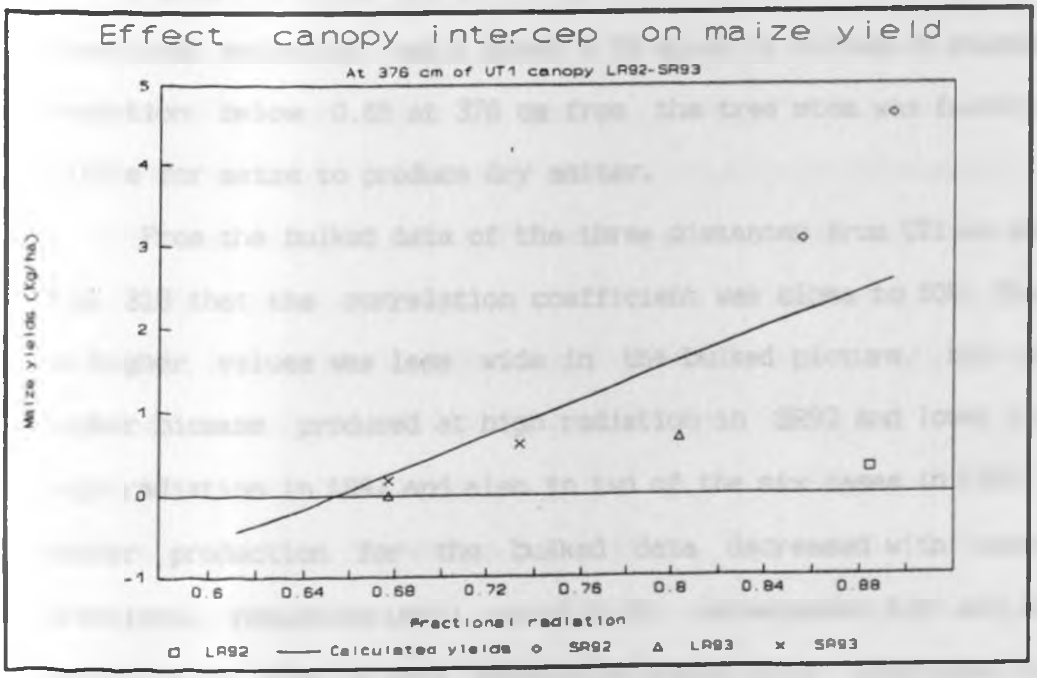

Fig. 317. The effect on maize dry matter yields of transmitted radiation through UT1 canopy at 376 cm from the tree during LR92-SR93 seasons.

dry matter production decreases with decrease in fractional radiation until also about 0.65 where it virtually stopped. Again, radiation below that ratio (TSLs/Tb) was found to be too little for maize to produce dry matter at 188 cm from the tree stem. Again cases with other limiting factors are clear.

We observe in Fig. 317 that at 376 cm from UT1's stem, the correlation coefficient (r=65.4%) increased slightly compared to 94 cm distance from the tree. This slight increase was also reflected in the regression coefficients 'a' and 'b' and in the error of estimate (say err of YLD_{est} = 1.47 t/ha and Rd coefficient = 5.53 t/ha) of yields (see Table 79). The scatter in higher values, in which high biomass produced at high radiation in SR92, was still wide. At 376 cm from the tree stem, shading was less and direct solar radiation was higher. At 376 cm from UT1 stem dry matter production decreased with decrease in fractional radiation until about 0.65 again it virtually stopped. Again radiation below 0.65 at 376 cm from the tree stem was found to be too little for maize to produce dry matter.

From the bulked data of the three distances from UT1 we observe in Fig. 318 that the correlation coefficient was close to 60%. The scatter in higher values was less wide in the bulked picture, but there was higher biomass produced at high radiation in SR92 and lower biomass at high radiation in LR92 and also in two of the six cases in LR93. The dry matter production for the bulked data decreased with decrease in fractional radiation until about 0.65, as measured for all distances individually, when no more production could occur. Fractional radiation below about 0.65 for the three distances from the tree stem was found to be too little for maize to produce much dry matter.

From the foregoing results it is obvious that the maize crop under Matanya conditions would not produce any crop if heavy tree shade resulted in fractional radiation dropping below about 65% of that in the open area. The gradients and intercepts of the regression lines for the three distances from UT1 were conservative and averaged 11.28±0.42 t/ha and -7.40±0.30 t/ha respectively. This suggested that dry matter produced per unit increase in intercepted radiation was a conservative quantity under UT1-type shading.

4.4.11 (c) Maize dry matter yield estimated from solar radiation on the eastern and western sides of UT1 in LR92-SR93

The gradient of the regression line for the eastern side of UT1 was 17.23 t/ha (Fig. 319) which widely differed from that for the western side, which was 7.47 t/ha (Fig. 320 and Table 79). The dry matter produced per unit radiation intercepted in the eastern side of UT1 was different from the western side. The eastern side of UT1 produced more dry matter per unit of radiation intercepted than the western side by 9.76 t/ha. This meant maize plants on the eastern side of UT1 were more efficient in utilization of radiation than the western side by a factor of 10 t/ha. These differences were reflected in their intercepts which also differed by 7.02 t/ha.

The reason is likely to be that on the western side of UT1 there was crop height depression (see Plate 11), which led to an open intercrop canopy whose likely causative factors have been discussed in sections 4.2 and 4.3. The plants there did not develop optimum canopy structure to intercept radiation, convert absorbed energy into photosynthate and partition assimilates between plant components to give total dry matter yields. In other words the crop canopy in the depressed area west of UT1 did not develop adequate canopy to cover the ground that would intercept optimum amount of incident radiation. For this matter the result for the western side is considered inaccurate, hence no inference may be drawn from it.

4.4.11 (d) Maize dry matter yields estimated from seasonal solar radiation in LR92 & LR93 and SR92 & SR93

The gradients of the regression line for Long rains period (LR92 & LR93) was 0.81 t/ha (Fig. 321) which greatly differed from that for Short rains (LR92 & LR93) period of 19.96 t/ha (Fig. 322 and Table 79). The amount of dry matter formed per unit radiation intercepted (also known as conversion efficiency, e), was much higher during the seasons of Short rains than during the seasons of Long rains. The Short rains crops produced more dry matter per unit of radiation intercepted than the Long rains crops by 19.15 t/ha. The Short rains maize crops were more efficient in utilization of radiation than the Long rains crops by a factor of about 20 t/ha. The correlation coefficient between radiation and dry matter produced was also very high during the Short rains seasons (r=93.6%) than during Long rains (r=40.0%). These differences were also reflected in their intercepts as -13.35 t/ha for the Short rains and -0.39 t/ha for the Long rains seasons. The intercepts therefore differed by 12.96 t/ha which was again very high.

The r for the eastern side, only for the Short rains, was 0.926 while that for the western side only was 0.940. When the dry matter produced in the control under full radiation load was included, r reduced to 0.545 in the eastern and to 0.638 in the western sides of UT1 (see Figs. 322 & 323 and 324 & 325). This shows that full radiation load was counter-productive with regard to dry matter production. The plants

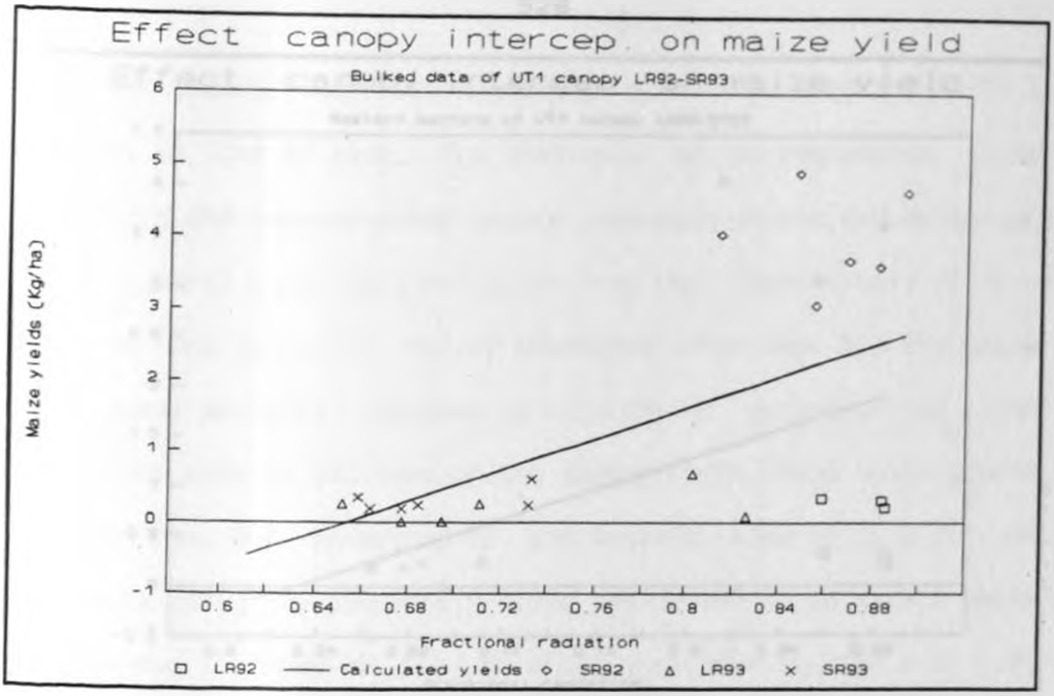

Fig. 318. The effect on maize dry matter yields of transmitted radiation through UT1 canopy for all the three distances (bulked data) from the tree during LR92-SR93 seasons.

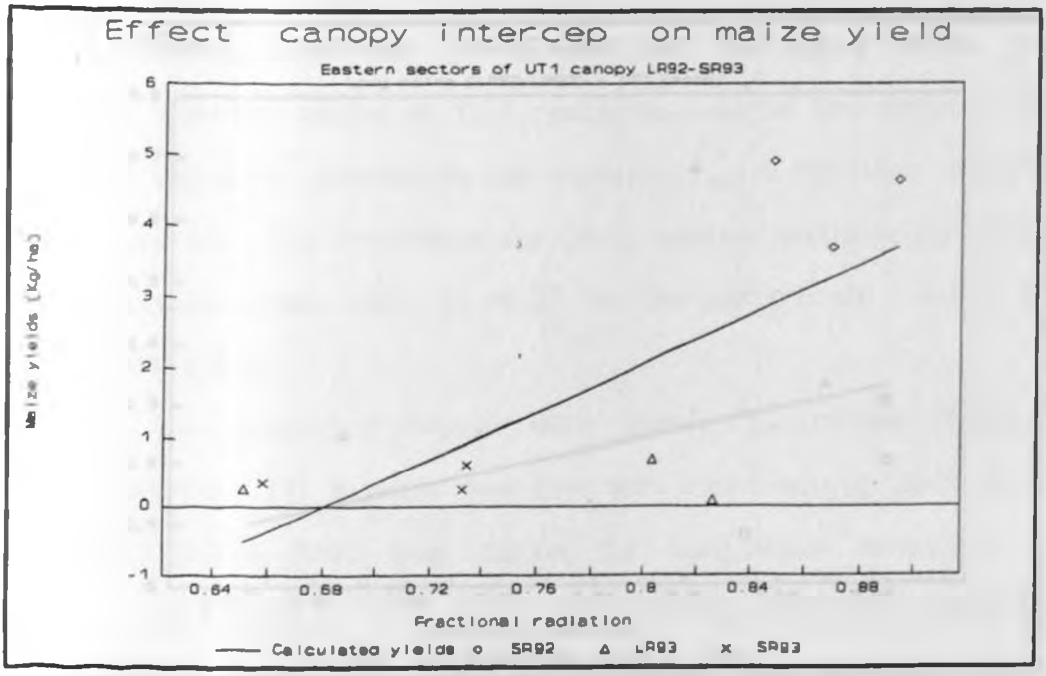

Fig. 319. The effect on maize dry matter yields of transmitted radiation through UT1 canopy on the eastern side of UT1 during LR92-SR93 seasons.

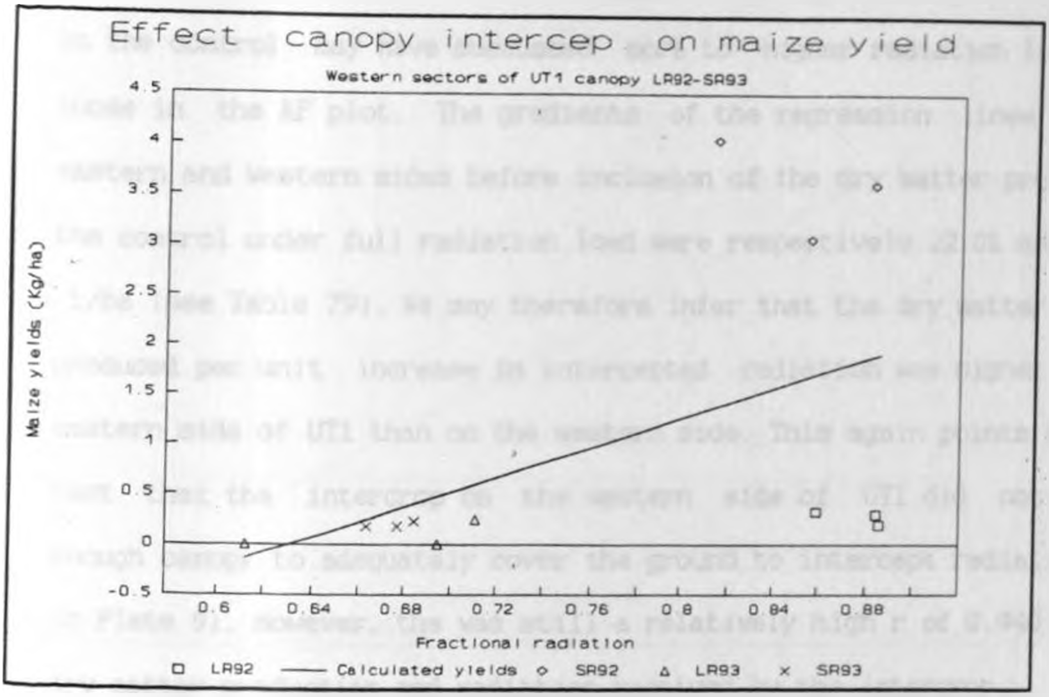

Fig. 320. The effect on maize dry matter yields of transmitted radiation through UT1 canopy on the western side of UT1 during LR92-SR93 seasons.

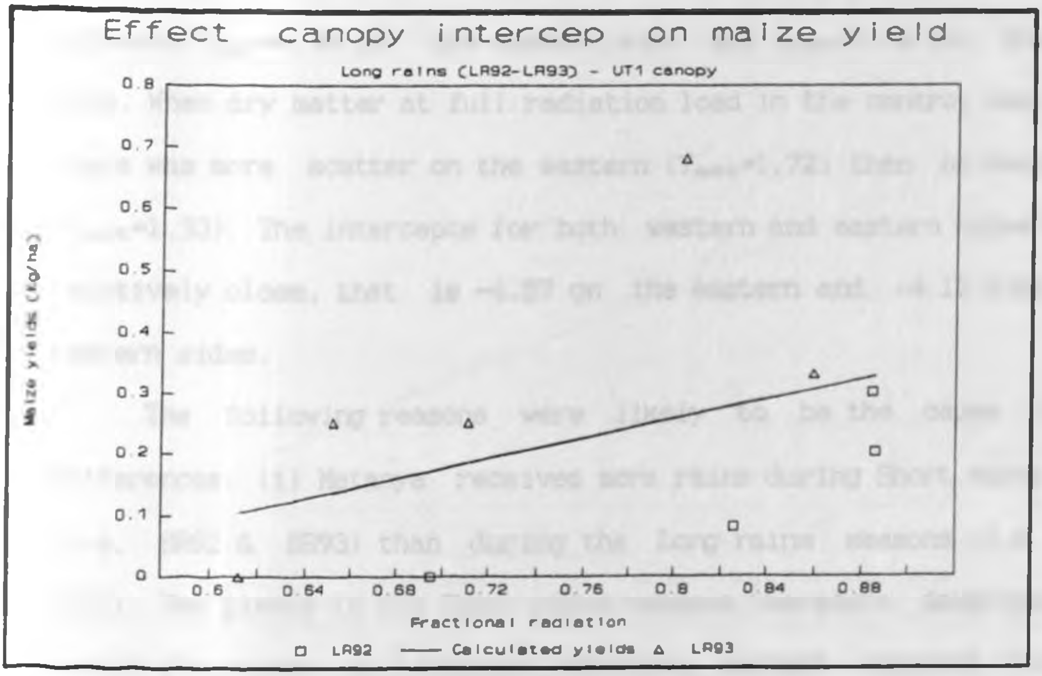

Fig. 321. The effect on maize dry matter yields of transmitted radiation through UT1 canopy during two Long Rains seasons (LR92 & LR93).

in the control may have succumbed more to higher radiation load than those in the AF plot. The gradients of the regression lines for the eastern and western sides before inclusion of the dry matter produced in the control under full radiation load were respectively 22.01 and 17.78 t/ha (see Table 79). We may therefore infer that the dry matter produced per unit increase in intercepted radiation was higher in the eastern side of UT1 than on the western side. This again points to the fact that the intercrop on the western side of UT1 did not develop enough canopy to adequately cover the ground to intercept radiation (see in Plate 9). However, the was still a relatively high r of 0.940 between dry matter production and radiation received by the intercrop.

The intercepts for the eastern and the western of UT1 were -14.98 and -11.68 t/ha which shows that the eastern side lost more dry matter to respiratory processes at nil radiation. The standard error of estimate $Y_{est}=0.94$ for the eastern side and $Y_{est}=0.72$ for the western side. When dry matter at full radiation load in the control was included there was more scatter on the eastern ($Y_{est}=1.72$) than on western side ($Y_{est}=1.33$). The intercepts for both western and eastern sides remained relatively close, that is -4.57 on the eastern and -4.10 t/ha on the western sides.

The following reasons were likely to be the cause of these differences: (i) Matanya received more rains during Short rains seasons (i.e. SR92 & SR93) than during the Long rains seasons (i.e. LR92 & LR93). The plants in the Short rains seasons therefore developed better canopy structures to intercept radiation, convert absorbed energy into photosynthate and partition assimilates between plant components which gave higher total dry matter yields in the Short rains seasons than in the Long rains seasons. (ii) Matanya had stronger wind speeds in the

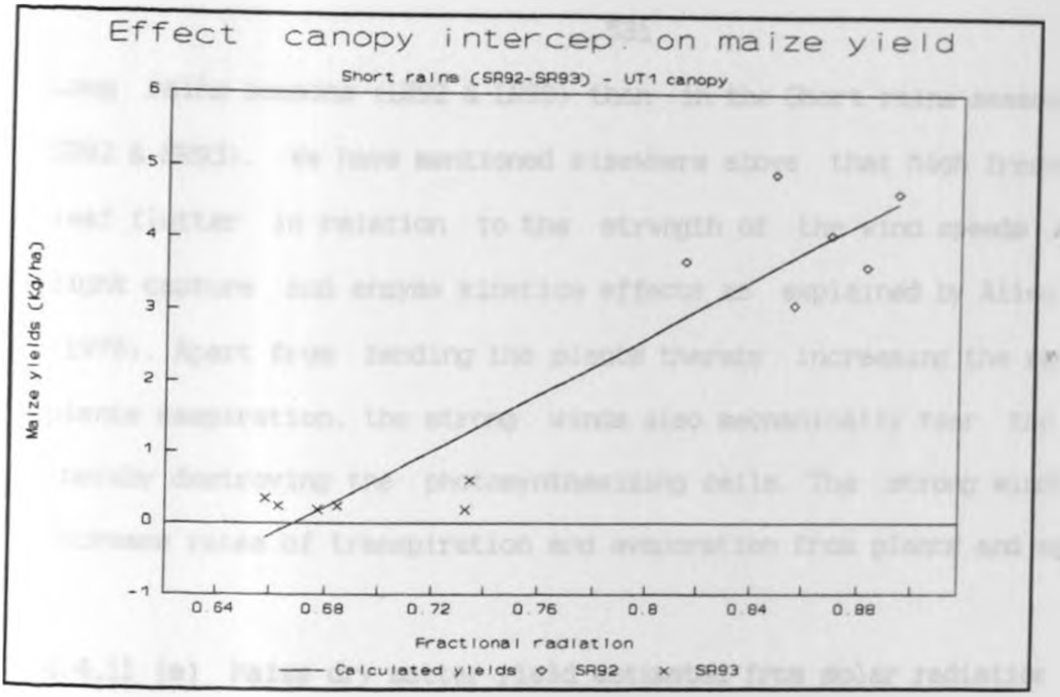

Fig. 322. The effect on maize dry matter yields of transmitted radiation through UT1 canopy during two Short Rains seasons (SR92 & SR93).

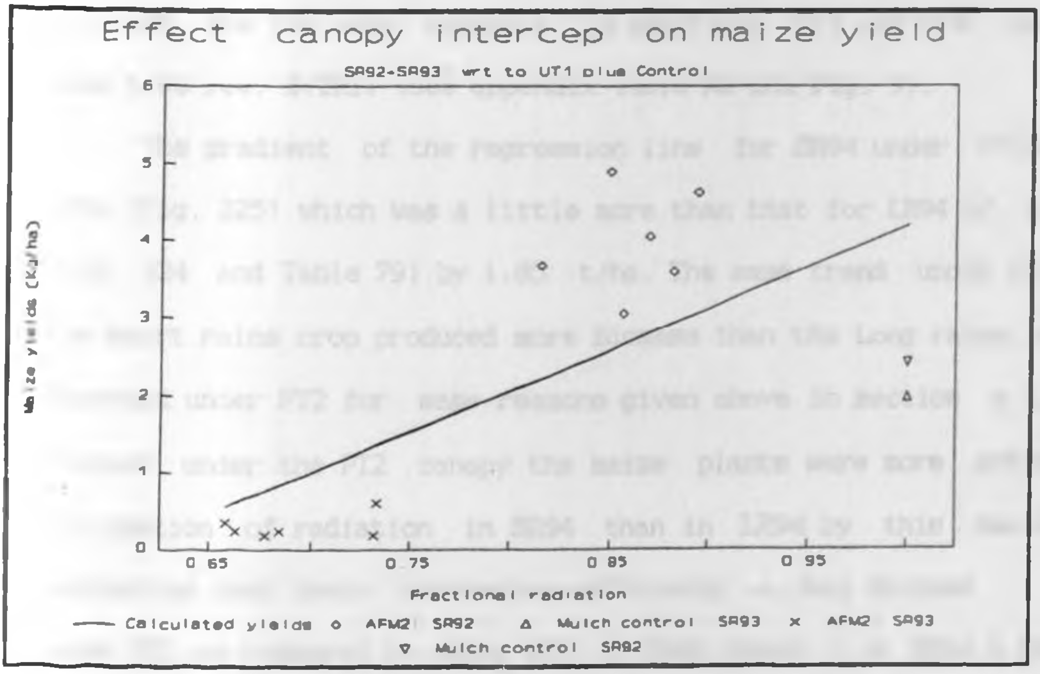

Fig. 323. The effect on maize dry matter yields of transmitted radiation through UT1 canopy and full radiation in Mulched control (M) during Short Rains seasons (SR92 & SR93).

Long rains seasons (LR92 & LR93) than in the Short rains seasons (i.e. SR92 & SR93). We have mentioned elsewhere above that high frequency of leaf flutter in relation to the strength of the wind speeds affects light capture and enzyme kinetics effects as explained by Allen *et al.* (1976). Apart from bending the plants thereby increasing the rates of plants respiration, the strong winds also mechanically tear the leaves thereby destroying the photosynthesizing cells. The strong winds also increase rates of transpiration and evaporation from plants and soils.

4.4.11 (e) Maize dry matter yield estimated from solar radiation under PT2 in LR94 & SR94

The pruned *Grevillea robusta* tree (PT2) had a more open and smaller canopy (or crown) than the unpruned *Grevillea robusta* tree (UT1), although the two were adjacent (in positions Tr3 and Tr4) and on the same tree row, B(TR1) (see appendix Table A8 and Fig. 9).

The gradient of the regression line for SR94 under PT2 was 4.93 t/ha (Fig. 325) which was a little more than that for LR94 of 3.08 t/ha (Fig. 324 and Table 79) by 1.85 t/ha. The same trend under UT1, where the short rains crop produced more biomass than the Long rains, was also observed under PT2 for same reasons given above in section 4.4.10 (c). However under the PT2 canopy the maize plants were more efficient in utilization of radiation in SR94 than in LR94 by this small margin indicating that their conversion efficiency, e, had dropped under PT2 as compared to under UT1. In both cases (i.e. SR94 & LR94) the fractional radiation was higher under PT2 canopy than under UT1. The high radiation loads under the PT2 canopy may have lowered the efficiency of conversion to dry matter. The correlation coefficients

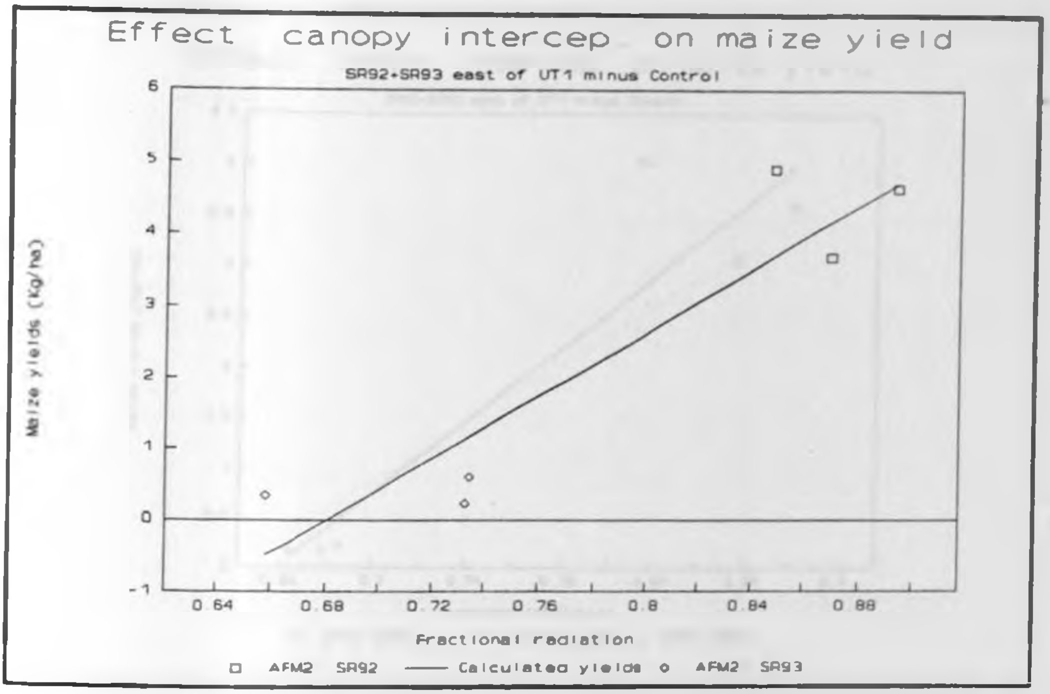

Fig. 324. The effect on maize dry matter yields on the east of UT1 of transmitted radiation through UT1 canopy during two Short Rains seasons (SR92 & SR93).

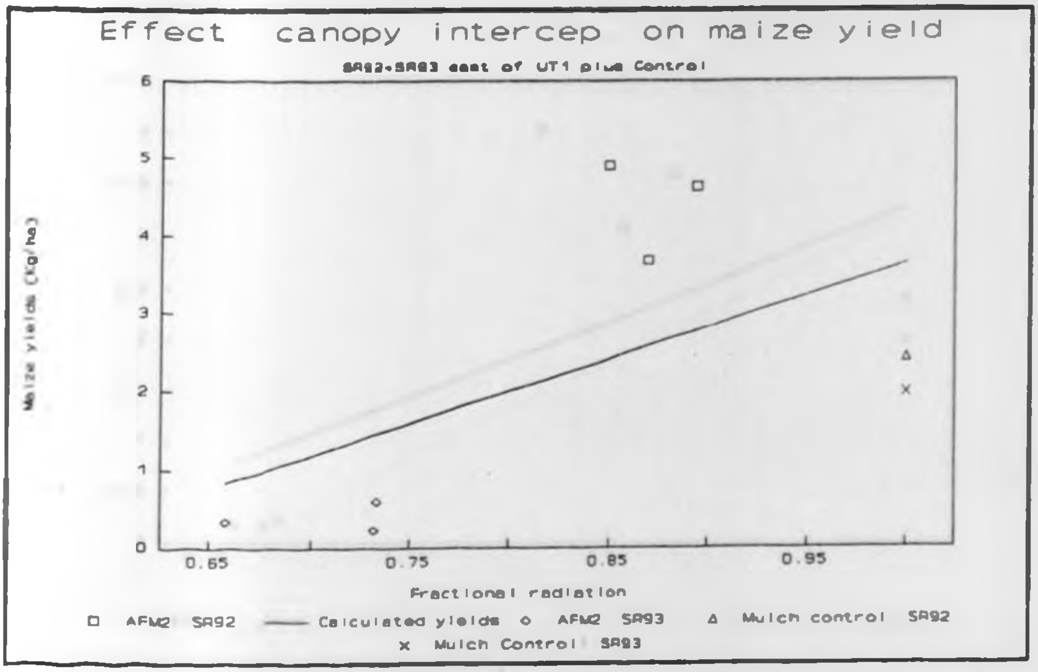

Fig. 325. The effect on maize dry matter yields on the east of UT1 of transmitted radiation through UT1 canopy and full radiation in Mulched control during two Short Rains seasons (SR92 & SR93).

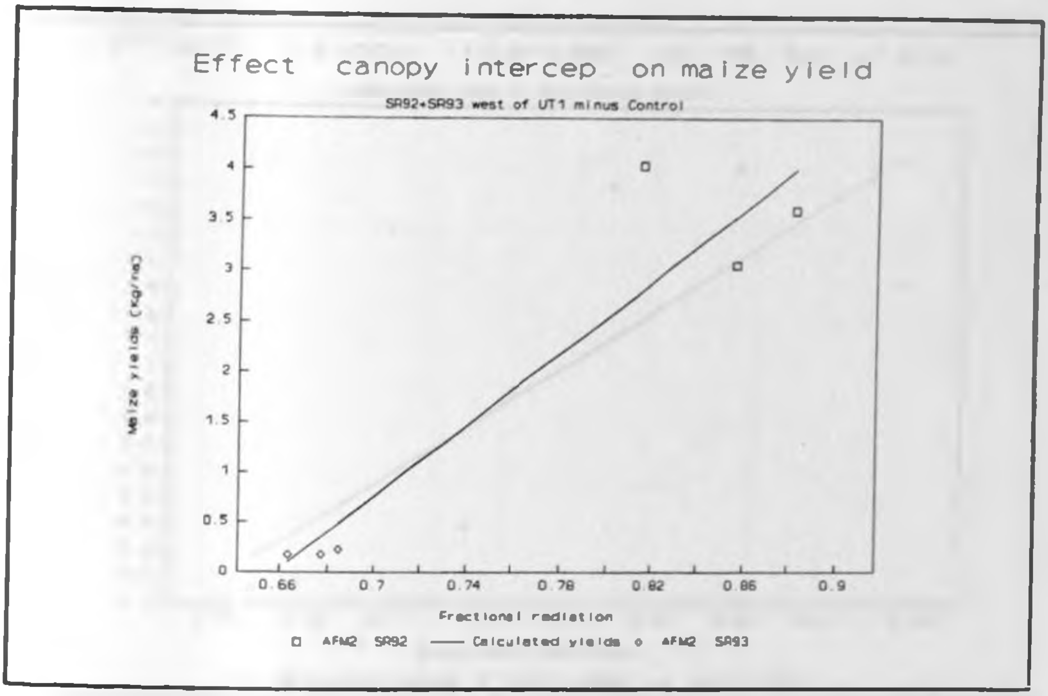

Fig. 326. The effect on maize dry matter yields on the west of UT1 of transmitted radiation through UT1 canopy during two Short Rains seasons (SR92 & SR93).

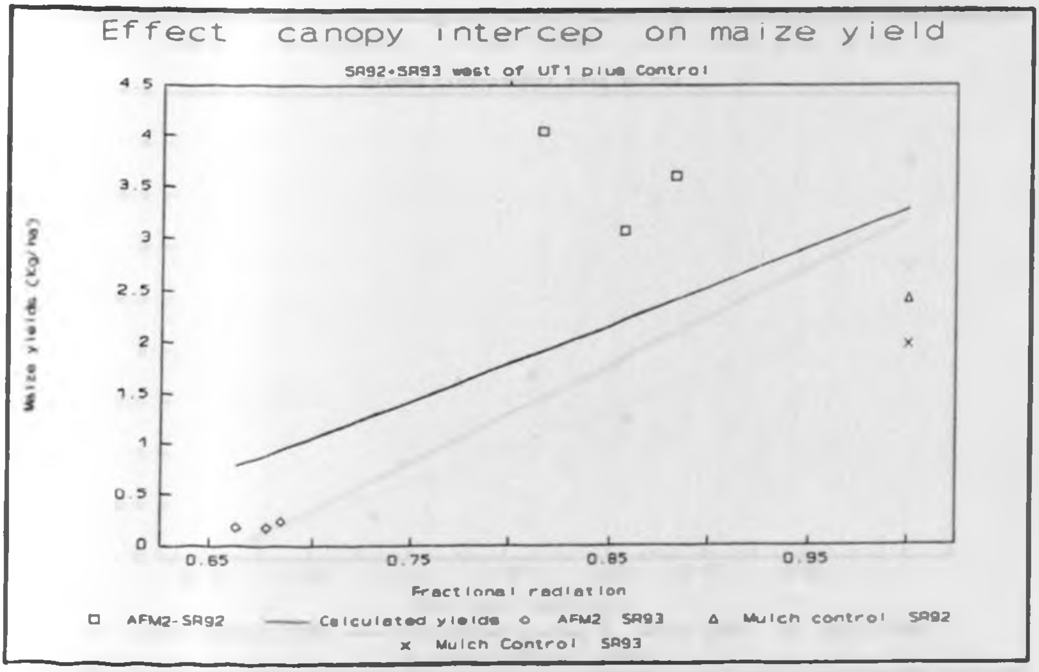

Fig. 327. The effect on maize dry matter yields on the west of UT1 of transmitted radiation through UT1 canopy and full radiation in Mulched control during two Short Rains seasons (SR92 & SR93).

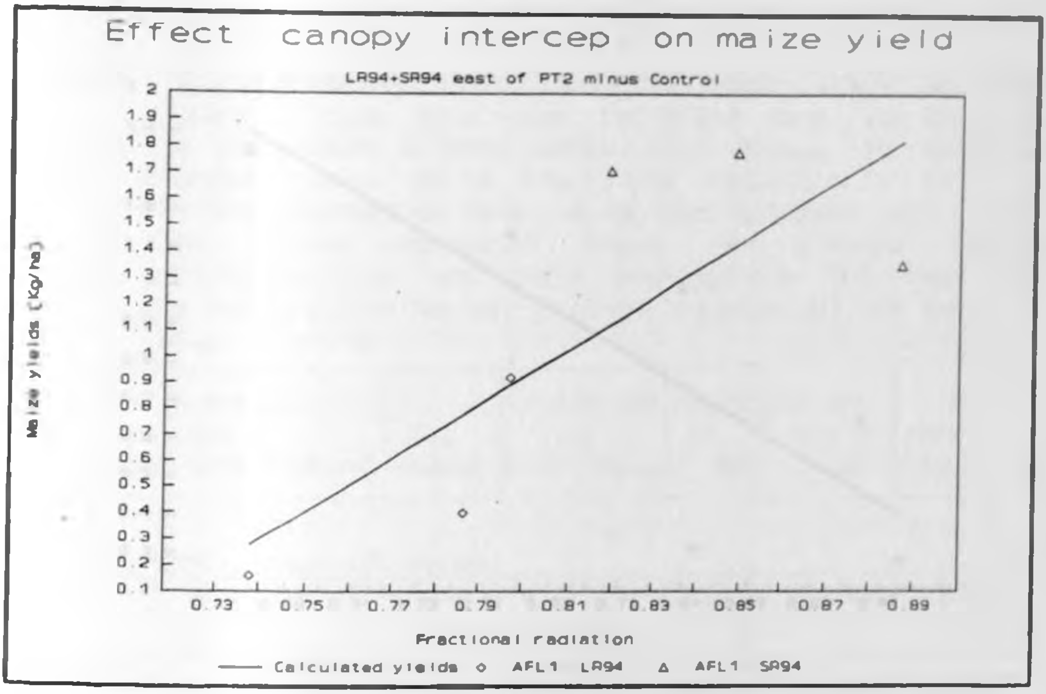

Fig. 328. The effect on maize dry matter yields on the east of PT2 of transmitted radiation through PT2 canopy during two rainy seasons of 1994 (LR94 & SR94).

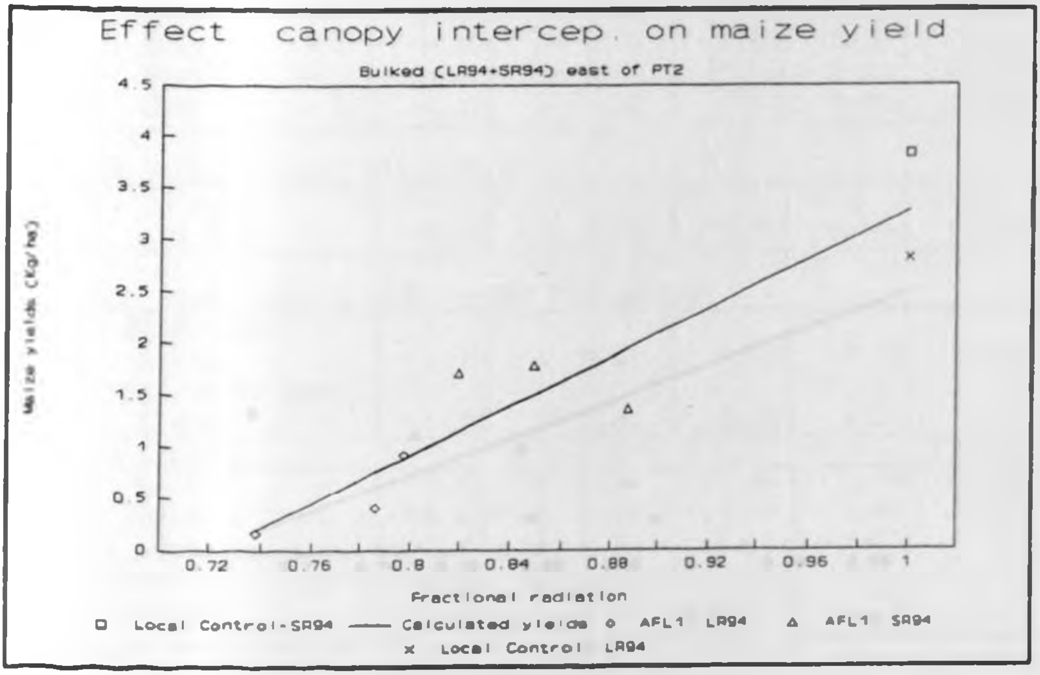

Fig. 329. The effect on maize dry matter yields on the east of PT2 of transmitted radiation through PT2 canopy and full radiation in Local control (L) during two rainy seasons of 1994 (LR94 & SR94).

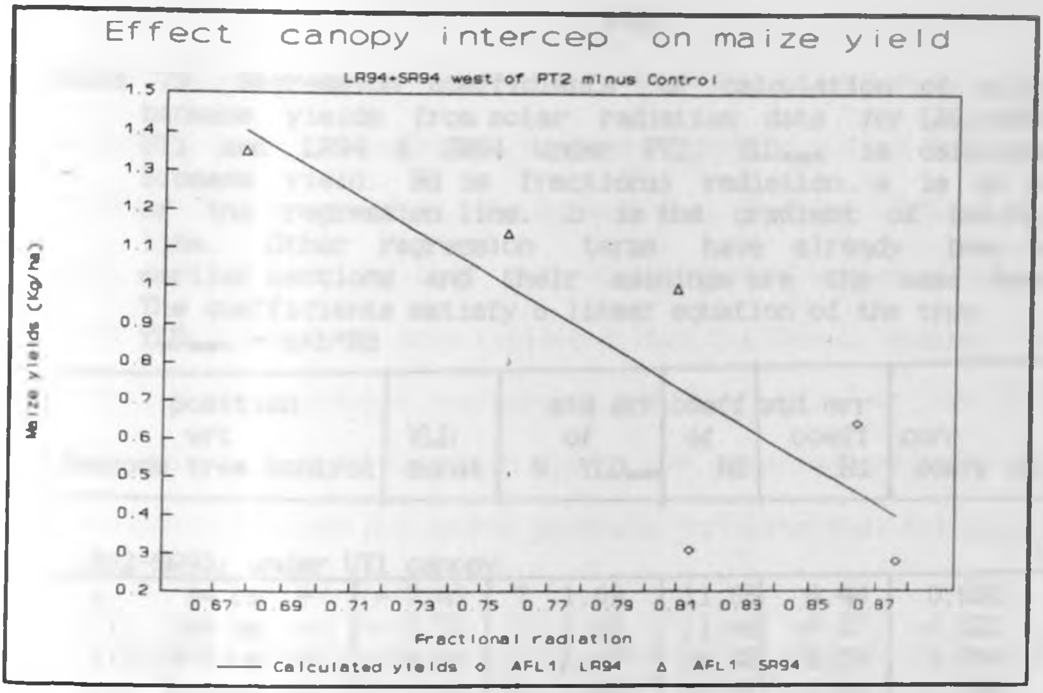

Fig. 330. The effect on maize dry matter yields on the west of PT2 of transmitted radiation through PT2 canopy during two rainy seasons of 1994 (LR94 & SR94).

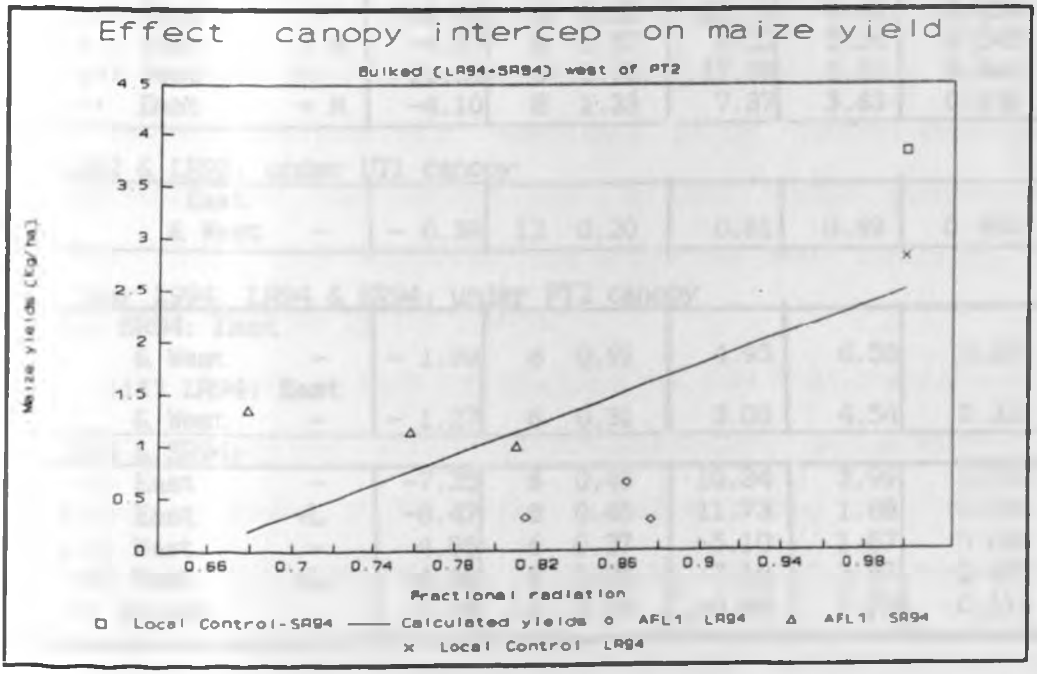

Fig. 331. The effect on maize dry matter yields on the west of PT2 of transmitted radiation through PT2 canopy and full radiation in Local control (L) during two rainy seasons of 1994 (LR94 & SR94).

Table 79. Regression coefficients of calculation of maize total biomass yields from solar radiation data for LR92-SR93 under UT1 and LR94 & SR94 under PT2. YLD_{est} is calculated maize biomass yield. Rd is fractional radiation. a is an intercept of the regression line. b is the gradient of the regression line. Other regression terms have already been met in earlier sections and their meanings are the same even here. The coefficients satisfy a linear equation of the type:
YLD_{est} = a+b*Rd

Seasons	position wrt tree	control	YLD const	N	std err of YLD_{est}	coeff of Rd	std err coeff Rd	corr coeff (r)
LR92-SR93: under UT1 canopy								
(i)	94 cm	-	- 7.49	7	1.69	11.68	6.44	0.630
(ii)	188 cm	-	- 7.72	7	1.69	11.46	8.37	0.522
(iii)	376 cm	-	- 6.99	7	1.47	10.70	5.53	0.654
(iv)	Bulked	-	- 7.03	21	1.47	10.85	3.44	0.586
(v)	East	-	-11.73	9	1.45	17.23	5.73	0.751
(vi)	West	-	- 4.71	12	1.41	7.47	4.10	0.499
SR92 & SR93: under UT1 canopy								
(i)	East & West	-	-13.35	12	0.73	19.96	2.37	0.936
(ii)	East	-	-14.98	6	0.95	22.01	4.49	0.926
(iii)	East	+ M	-4.57	8	1.72	8.22	5.16	0.545
(iv)	West	-	-11.68	6	0.72	17.78	3.23	0.940
(v)	East	+ M	-4.10	8	1.33	7.37	3.63	0.638
LR92 & LR93: under UT1 canopy								
(i)	East & West	-	- 0.39	12	0.20	0.81	0.69	0.400
Year 1994: LR94 & SR94: under PT2 canopy								
(i) SR94:	East & West	-	- 1.99	6	0.91	4.93	6.58	0.351
(ii) LR94:	East & West	-	- 1.27	6	0.31	3.08	4.54	0.321
LR94 & SR94:								
(i)	East	-	-7.35	6	0.46	10.34	3.99	0.792
(ii)	East	+L	-8.47	8	0.48	11.73	1.88	0.931
(iii)	West	-	4.86	6	0.27	-5.10	1.67	0.836
(iv)	West	+L	-4.68	8	1.05	7.18	3.57	0.635
(v)	Bulked	-	2.34	12	0.56	-0.98	2.79	0.110

under PT2 were very low indeed (r=32.1% for LR94 and r=35.1% for SR94) (see Table 79). Low conversion efficiencies, e. under PT2 (Figs. 324 & 325) meant that very higher fractional radiation and therefore very high radiation amounts were needed to attain lowest cut-off limit, which may lead to high radiation loads and crop physiological damage under such canopies. However, in Matanya water as a major limiting factor may have drastically influenced ε. The bulked data in Figs. 326 & 327 showed even gloomier picture than each of the season values. The open canopy under PT2 allowed in more radiation than the level necessary which may have led to increased respiration and destruction of dry matter with every added unit of radiation, hence the negative gradient, -0.98. The correlation between dry matter produced (or destroyed) and radiation was very small (i.e r= 11.0%).

Examining the dry matter produced on the eastern and western sides of PT2 with and without control plots data (Figs. 328 & 329 and 330 & 331) we see that r for the eastern side of PT2 was 0.792 which increased by 17.6% to 0.931. However, r for the western side of PT2 (which also did not develop full intercrop canopy cover) was 0.836 which dropped by 16.8% to 0.635 when dry matter data for the Local control were included. The latter, decrease in r when data in the control were added, was consistent with the findings for the SR92 & SR93 seasons discussed above. Again this suggested the effect of open canopy of the solar radiation received by the plants.

We observe in both for the LR94 and SR94 that there was higher dry matter produced per unit radiation intercepted in the eastern than in the western sides of PT2 before and after adding data in the control plots. The gradients of the regression line for the eastern side was 10.34 t/ha which slightly improved to 11.73 t/ha when data in the control were added. However, on the western side every added unit of radiation decreased dry matter by 5.10 t/ha. This nevertheless changed the trend which increased when the control data were included. This change of the trend points to the fact that other factors such as water are much more important. Higher radiation when water is available, as for the SR92, increased dry matter production.

We may conclude here that only Short rains seasons have a chance for a sensible correlation between radiation and biomass yields if no depressions, for other reasons other than radiation, occur. A part from SR92 other seasons suffered from drought.

CHAPTER FOUR

4.5 Results on soil temperature at Matanya

4.5.1 Results of thermistor calibration

We can see from the results of calibration in the Calibration Chamber as given in Fig. 332 that the two sets of instruments were very close. The correlation coefficient (r=0.999) of the resistances was very high and close to one. The gradient of the regression line of TM2 on TM1 was 1.05 while the intercept was -0.25. They responded very closely to the thermostat temperature in the calibration Chamber. Fig. 333 shows an asymptotic inverse quadratic curve of thermistor resistance versus the chamber temperatures.

The high relationship between the sensors implies that temperatures measured are nearly the same and any irregularity is not because of differences in the sensors but other factors.

4.5.2. Average weekly soil temperatures (AWT) at Matanya

Soil temperatures, like other parameters, respond to between season changes in the factors that influence surface and near-surface temperatures and temperature gradients (e.g. Mungai, 1991, Bussiere and Cellier, 1994). Hence, interpretation of soil temperature data for an experimental area may require a knowledge of these factors. The factors include: atmospheric conditions, soil moisture content and soil porosity, soil as well as surface cover. Others are soil albedo (be it as a minor factor), long wave radiation emissivity, volumetric heat capacity and thermal conductivity, all of the near surface soil and the surface cover, such as mulch.

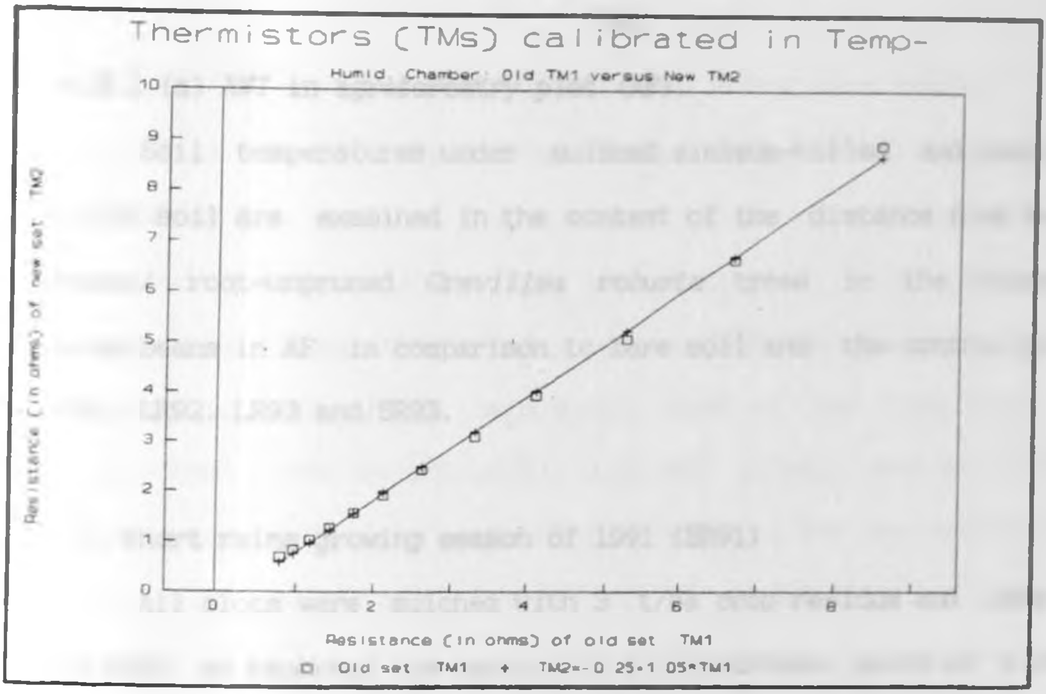

Fig.332. The correlation curve for the old (TM1) and new (TM2) sets of Grant thermistors

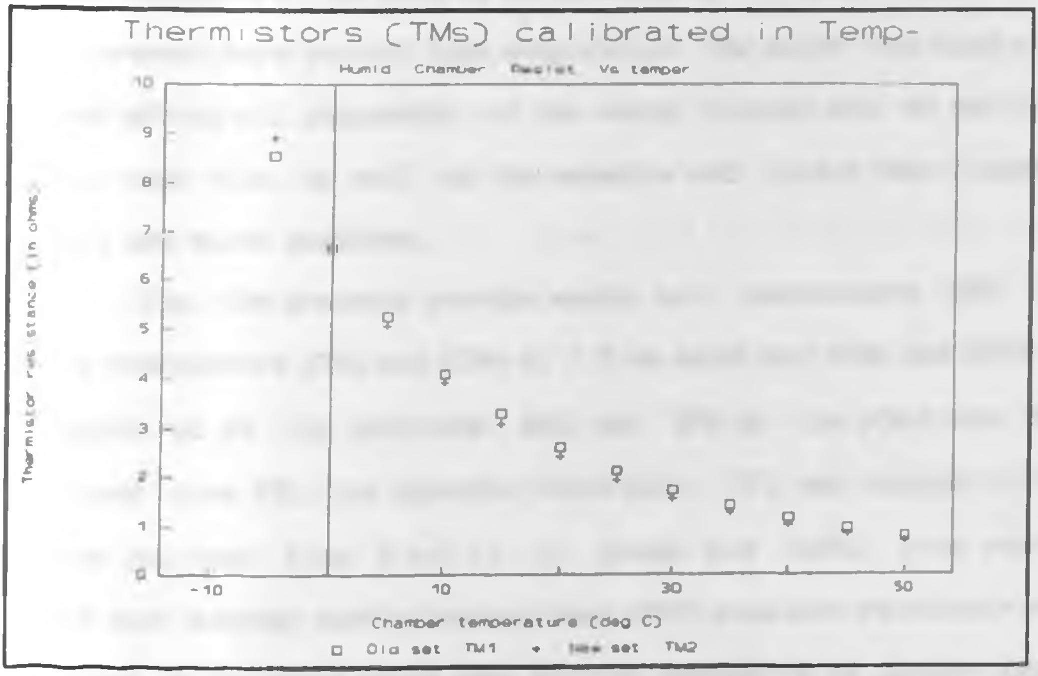

Fig. 333. The correlation curve for the old and new sets of Grant thermistors against temperature in the Temperature-Humidity Calibration Chamber.

4.5.2 (a) AWT in agroforestry plot (AF).

Soil temperatures under mulched minimum-tilled and Local deep-tilled soil are examined in the context of the distance from the root-pruned/ root-unpruned *Grevillea robusta* trees in the intercrop of maize/beans in AF in comparison to bare soil and the control plots for SR91. LR92, LR93 and SR93.

(i) Short rains growing season of 1991 (SR91)

All plots were mulched with 3 t/ha crop residue and deep tilled for SR91 as reported in section 4.1. A surface mulch of relatively large, non layered elements loses intercepted water rapidly and only somewhat limits the heat and water vapour exchanges between the soil and the atmosphere. The kind of mulch existing of maize stalks is expected to prevent more run-off than evaporation. The mulch and kind of tillage used affect all components of the energy balance and so net radiation. soil heat flux, as well as the sensible and latent heat fluxes at the soil and mulch surfaces.

Fig. 334 presents average weekly soil temperatures (AWT) for SR91 for thermistors ATM2 and ATM4 at 7.5 cm depth and ATM1 and ATM3 at 15 cm depths at 94 (in positions AM1) and 376 cm (in positions BM1) from pruned tree PT1 (see appendix Table A11). PT1 was located in the upper tree row (see Figs. 8 and 11) in pruned plot (AFM1). From week wk1 to wk9 the average weekly temperatures (AWT) remained relatively stable at around 18.7°C after which they started increasing as January approached. AWT in AM1 and BM1 were sometimes highest at 15 cm depth, but the temperature differences are initially small. We can see from Fig. 334 that AWT in positions AM1 and BM1 were generally on the upward trend after wk9. AWT in position BM1 decreased rather more rapidly after wk6 than AWT in AM1. AWT in position AM1 increased somewhat faster after wk9 than AWT in BM1.

The increase after wk9 was associated with expected high temperatures during the hot dry season (HD) which occurs from late December to early March before the onset of the Long Rains season (March-June) (see section 4.1). High AWT in week wk3 were associated with a drier (more sunny) week while low AWT in WK9 were associated with a less sunny wetter one. The AWT at AM1 decreased rather slowly with time after wk5 because the tree canopy impeded radiative exchange between the sky and the soil surface with respect to both long wave radiation, most important during night-time, and short wave radiation during day-time. This exchange affected differently the heat balance of the soil next to PT1 in position AM1 and further away in position BM1. Thermistors in BM1 were further from PT1, hence heat loss to the atmosphere through radiative cooling, evaporative cooling and sensible heat loss (surface cooler or warmer than air above it) tend to be more in position BM1 than in position AM1.

Fig. 335 presents average weekly soil temperatures (AWT) for thermistors ATM5, ATM6, ATM7 and ATM8 in positions AL1 and BL1 from PT2 for SR91 (see appendix Table A11). PT2 was located in pruned (AFL1) plot in the same tree row as PT1.

AWT for PT2 behaved in a similar way to AWT for PT1. However AWT in wk9 was still lower at 7.5 cm compared to those at 15 cm, but then the ones at 94 cm were more. Again wk3 had generally high AWT while wk9 had low AWT for the same reasons already advanced.

AWT in the lower part of AF (Fig. 336) at unpruned tree UT4 in plot AFM2 had similar trend to AWT at tree PT1 although the temperatures

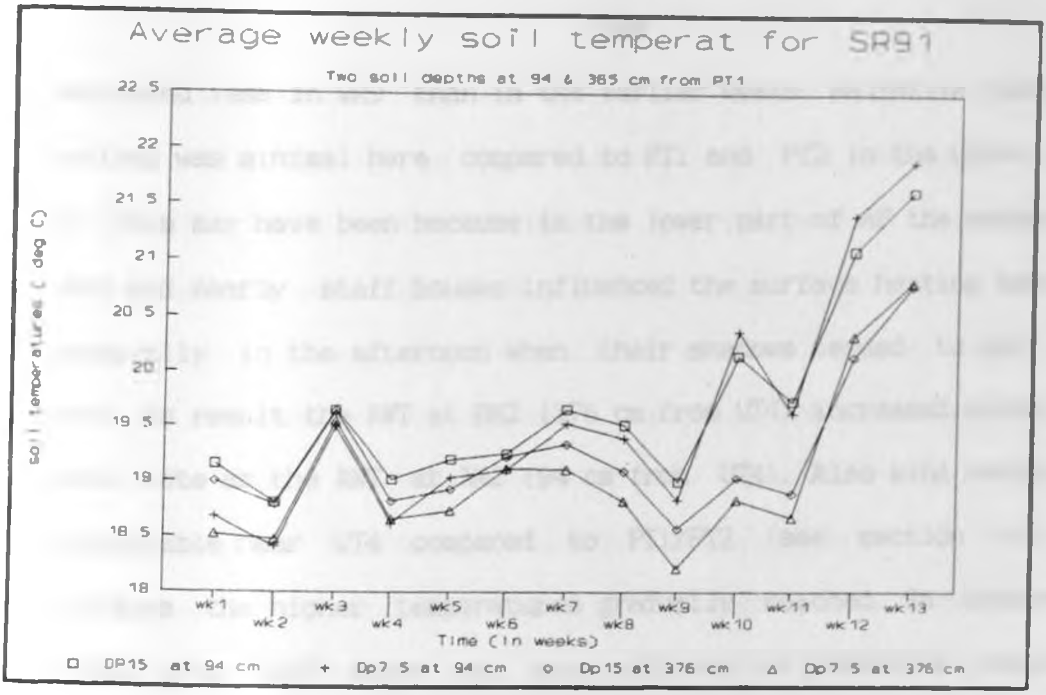

Fig. 334. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from pruned tree PT1 in Mulched plot (AFM1) during SR91.

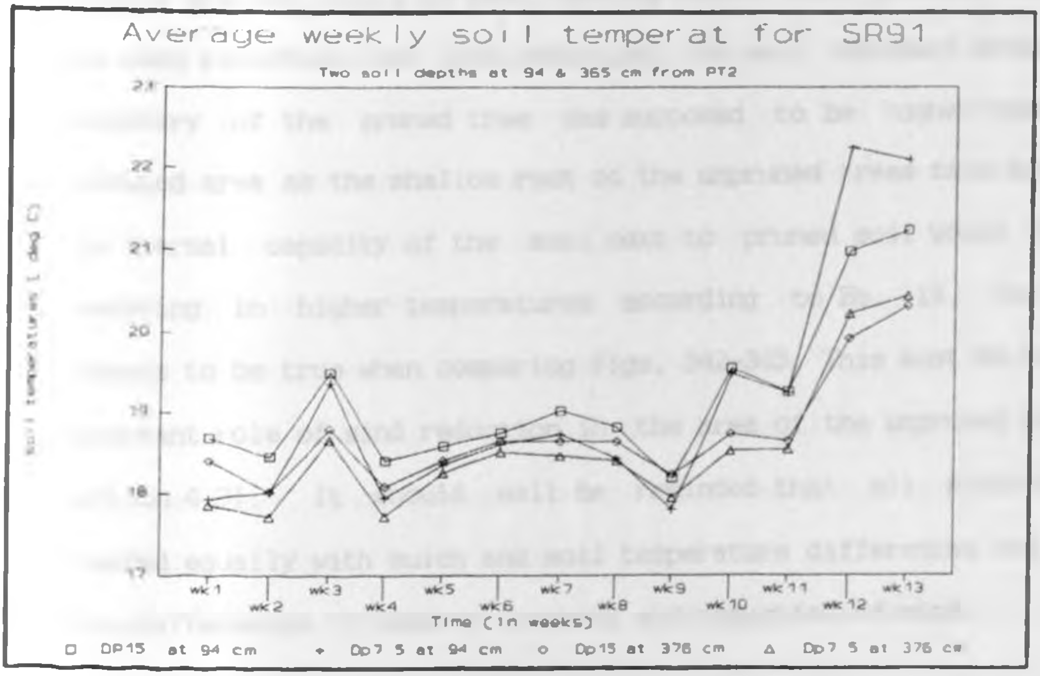

Fig. 335. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from pruned tree PT2 in Local plot (AFL1) during SR91.

decreased less in wk9 than in the earlier weeks. Radiative heating and cooling was minimal here compared to PT1 and PT2 in the upper part of AF. This may have been because in the lower part of AF the western hedge (WH) and nearby staff houses influenced the surface heating negatively, especially in the afternoon when their shadows tended to fall on this part. As result the AWT at BM2 (376 cm from UT4) increased almost at the same rate as the AWT at AM2 (94 cm from UT4). Also wind reduction was appreciable near UT4 compared to PT1/PT2 (see section 4.3). This explains the higher temperatures gradually reached. In unpruned area (AFL2) (Fig. 337) there was more evidence of radiative heating and cooling at BL2 than at AL2 (thermistor ATM16 for 7.5 cm was faulty, so we did not instal it in the field). The behaviour of AWT at 15 cm depth (ATM15) pointed to more radiative cooling at BL2 than at BM2. For the equally treated plots of SR91, the variables were pruning/ not pruning and wind reduction /non wind reduction. The soil moisture status in the periphery of the pruned tree was supposed to be higher than in the unpruned area as the shallow root of the unpruned trees take more water. The thermal capacity of the soil next to pruned soil would be higher resulting in higher temperatures according to Eq. 16. The opposite appears to be true when comparing Figs. 342-345. This must be due to the important role of wind reduction in the area of the unpruned trees (see section 4.3). It should well be reminded that all plots had been treated equally with mulch and soil temperature differences had to come from differences in shading, pruning and reduction of wind.

(ii) Long rains growing season of 1992 (LR92)

For LR92 the AF plot was sub-divided into four strips running East-West, two of which were mulched and minimum tilled to a depth of

4.0-5.0 cm while the other two were unmulched and deep tilled to a depth of 20.0-25.0 cm as we have already seen in section 4.1.2. The thermistors were installed before land preparation for the coming growing season and remained in place througnout that season and the dry season that followed. Initialization problems, however, resulted from frequent removal of the Grants to download the data and change the batteries. This somewhat caused some instability in temperature fluctuations as it would take one to two days before these fluctuations would tabilize again. We did soil temperature measurements in four experimental periods: P1, P2, P3 and P4. Weeks wk1-wk3 were in P1, wk4-wk8 were in P2, wk9-wk11 were P3 and wk12-wk15 were in P4 (see appendix Table A12 for the dates of these weeks).

Fig. 338 presents AWT for LR92 at PT1 in pruned, now Mulched and minimum-tilled plot (AFM1). Periods P1 and P4 had generally lower AWT than periods P2 and P3. In P1 high AWT were observed at 15 cm depth in positions AM1 and BM1. In positions AM1 and BM1 we observe small temperature differences, highest AWT at 15 cm depth and the lowest at 7.5 cm depth, with the highest differences even at 94 cm. The lowest temperatures at 7.5 cm were most likely due to a difference in mulch effect, differences in soil moisture between the two distances and differences in damping depths discussed. Comparing Figs. 346 and 347 both the above arguments are strengthened. Under non-mulched conditions and deep tillage 94 cm remains below 376 cm at both depths but particularly at 15 cm. We also expect influence from air mass temperatures due to south east monsoon, that flows in from the Indian Ocean during this time of the year, as seen in Fig. A5 (Griffiths, 1972) and from day time radiation as shown by strong reactions in wk7. In P2 (wk4-wk8) the situation was very different. High AWT were observed

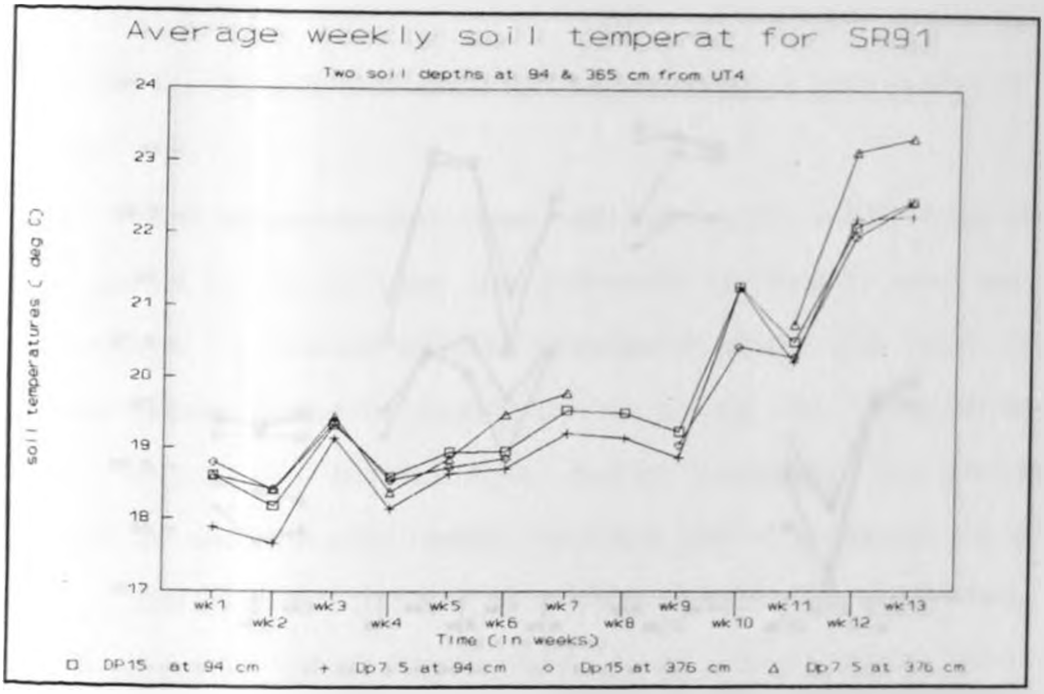

Fig. 336. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from unpruned tree UT4 in Mulched plot (AFM2) during SR91.

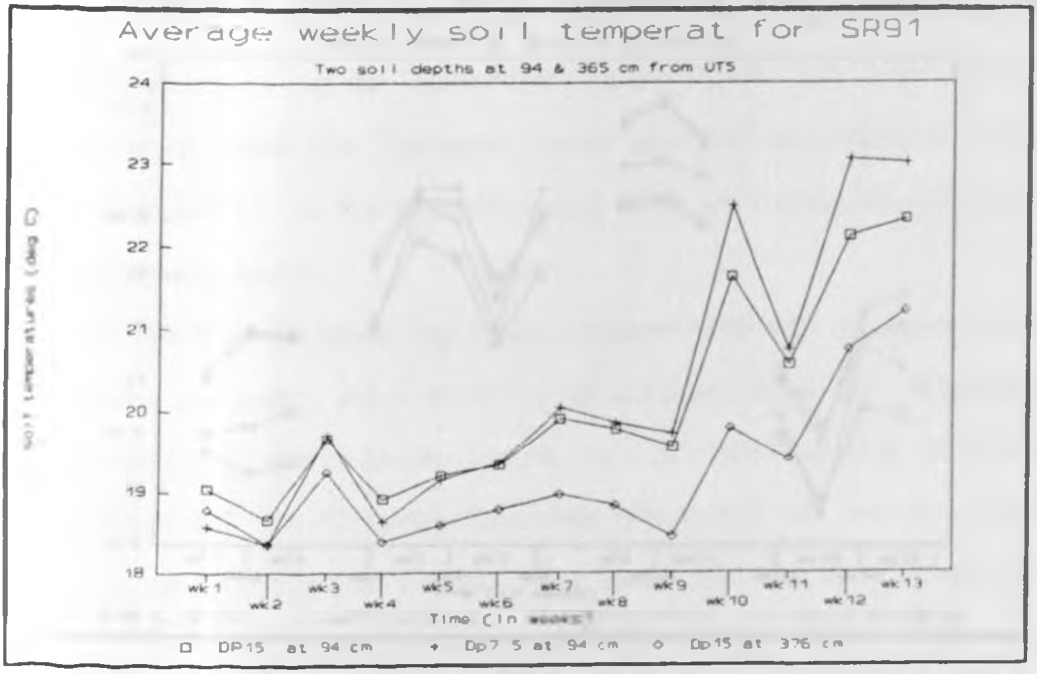

Fig. 337. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from unpruned tree UT5 in Mulched plot (AFL2) during SR91

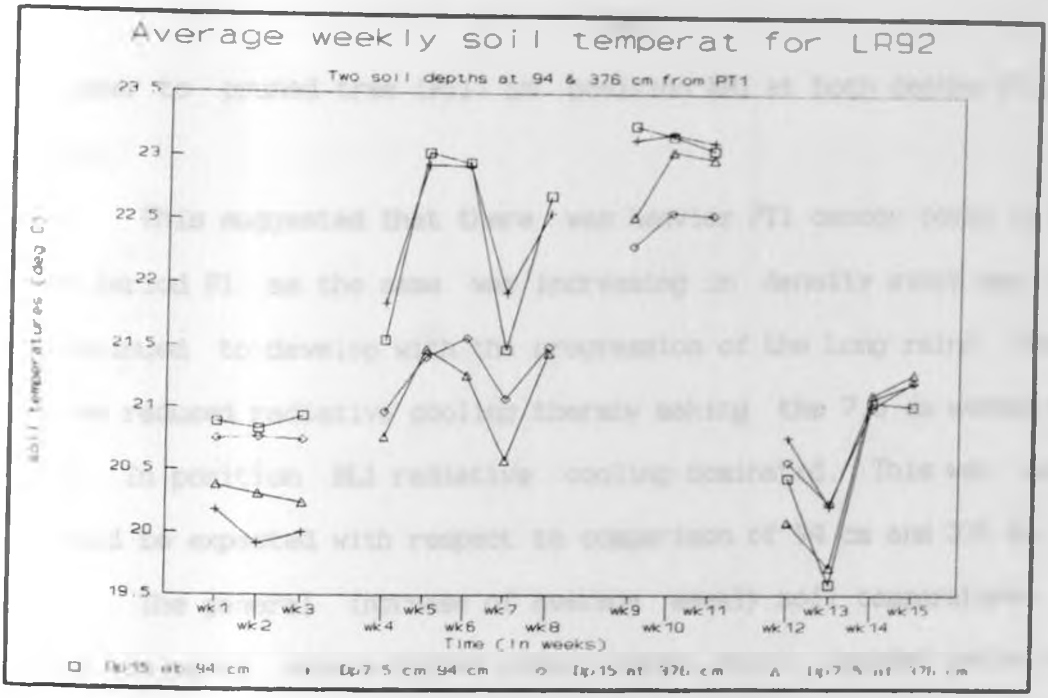

Fig. 338. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from pruned tree PT1 in Mulched plot (AFM1) during LR92.

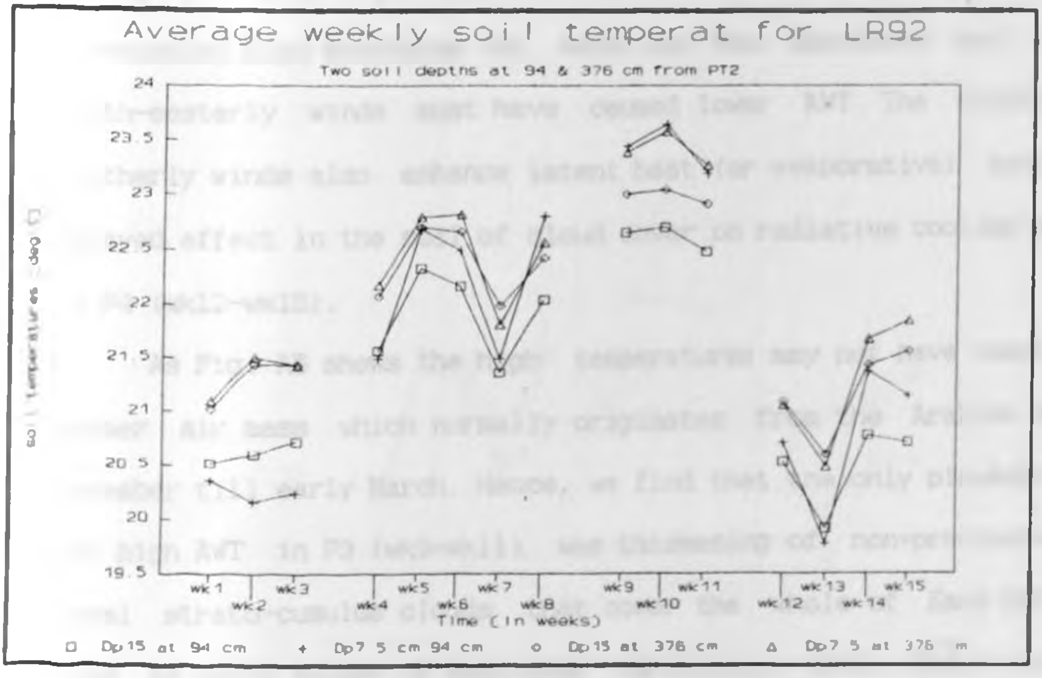

Fig. 339. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from pruned tree PT2 in Local plot (AFL1) during LR92.

closer to pruned tree (PT1) in position AM1 at both depths (7.5 and 15 cm).

This suggested that there was heavier PT1 canopy cover in P2 than in period P1 as the same was increasing in density since new foliage continued to develop with the progression of the Long rains. This might have reduced radiative cooling thereby making the 7.5 cm warmer than 15 cm. In position BL1 radiative cooling dominated. This was more what could be expected with respect to comparison of 94 cm and 376 cm.

The general increase of average weekly soil temperatures P2 was due to among others higher cloud cover, which impeded radiative heat loss to the atmosphere and increased long wave counter radiation from the clouds, even though there was some radiative input during day-time. Mulching assisted in keeping the soil warmer and moister. Rainfall during wk7 and night-time air mass (katabatic winds) from the surrounding high mountains (Mt. Kenya and Mts. Aberdares) and also cool south-easterly winds must have caused lower AWT. The strong, mainly southerly winds also enhance latent heat (or evaporative) cooling. The delayed effect in the soil of cloud cover on radiative cooling showed up in P4 (wk12-wk15).

As Fig. A5 shows the high temperatures may not have resulted from warmer air mass which normally originates from the Arabian desert in December till early March. Hence, we find that the only plausible reason for high AWT in P3 (wk9-wk11), was thickening of non-precipitating low level strato-cumulus clouds that cover the whole of East Africa from June to early August of each year (Griffiths, 1972). These clouds come with S.E. winds that blow from the Indian ocean during this time, but not deep enough to precipitate (Griffiths, 1972). Such clouds impede long wave radiation loss to the atmosphere.

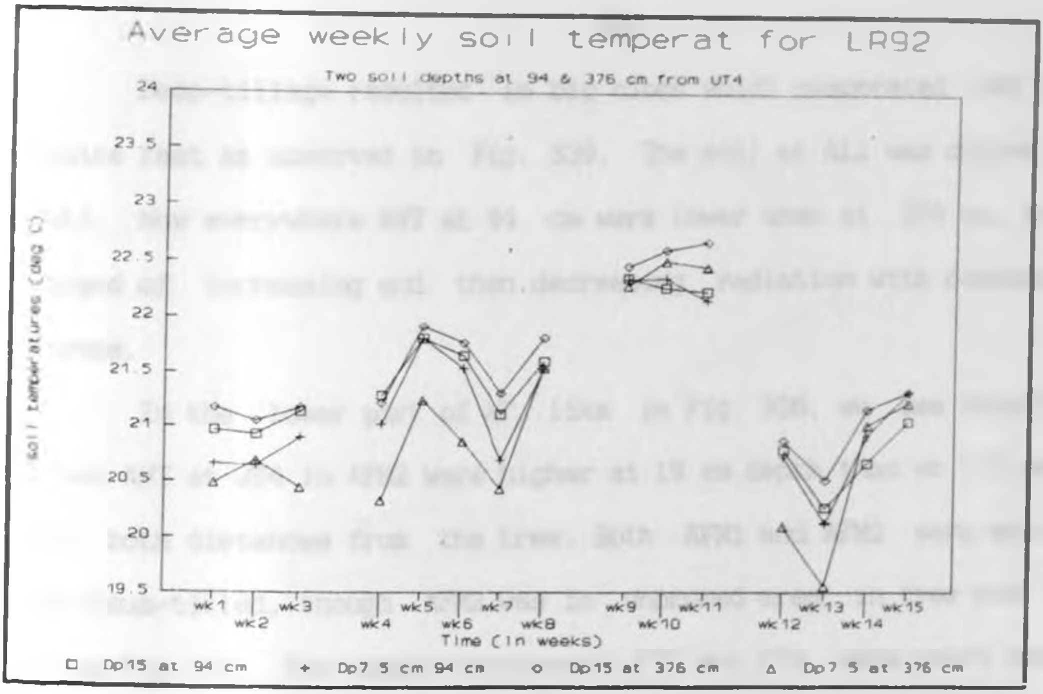

Fig. 340. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from unpruned tree UT4 in Mulched plot (AFM2) during LR92.

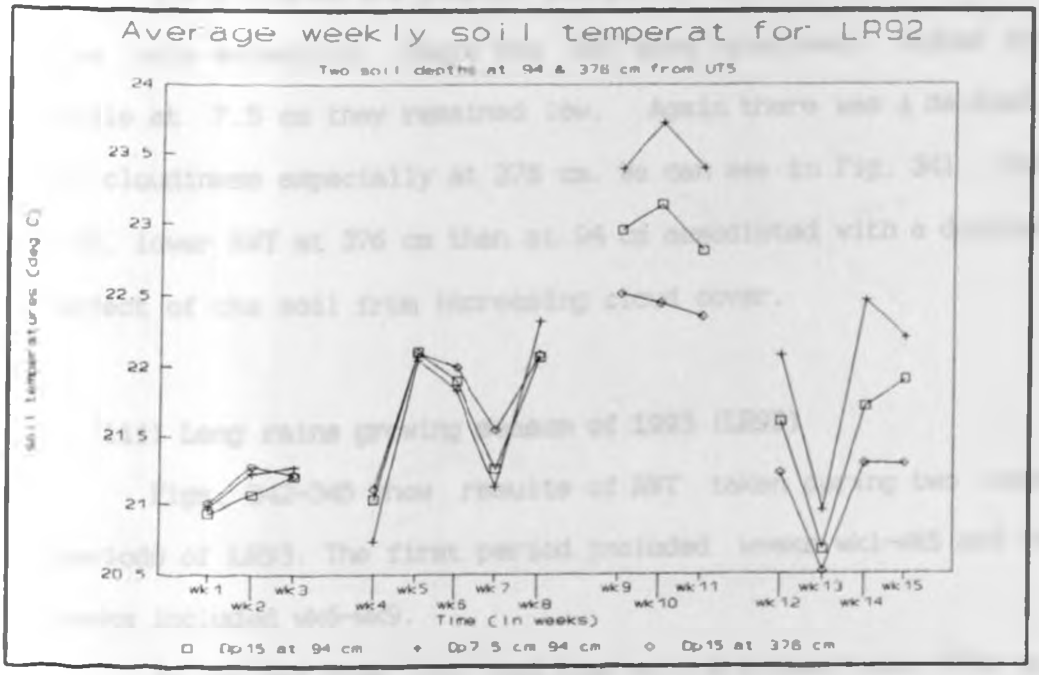

Fig. 341. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from unpruned tree UT5 in Local plot (AFL2) during LR92.

Deep-tillage resulted in big clods which evaporated and dried up quite fast as observed in Fig. 339. The soil at AL1 was cooler than at BL1. Now everywhere AWT at 94 cm were lower than at 376 cm, showing a trend of increasing and then decreasing radiation with distance from trees.

In the lower part of AF, like in Fig. 338, we see from Fig. 340 that AWT at UT4 in AFM2 were higher at 15 cm depth than at 7.5 cm depth at both distances from the tree. Both AFM1 and AFM2 were mulched and Minimum-tilled, though AFM2 was in unpruned area in tree row D (TR3) (see Fig. 9). The common treatments PT1 and UT4 were mulch cover and minimum tillage. Lower AWT at 7.5 cm at both trees (PT1 & UT4) and distances (94 and 376 cm) were therefore due to these common treatments, particularly mulch cover.

The pictures are roughly identical, but 15 cm depth at 376 cm is the only exception, where the AWT were relatively higher throughout, while at 7.5 cm they remained low. Again there was a delayed reaction to cloudiness especially at 376 cm. We can see in Fig. 341, like in Fig. 339, lower AWT at 376 cm than at 94 cm associated with a delayed cooling effect of the soil from increasing cloud cover.

(iii) Long rains growing season of 1993 (LR93)

Figs. 342-345 show results of AWT taken during two experimental periods of LR93. The first period included weeks wk1-wk5 and the second weeks included wk6-wk9.

We can see from Fig. 342 that at the pruned tree (PT1) in Mulched and minimum-tilled plot (AFM1) there was a general drop in AWT from wk1 to reach minimum in wk2 as hot dry season receded and the Long Rains season of 1993 (LR93) set in. In the first period (wk1-wk5) the highest

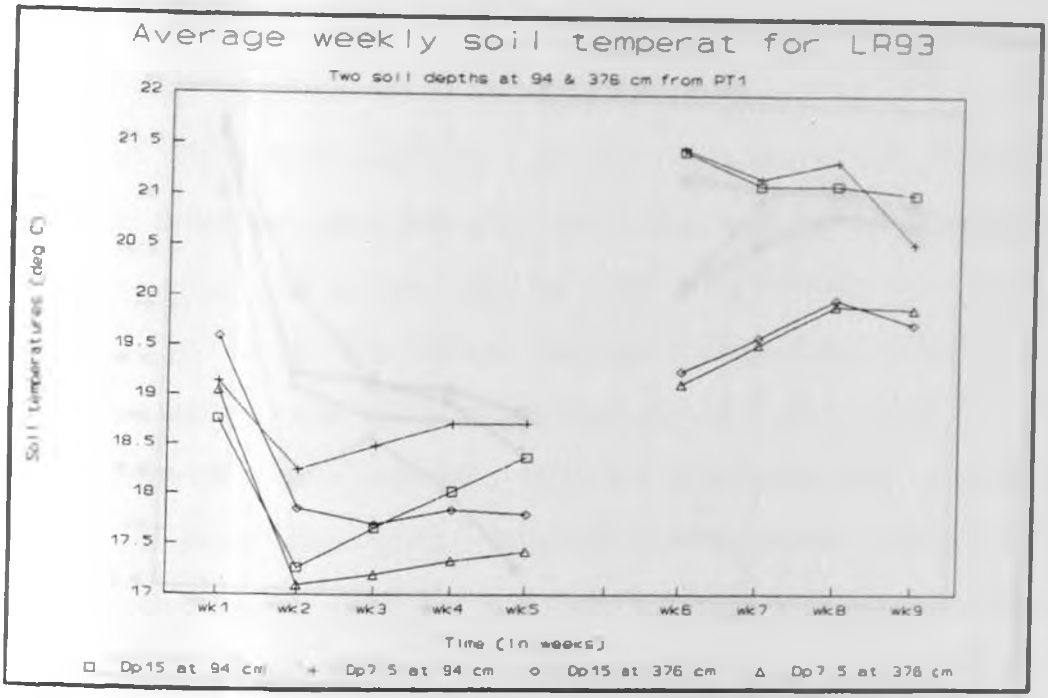

Fig. 342. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from pruned tree PT1 in Mulched plot (AFM1) during LR93.

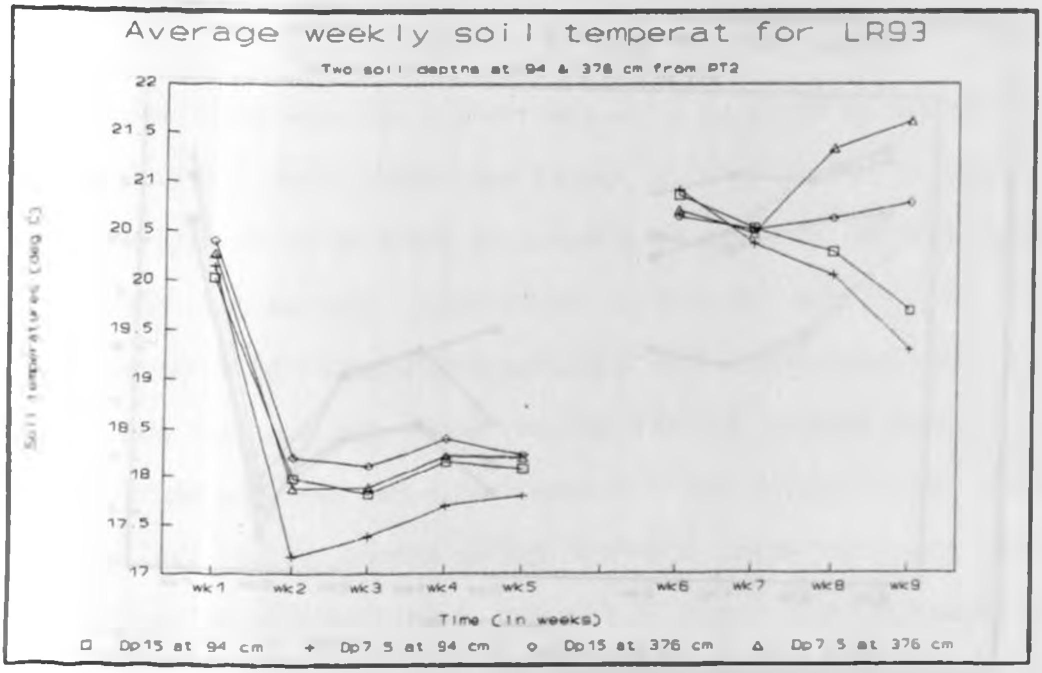

Fig. 343. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from pruned tree PT2 in Local plot (AFL1) during LR93.

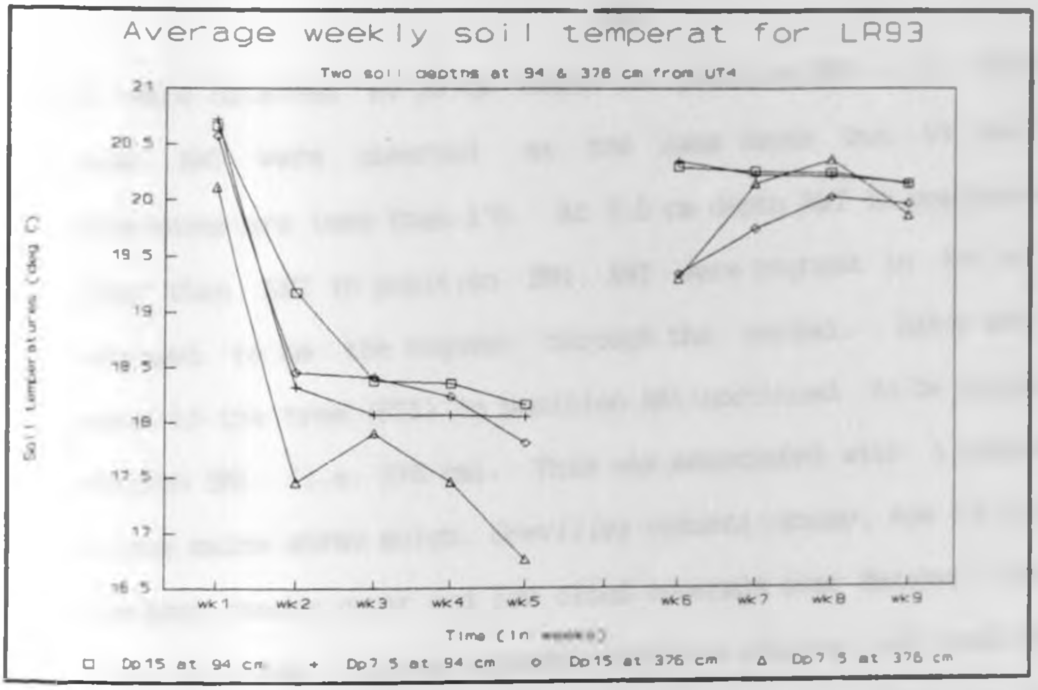

Fig. 344. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from unpruned tree UT4 in Mulched plot (AFM2) during LR93.

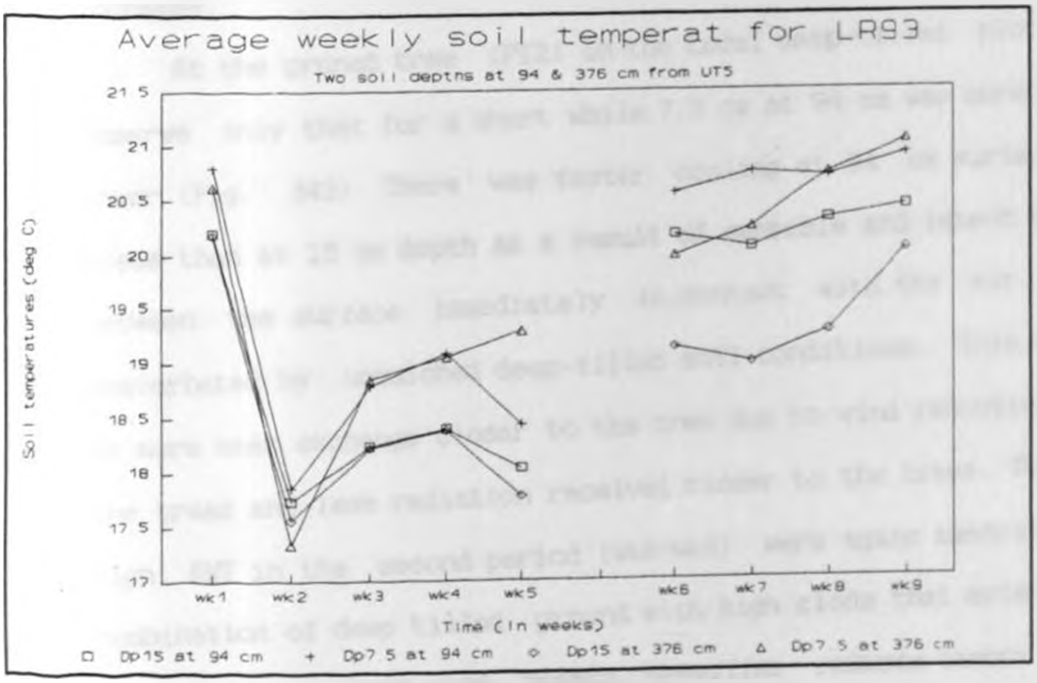

Fig. 345. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from unpruned tree UT5 in Local plot (AFL2) during LR93.

AWT were obtained at 15 cm depth in position BM1 (i.e. 376 cm). The lowest AWT were observed at the same depth but 94 cm PT1. All differences are less than 1°C. At 7.5 cm depth AWT in position AM1 were higher than AWT in position BM1. AWT were highest in AM1 in wk2 and continued to be the highest through the period. After wk3 the AWT nearer to the tree (PT1) in position AM1 continued to be higher than in position BM1 (i.e. 376 cm). This was associated with a combination of surface maize straw mulch, *Grevillea robusta* canopy, now fully developed intercrop canopy cover and low cloud coverage over Matanya. The combined effect of these factors impeded radiative cooling and resulted in the high temperatures in the second period as they affected radiative, sensible, latent heat exchanges. In the second period (wk6–wk9) the AWT at 94 cm and at 376 cm had very small differences but with a tendency to increase.

At the pruned tree (PT2) in the Local deep-tilled plot (AFL1) we observe only that for a short while 7.5 cm at 94 cm was more than 0.5°C lower (Fig. 343). There was faster cooling at 94 cm surface near to trees than at 15 cm depth as a result of sensible and latent heat fluxes between the surface immediately in contact with the air, which are exacerbated by unmulched deep-tilled soil conditions. This was because of more heat exchange closer to the tree due to wind reduction effect of the trees and less radiation received closer to the trees. The generally high AWT in the second period (wk6-wk9) were again associated with a combination of deep tilled ground with high clods that acted as surface mulch and miniature wind breaks, *Grevillea robusta* canopy, now fully developed intercrop canopy cover and low cloud coverage over Matanya. These factors combined impeded radiative cooling and resulted in the high temperatures in the second period (wk6-wk9). The AWT nearer PT2 (at 94 cm) continued to fall whereas those at 376 cm (position BL1) continued to rise after wk7. The cooling next to PT2 was as a result of thickening tree canopy as new leaves emerged and expanded laterally. The canopy then impeded more than before radiative but because of strong wind through the deliberate gap (DGP, see Fig. 8) building up latent and sensible heat flux exchanges with the atmosphere were little affected. The temperature in control Local plots (Fig. 352) were negligibly small just as in agroforestry Local (AFL1) where PT2 is situated. In both cases there were slight increases in the AWT differences. The actual temperatures for AFL1 increased in the last half of the measuring periods while in the control Local they decreased. All other things being equal this points to the fact that tree canopy develop and cut-off out going long wave radiation which effect reduced radiative heat exchange with the atmosphere, causing higher temperatures.

At unpruned UT4 in the lower part of mulched AFM2 (Fig. 344) in position BM2 at 376 cm the AWT from wk2 to wk5 in the first period at 15 cm higher than those at 7.5 cm. The AWT at 7.5 and 15 cm at 94 cm distance (at AM2) were close to those at 15 cm depth and 376 cm from PT2. In second period both the AWT at both sites were very close but those at AM2 significantly differed from those at BM2. This may be associated with wind protection in this part of the plot, differences in soil moisture conditions and the influence of the tree shades. The slight variations of AWT at UT4 in unpruned from AWT in PT1 in pruned may be associated with differences in soil moisture conditions at both sites due to root pruning of PT1. The AWT at 376 cm had dropped faster than at 94 cm as the LR93 approached lower temperatures near the surface further from the trees, while temperatures first fell then rose, in a mulched plot, which must be falling/ rising temperatures above the mulches. These plots are wind protected, making radiation exchange relatively more important than in the upper part of the plot. At 376 cm more radiation may reach the soil in day time and leave the plot at night. The AWT at both sites had dropped sharply between wk1 and wk2 due to a factor associated more with instrument initialization problem than with changes in the thermal properties of the soil.

At unpruned UT5 in the lower part of Local AFL2 (Fig. 345) AWT dropped suddenly between wk1 and wk2 and started rising but stayed very close till wk3. With the same exposure, the differences must come from surface treatments only the 376 cm are having some differences between each other of some significance. After all only the 376 cm differ in reaction, the one at the surface (7.5 cm depth) remaining higher from wk3 onwards till wk9. This is a normal reaction against a possible change in the energy balance.

(iv) Short Rains growing season of 1993 (SR93)

Fig. 346 shows AWT for Short Rains growing season of 1993 (SR93) in pruned Mulched plus minimum tillage plot at tree PT1. We see here that in position AM1 (94 cm) higher AWT were observed at 7.5 cm depth than at 15 cm while the reverse was the case in position BM1 (at 376 cm) (although they come together in the end). These differences all remain within one degree. The AWT generally decreased from wk1 in October to December. The AWT values were lowest in November and but higher in December as the hot dry month (HD) approached. In wk4 these values were slightly higher than the preceding weeks or later weeks. This may have been due to the PT1 canopy cover playing a part in reducing the escape of long wave radiation into the sky. However, due to the wetness of the

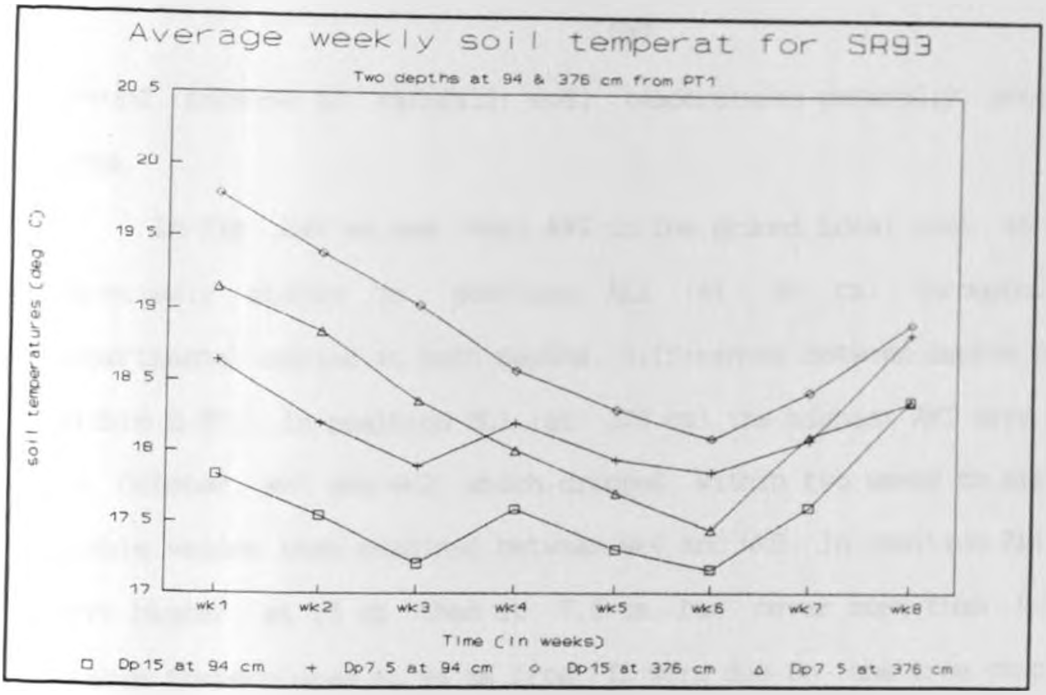

Fig. 346. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from pruned tree PT1 in Mulched plot (AFM1) during SR93.

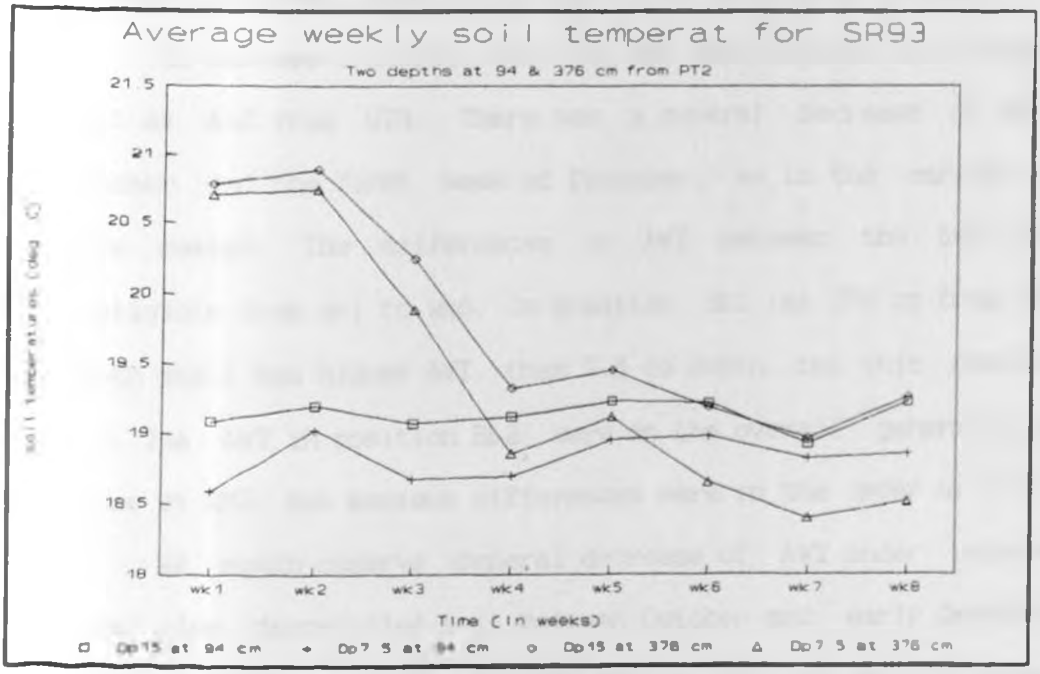

Fig. 347. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from pruned tree PT2 in Local plot (AFL1) during SR93.

ground because of rainfall, soil temperatures generally proceeded to drop.

In Fig. 347 we see that AWT in the pruned Local plot at PT2 were relatively stable in position AL1 (at 94 cm) throughout this experimental period at both depths, differences between depths remaining within 0.5°C. In position BL1 (at 376 cm) the highest AWT were observed in October, wk1 and wk2, which dropped within two weeks to attain near stable values that remained between wk4 and wk8. In position AL1 the AWT were higher at 15 cm than at 7.5 cm, but never more than 0.5°C. The stable temperatures at 94 cm from PT2 were due to the tree canopy which shielded the unmulched deep-tilled soil from excessive heat load. As SR93 progressed the wetter conditions caused a drop of temperatures, which was for BL1 faster at 7.5 cm, so nearer the surface. We have already discussed above higher AWT at 15 cm than at 7.5 cm.

We can see from Fig. 348 that AWT were high at both depths in the soil at AL2 from UT4. There was a general decrease of AWT between October and the first week of December, as in the earlier figures of this season. The differences in AWT between the two depths was negligible from wk1 to wk6. In position BL2 (at 376 cm from UT4) 15 cm depth still had higher AWT than 7.5 cm depth, but this remained within 1°C. The AWT in position BL2 were on the overall generally lower than those at AM2, but maximum differences were in the order of 2°C.

We again observe general decrease of AWT under unpruned UT5 on Local plus deep-tilled soil between October and early December in Fig. 349. The picture is close to that of Fig. 347, maximum differences, with only one exception, remaining within 1.5°C. The decrease in position AM2 (at 94 cm from UT5) was gradual at both depths while that at BM2 (376 cm) was more sudden, especially between wk3 and wk4. We have seen that

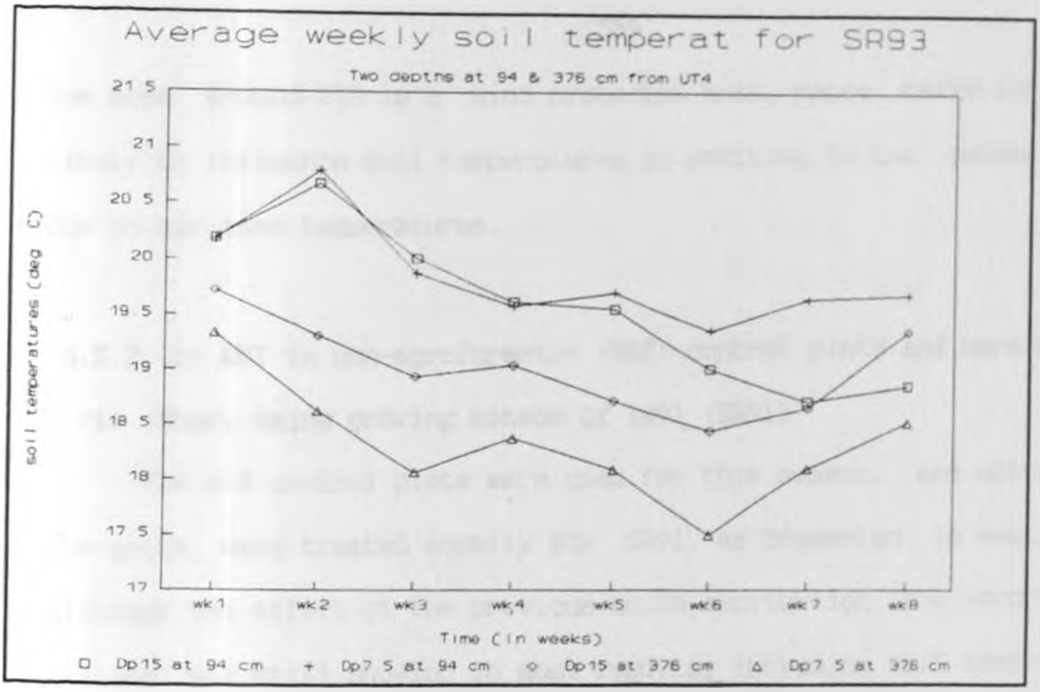

Fig. 348. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from unpruned tree UT4 in Mulched plot (AFM2) during SR93.

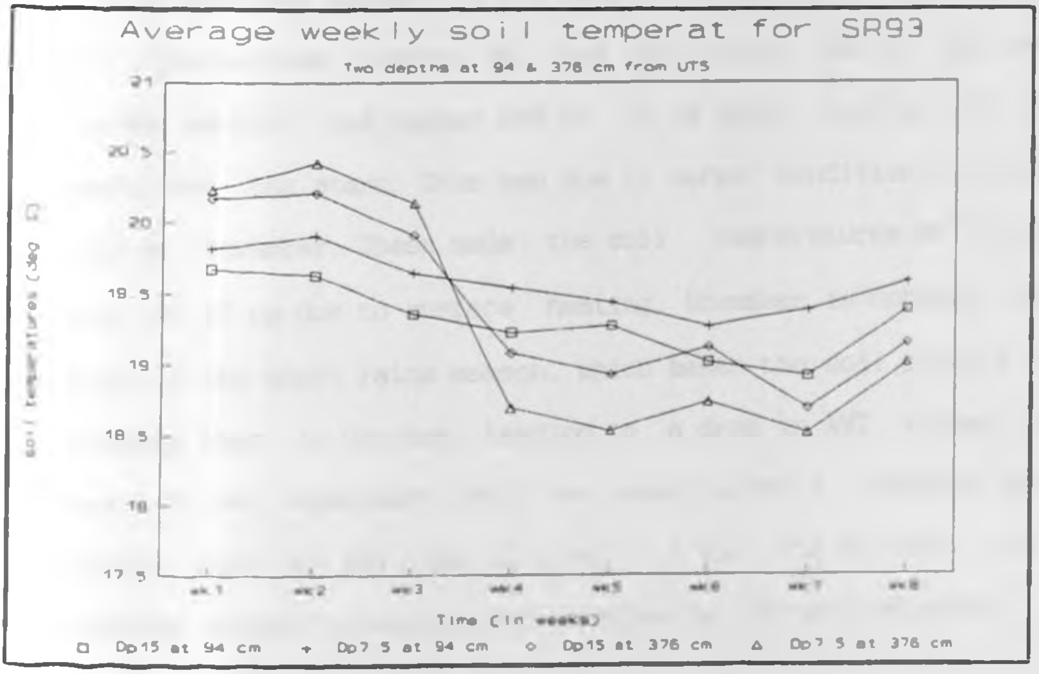

Fig. 349. Weekly average soil temperatures at the depths of 7.5 and 15 cm at the distances of 94 and 376 cm from unpruned tree UT5 in Local plot (AFL2) during SR93.

the area around UT5 is a wind protected area, hence radiation is more likely to influence soil temperatures in addition to the general trend, due to air mass temperatures.

4.5.2 (b) AWT in non-agroforestry (NAF) control plots and bare soil

(i) Short Rains growing season of 1991 (SR91)

The old control plots were used for this season, see section 4.1. The plots were treated equally for SR91, as presented in section 4.1, although the effect of the previous mulch application (now incorporating tilling) was still showing in most results, including soil temperatures. The bare soil however remained as such. It had just been created as bare soil.

Fig. 350 presents AWT for SR91 for the old control plots. The AWT were as expected highest in the bare soil (BS) followed by Local control (L). The Mulched control (M) had the lowest AWT of all plots. The Mulched control had higher AWT at 15 cm depth than at 7.5 cm depth, apart from the start. This was due to warmer conditions in October 1991 than in November. These made the soil temperatures at 7.5 cm warmer than at 15 cm due to surface heating. November is normally the central month of the short rains season, which makes the soil surface moister in November than in October, leading to a drop in AWT values. The second week of the experiment (wk2) had some rainfall episodes resulting in general fall in AWT, but only at 7.5 cm. The Mulched soil remained somewhat cooler throughout the experimental period (wk1-wk4).

(ii) Long Rains growing season of 1992 (LR92)

Fig. 351 presents AWT in the control plots for the months of June and July 1992. Although June and July fall outside the designated Long

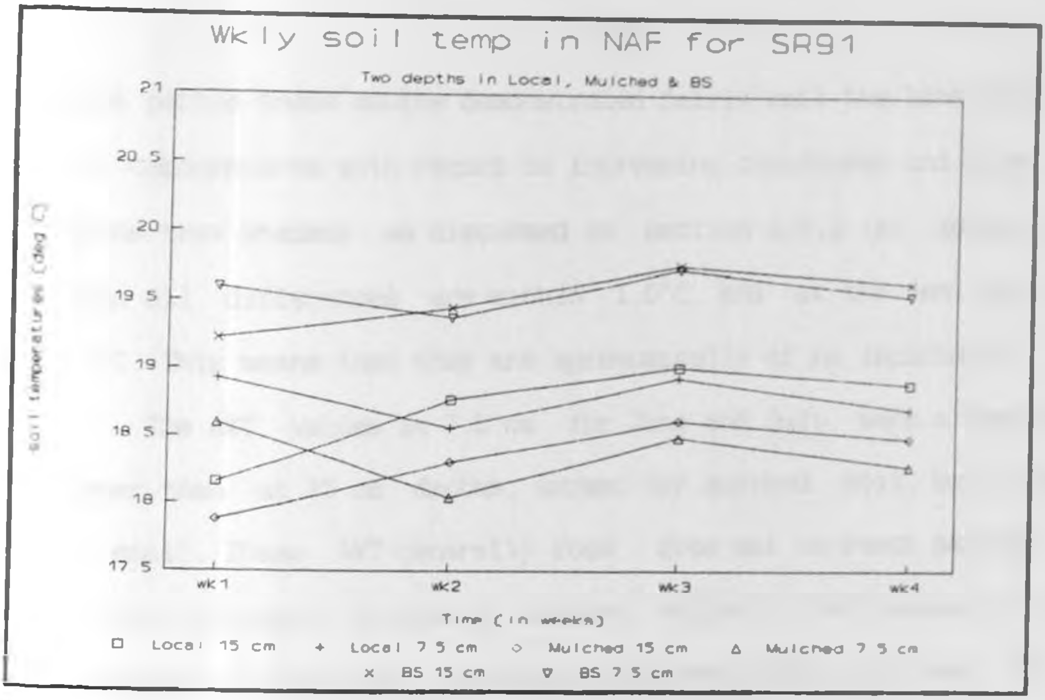

Fig. 350. Weekly average soil temperatures at the depths of 7.5 and 15 cm in the control and bare soil plots during SR91.

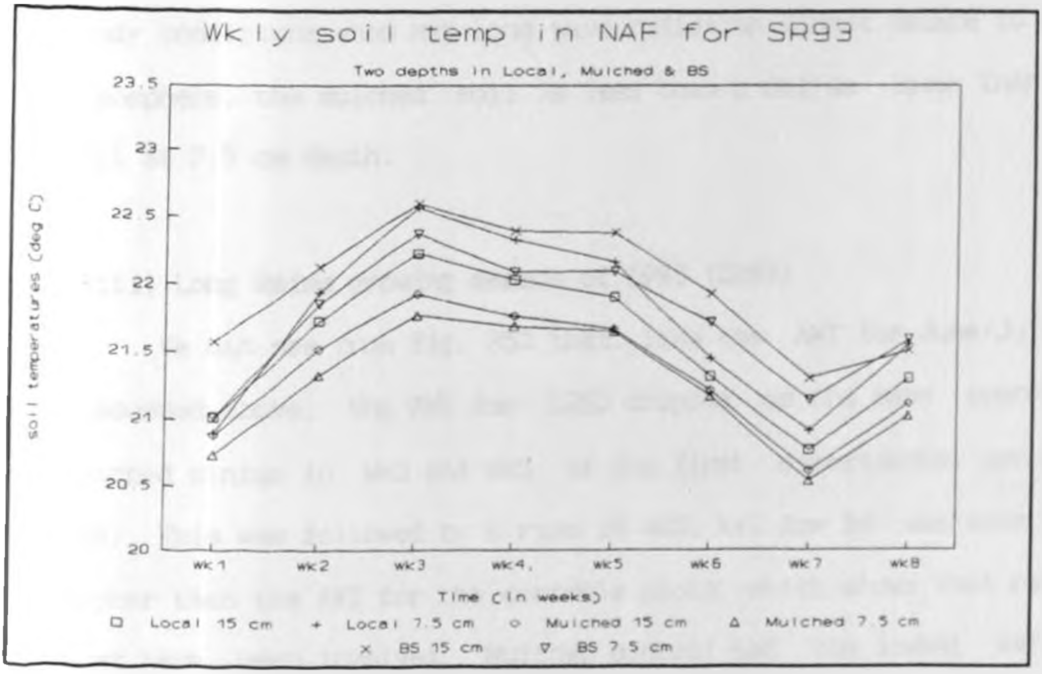

Fig. 351. Weekly average soil temperatures at the depths of 7.5 and 15 cm in the control and bare soil plots for June and July 1992.

Rains period these months demonstrated fairly well the behaviour of the soil temperatures with regard to increasing cloudiness and other factors (minus tree shades) as discussed in section 4.5.2 (a) above. However, again all differences are within 1.0°C, and at the end even within 0.5°C. This means that they are agronomically of no importance.

The AWT values at 7.5 cm for June and July were always somewhat higher than at 15 cm depths, except for mulched soil, but differences are small. These AWT generally rose from wk1 to reach maximum in wk3 and then gradually dropped to minimum values in wk7 because of rainfall occurrence in that week. As expected Mulched plots had lower AWT values than the Local. In wk3 the Mulched controls had AWT values at 7.5 cm of 21.7± 0.6°C (that is average soil temperature plus standard deviation as error margin) while BS had 22.1± 1.0°C. This suggested that under cloudy windy conditions when net long wave radiation cannot escape to the outer atmosphere, the mulched soil is less than a degree lower than the bare soil at 7.5 cm depth.

(iii) Long Rains growing season of 1993 (LR93)

We can see from Fig. 352 that, like the AWT for June/July of LR92 discussed above, the AWT for LR93 dropped as the same approached and reached minima in wk3 and wk5 of the first experimental period (wk1-wk6). This was followed by a rise in wk5. AWT for BS was this time much higher than the AWT for the controls plots, which shows that radiation must have been involved. Mulched control had the lowest AWT at both depths, but the differences were generally within 1.0°C. The differences between AWT at 7.5 and those at 15 cm were visibly also very small. In the second experimental period (wk7-wk10) the differences between depths had very slightly widened especially in the Mulched control plots as the

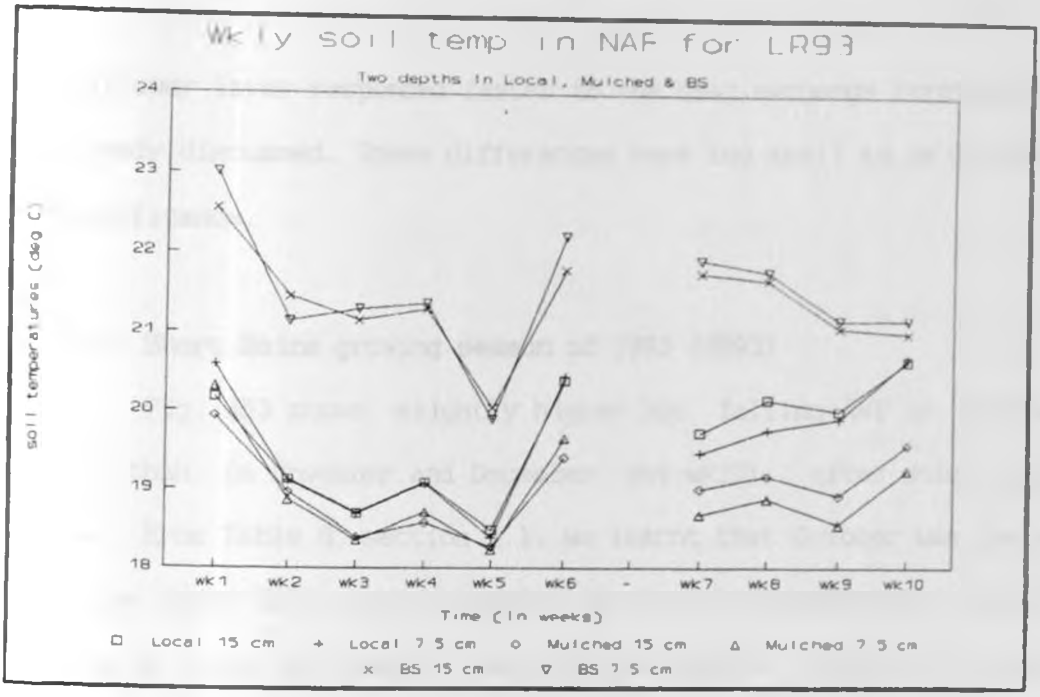

Fig. 352. Weekly average soil temperatures at the depths of 7.5 and 15 cm in the control and bare soil plots during LR93.

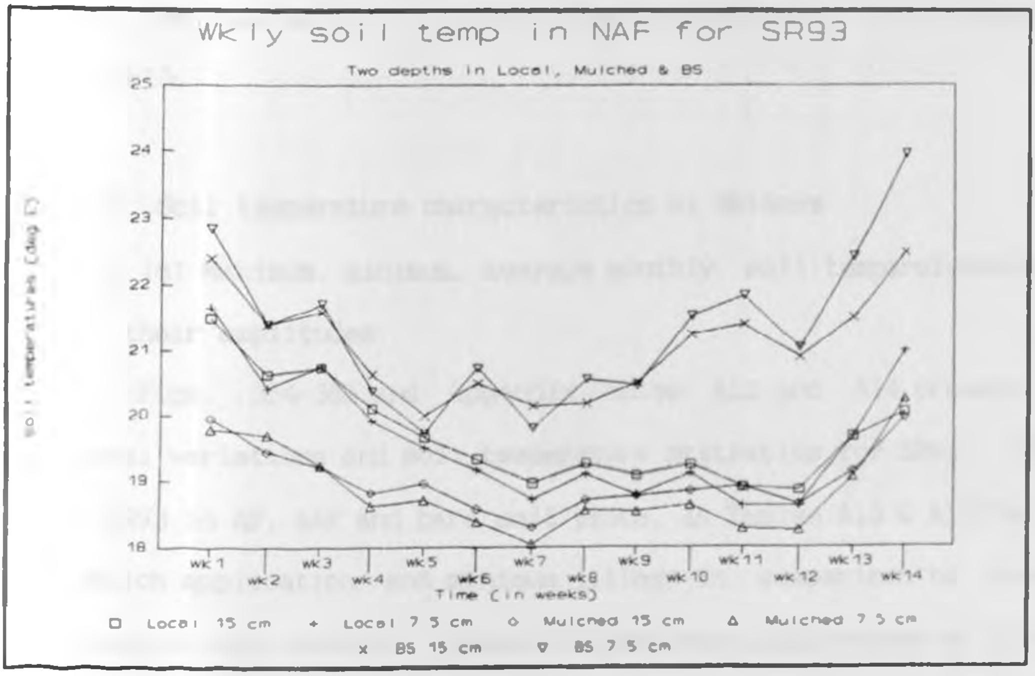

Fig. 353. Weekly average soil temperatures at the depths of 7.5 and 15 cm in the control and bare soil plots during SR93.

shallower layer responded faster to the heat exchange forcing factors already discussed. These differences were too small to be of agronomical significance.

(iv) Short Rains growing season of 1993 (SR93)

Fig. 353 shows slightly higher but falling AWT in October (wk1-wk3) than in November and December (wk4-wk12), after which it slightly rose. From Table 8. section 4.1. we learnt that October was the rainiest of the three SR93 months, causing the drop in temperature. Fig. 353 also shows a clear delineation among the treatments from wk1 to almost wk10 and for BS throughout. The BS had still the highest AWT at both depths, because of direct solar heating on a clean weeded soil, although this must have resulted in large latent heat fluxes during and after rainy days. The Mulched plot had the lowest temperature at both depths from wk1-wk10.

4.5.3. Soil temperature characteristics at Matanya

4.5.3 (a) Maximum, minimum, average monthly soil temperatures and their amplitudes

Figs. 354-365 and Appendix Tables A13 and A14 present monthly diurnal variations and soil temperature statistics for SR91, LR92, LR93 and SR93 in AF, NAF and bare soil plots. In Tables A13 & A14 the effect of mulch application and minimum tillage in comparison to Local deep tillage on soil average, maximum and minimum temperatures at 94 cm from pruned trees PT1 and PT2 is demonstrated by comparing the results in the first column under AFM1 (i.e. in position AM1) with those in the first column under AFL1 (i.e. in position AL1). Similarly at 376 cm from the trees the effect of mulching is demonstrated by comparing the results

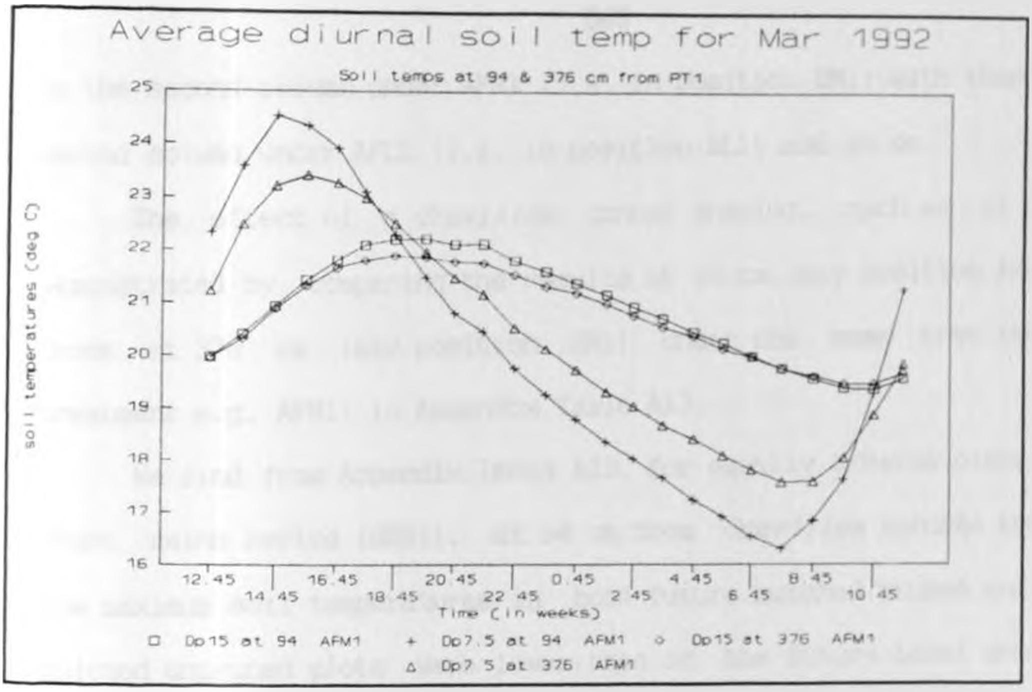

Fig. 354. Monthly diurnal patterns of soil temperatures at 15 and 7.5 cm depths as a function of distances (94 and 376 cm) from pruned PT1 in Mulched plot (AFM1) for March 1992.

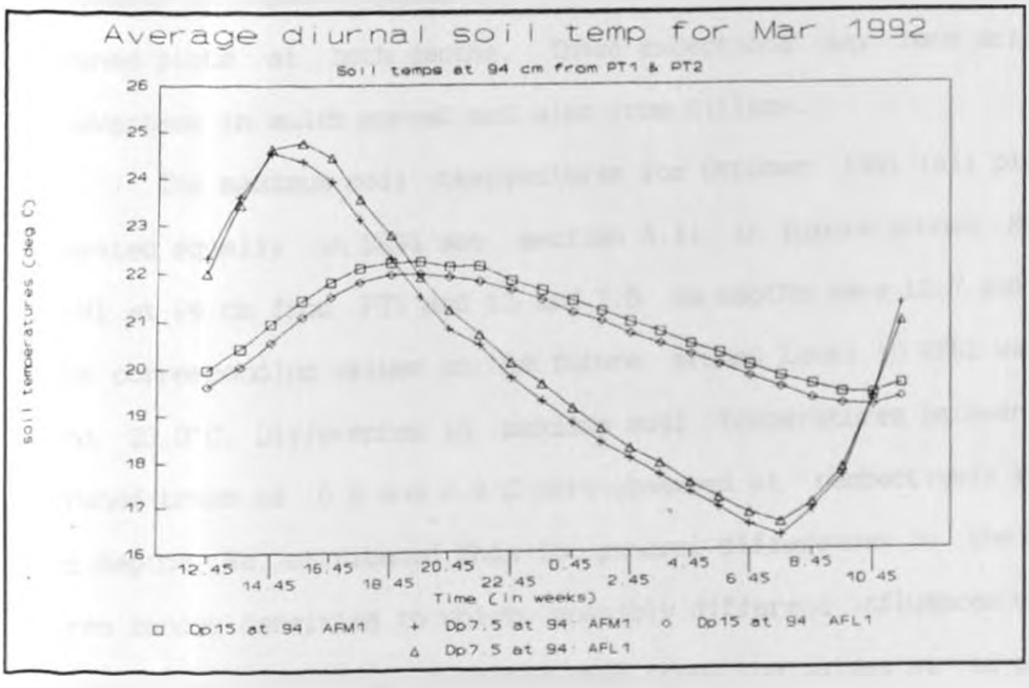

Fig. 355. Monthly diurnal patterns of soil temperatures to show mulch effect in AF at 15 and 7.5 cm depths and a distance of 94 cm from PT1 in AFM1 and PT2 in AFL1 for March 1992.

in the second column under AFM1 (i.e. in position BM1) with those in the second column under AFL1 (i.e. in position BL1) and so on.

The effect of a *Grevillea* canopy shading, such as of PT1, is demonstrated by comparing the results at 94 cm (say position AM1) with those at 376 cm (say position BM1) under the same tree (and same treatment e.g. AFM1) in Appendix Table A13.

We find from Appendix Table A13, for equally treated plots of 1991 Short rains period (SR91), at 94 cm from *Grevillea robusta* tree, that the maximum soil temperatures in both future mulched pruned and future mulched unpruned plots were lower than in the future Local pruned and future Local unpruned plots respectively, while the reverse was true at 376 cm. A few exceptions to the above rule include: (i) at 94 cm in December 1991 in pruned plots at 7.5 cm, (ii) at 376 cm in October and November in unpruned plots at 7.5 cm and (iii) at 376 cm in December in pruned plots at both depths. These exceptions may have arisen from unevenness in mulch spread and also from tillage.

The maximum soil temperatures for October 1991 (all plots were treated equally in SR91 see section 4.1) in future pruned Mulched in AFM1 at 94 cm from PT1 and 15 and 7.5 cm depths were 19.7 and 20.1°C. The corresponding values in the future pruned Local in AFL1 were 20.23 and 23.0°C. Differences in maximum soil temperatures between the two pruned trees of 0.6 and 2.9°C were observed at respectively 15 and 7.5 cm depths. We attributed this to general differences in the *Grevillea* tree canopy densities to which possibly different influences of pruning contributed. At 376 cm from the same trees the values at 15 and 7.5 cm depths were 19.6 and 20.4°C in AFM1 and 19.2 and 20.1°C in AFL1. The little differences may have been due to differences in radiative cooling of the equally treated soil at this distance from the trees, due to canopy differences of the trees and perhaps unevenness in mulch spread at the two sites, which we found to be common with large maize stover residue mulches. In future unpruned Mulched in AFM2 at 94 cm from PT1 and 15 and 7.5 cm depths maximum soil temperatures were 19.5 and 20.4°C. The corresponding values in the future unpruned AFL2 were 19.9 and 21.1°C. The differences were 0.4 and 0.7°C at 15 and 7.5 cm depths which again we attributed to differences between the two trees and unevenness in maize stover mulch. A larger difference for the pruned tree case above was attributed to canopy differences which also were observed in unpruned trees.

In comparison with SR91, differently treated plots of 1993 Short rains period (SR93), in Appendix Table A13 (d) at both distances from *Grevillea robusta* tree (94 and 376 cm), the maximum soil temperatures in both minimum tilled mulched pruned and minimum-tilled mulched unpruned plots were lower than in the deep-tilled Local pruned and deep-tilled Local unpruned respectively. Again few exceptions to the above rule include: (i) at 94 cm in October 1993 in unpruned plots, and (ii) at 94 cm in November in unpruned plots at 15 cm depth.

For the differently treated plots in AF and NAF the maximum soil temperatures, say for October 1993 (Tables A13d & A14), in the pruned Mulched minimum-tilled soil in AFM1 at 94 cm from PT1 and 15 and 7.5 cm depths were 19.0 and 19.1°C. The corresponding values in the pruned unmulched deep-tilled (AFL1) were 20.0 and 21.0°C. We attributed the reductions of 1.0 and 1.9°C at 15 and 7.5 cm depths to mulch depressing effect on maximum soil temperatures. However, again tree canopy differences may be involved, as the same was true in SR91 for equally treated plots. At 376 cm from the same trees the values at 15 and 7.5 cm depths were 20.2 and 21.1°C in AFM1 and 21.9 and 24.3°C in AFLi. Again the reductions of 1.65 and 3.2°C at 15 and 7.5 cm depths may be attributed to mulch depressive effect on soil temperatures. The October 1991 maximum temperatures for bare soil were at 20.0 and 20.2°C at 15 and 7.5 cm depths. The November 1991 maximum temperatures for bare soil were at 20.2 and 20.9°C at 15 and 7.5 cm depths. The October 1993 maximum temperatures for bare soil were at 22.6 and 20.0°C at 15 and 7.5 cm depths. The November 1993 maximum temperatures for bare soil were at 21.7 and 28.7°C at 15 and 7.5 cm depths. The maximum temperatures for 376 cm distance from AFM1 and AFL1 were therefore higher than the maximum soil temperatures in the bare soil for October but lower in November in SR91 and SR93.

From Table A13 (b) we observe in LR92 that maximum soil temperatures were higher at 94 cm in pruned Mulched plots than in pruned Local plots at 15 cm depth, although differences were small, and lower at 376 cm, where differences. were between 0.5° and 2°C. At 7.5 cm the reverse tended to be the case.

For instance in March, May, June July and August 1992 maximum soil temperatures in position AM1 (i.e. at 94 cm from PT1) at 15 cm in the Mulched plot were 22.2°, 24.1°, 22.4°, 25.1° and 22.3°C respectively. The corresponding values in position AL1 at the same depth were 22.0°, 23.8°, 21.6°, 24.8° and 22.3°C which were slightly lower than those in position AM1. Similar results were obtained for LR93 in the same positions at 15 cm depth in April, June, July and August.

In the same months as above the maximum soil temperatures in position AM1 for LR92 (i.e. at 94 cm from PT1) at 7.5 cm in the Mulched plot were 24.5°, 28.1°, 25.0°, 29.4° and 25.4°C respectively. The corresponding values in position AL1 at the same depth were 24.75. 28.8°, 23.3°, 31.5° and 26.9°C which with the exception of June were higher than those in position AM1. The maximum soil temperatures in position BM1 for LR92 (i.e. at 376 cm from PT1) at 7.5 cm in the Mulched plot were 22.2°, 24.1°, 22.4°, 25.1° and 22.3°C respectively. The corresponding values in position BL1 at the same depth were 23.1°, 24.0°, 22.8°, 24.8° and 22.6°C which with the exception of June were higher than those in position AM1. For BM1/BL1 comparison at 15 cm depth for 376 cm distance results in LR92 and LR93 are the same in that the Mulched plots had maxima below that of the Local plot. For 7.5 cm the LR93 results are the same as the for 15 m, without exceptions.

The results for LR93 give opposite picture from the LR92 at 7.5 cm. Now higher maximum soil temperatures were observed in position AM1 than in position AL1, up till 2.5°C.

The slightly lower maximum soil temperatures in the Local plots at 94 cm during LR92 and LR93 (Appendix Tables A14 (b) & (c)) may be attributed to canopy differences of the trees and increased evaporation from the unmulched deep-tilled soil, assisted by higher wind speeds in the course of the Long Rains. At 376 cm the reverse was the case as the Mulched plot registered lower values than the Local for both LR92 and LR93. In the unpruned area there were generally lower maximum soil temperatures than the Local. June 1992, however, was an exception in that at all depths and distances from the trees the maximum soil temperatures were higher in the Mulched than in the Local plots, except BM1 and BL1 at 15 cm depth, where the reverse was the case. June 1992 had the lowest rainfall amount of the season, of 5.2 mm and the highest pan evaporation of 180.9 mm (Table 8). This indicated that evaporation from the unmulched deep-tilled plot was at its highest since it was assisted by the net radiation balance and canopy differences of the trees in the strongly protected AF zone, especially at 376 cm away from UT4. By the end of June the maize/beans intercrop was still in the field, as beans harvesting was done one week later (7-9th July, 1992). The maize plants were 2.4 m high and bent by strong winds. The bean leaves were drying up and were blown away by strong winds, thus exposing the unmulched soil to atmospheric evaporative demands (see section 4.1.2 on results on crop). Lower maximum soil temperatures, in the other months, in Mulched than in Local plots (in Tables A13 and A14) may have been due to shading by the mulch, taking the intercrops as a common factor in both cases.

Pruning affects the rates of soil moisture extraction by the trees. It may well be that deeper roots compensate for these losses, because the evaporative demand from the leaves basically does not change. When there is enough water in the deeper layers this may be (partly) the case. Under water limiting conditions, the situation is of course different. The pruned trees lose the contribution of the roots in the shallow layers (till 30 cm deep) that have been cut off. These in turn may affect soil temperatures in the periphery of the roots when more water remains. The maximum soil temperatures in the same plots but at different distances from the trees show that at PT1 maximum temperatures were lower at 376 cm than at 94 cm from the trees for all the seasons and plots.

We can see in Tables A13 & A14 that high minimum temperatures were observed at depths where low maximum temperatures were observed, with differences between treatments at equal distances from the trees. In Short Rains seasons the maximum temperatures tended to be higher in December than in October, and November. The hot dry season (HD) approached, while minimum temperatures tended to lower. This resulted in high monthly diurnal soil temperature ranges in December. However, in the Long Rains seasons the diurnal soil temperature ranges tended to be smaller as the windy cold season of June-September approached.

On the other hand average soil temperatures were mostly lower in the Local plot than in Mulched plot at the same distance from the trees for all the seasons except SR93. The differences between temperatures near the trees under the same wind regime must have been due to geometry differences of canopies of the trees, of crops or of mulch.

The soil temperature amplitudes are affected in the process of moderation by the mulches and tree canopy shading. In Tables A13 & A14 and Figs. 354-365 we observe lower soil temperature amplitudes in Mulched plots (AFM1 & AFM2) than Local plots (AFL1 & AFL2).

For the months of SR91 (Table A14) the respective maximum temperatures for October 1991 at 15 and 7.5 cm depths in the Local control were 20.1° and 21.1°C and in the Mulched control were 19.5° and 20.1°C. The maximum soil temperatures for the bare soil were 20.0° and 20.2°C. The maximum temperatures were therefore lowest in the Mulched control and highest in the Local control at 7.5 cm, while at 15 cm depth the bare soil temperatures were the highest. The same was true for November 1991 temperatures.

For the months of LR92 (Table A14) the maximum temperatures for June 1992 at 15 and 7.5 cm depths in the Local control were 24.0° and 26.2°C and in the mulched control were 23.0 and 23.5°C. The respective maximum soil temperatures for the bare soil were 23.9 and 25.9°C. Therefore, for June maximum temperatures were lowest in the Mulched control and highest in the Local control at both depths. For July and August, however, the bare soil had the highest maximum temperature at

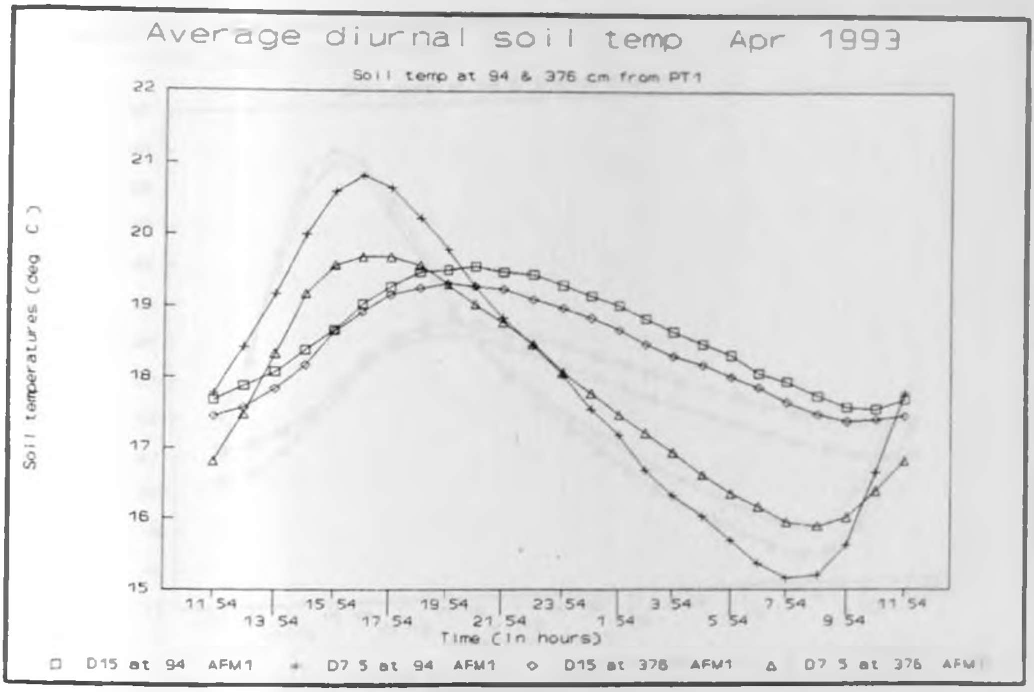

Fig. 356. Monthly diurnal patterns of soil temperatures at 15 and 7.5 cm depths as a function of distances (94 and 376 cm) from pruned PT1 in Mulched plot (AFM1) for April 1993.

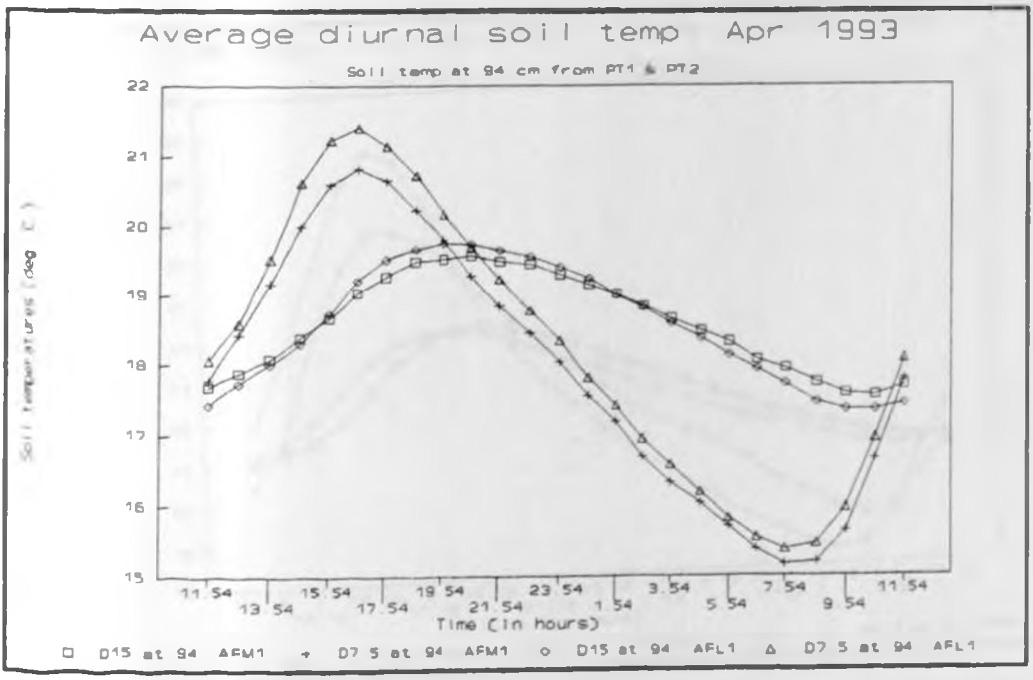

Fig. 357. Monthly diurnal patterns of soil temperatures to show mulch effect in AF at 15 and 7.5 cm depths and a distance of 94 cm from PT1 in AFM1 and PT2 in AFL1 for April 1993.

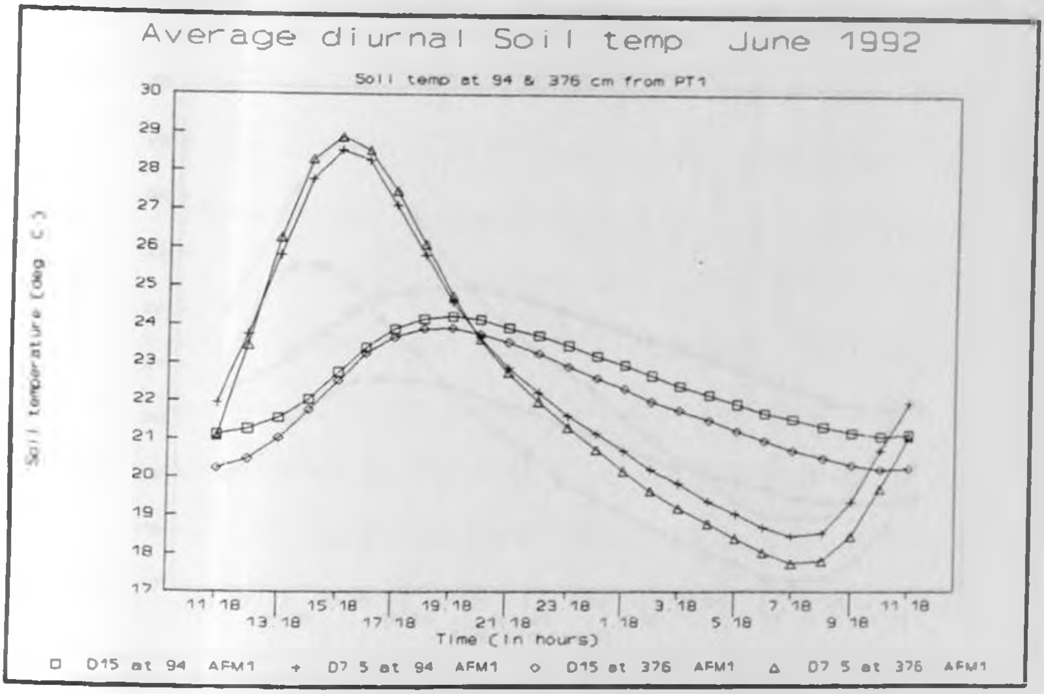

Fig. 358. Monthly diurnal patterns of soil temperatures at 15 and 7.5 cm depths as a function of distances (94 and 376 cm) from pruned PT1 in Mulched plot (AFM1) for June 1992.

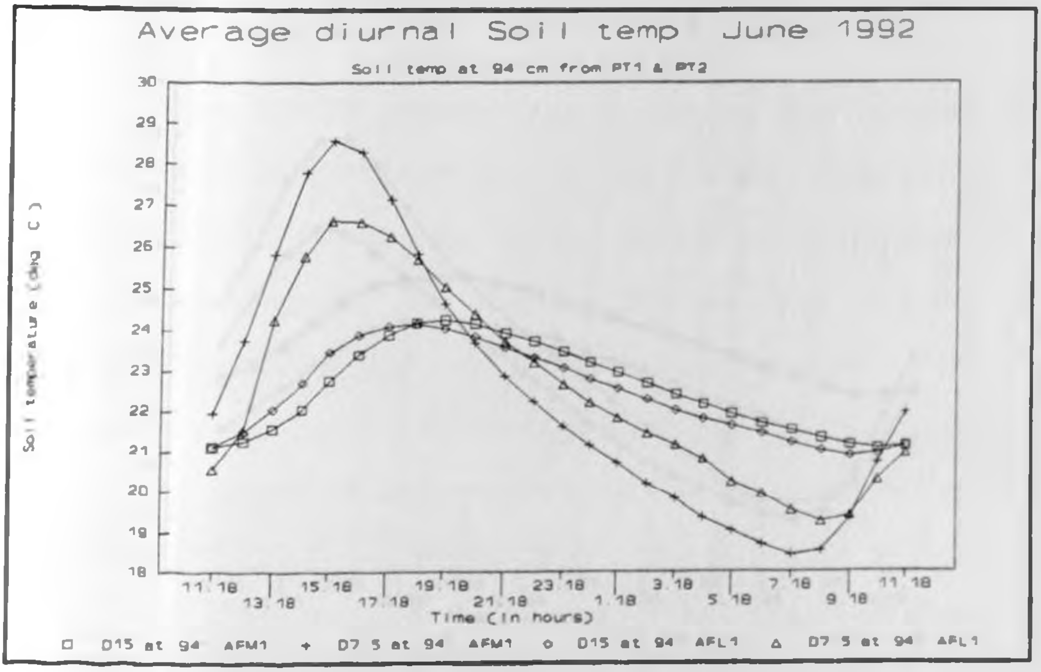

Fig. 359. Monthly diurnal patterns of soil temperatures to show mulch effect in AF at 15 and 7.5 cm depths and a distance of 94 cm from PT1 in AFM1 and PT2 in AFL1 for June 1992.

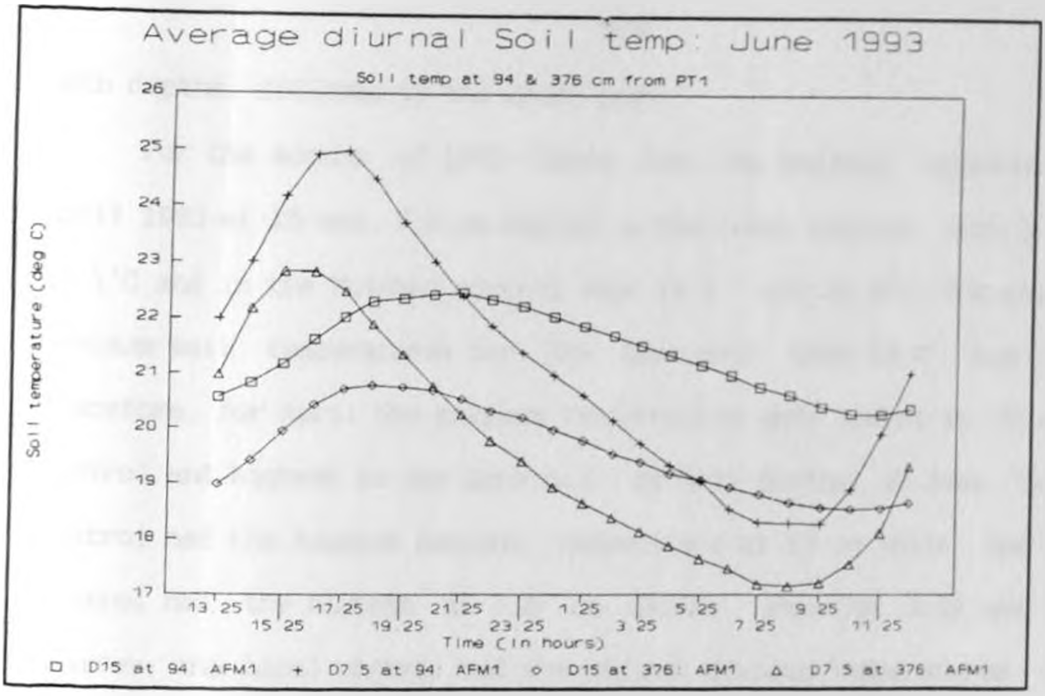

Fig. 360. Monthly diurnal patterns of soil temperatures at 15 and 7.5 cm depths as a function of distances (94 and 376 cm) from pruned PT1 in Mulched plot (AFM1) for June 1993.

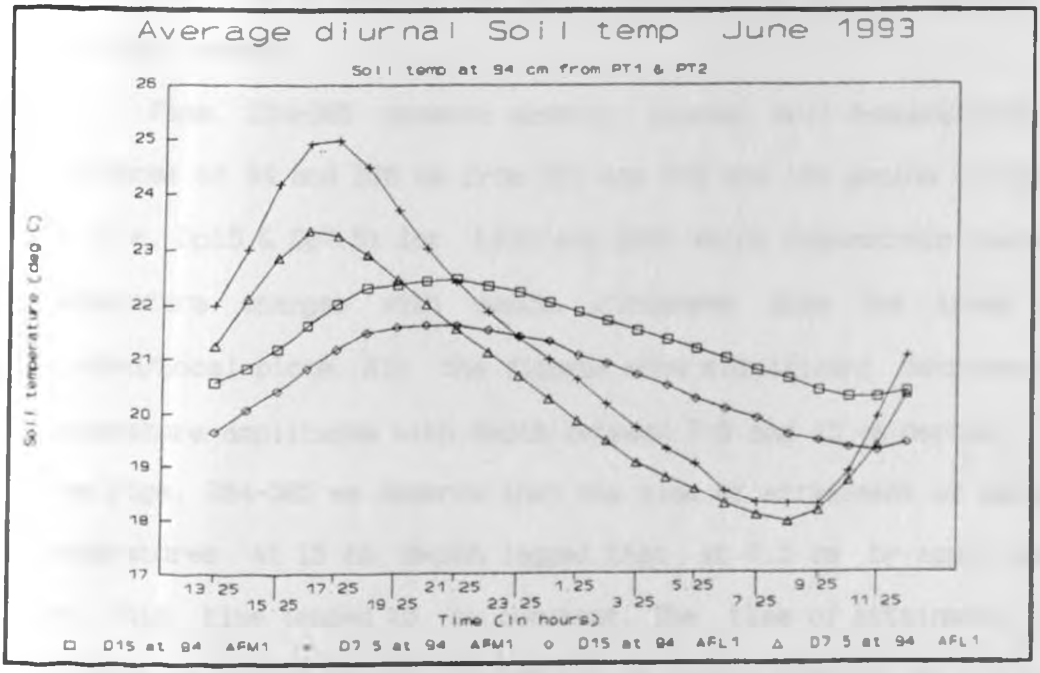

Fig. 361. Monthly diurnal patterns of soil temperatures to show mulch effect in AF at 15 and 7.5 cm depths and a distance of 94 cm from PT1 in AFM1 and PT2 in AFL1 for June 1993.

both depths. followed by the Local plot.

For the months of LR93 (Table A14) the maximum temperatures for April 1993 at 15 and 7.5 cm depths in the Local control were 21.6° and 23.1°C and in the Mulched control were 19.9° and 21.4°C. The respective maximum soil temperatures for the bare soil were 23.4° and 24.2°C. Therefore. for April the maximum temperatures were lowest in the mulched control and highest in the bare soil at both depths. In June. the Local control had the highest maximum temperature at 15 cm while the Mulched control had the highest at 7.5 cm depth. For the July and August however. the Local control had the highest maximum temperatures at both depths followed by the bare soil plot. The main reasons for these differences (for SR91. LR92 & LR93) have been the radiative balances and the weather situation in each period and the surface cover of these treatments. As a result the soil temperatures in the Mulched control were the lowest.

Figs. 354-365 present monthly diurnal soil temperatures at the distances of 94 and 376 cm from PT1 and PT2 and the depths of 15 and 7.5 cm (i.e. Dp15 & Dp7.5) for LR92 and LR93 which demonstrate diurnal soil temperature changes with depth, distances from the trees and in Mulched/Local plots. All the figures show significant decrease of soil temperature amplitudes with depth between 7.5 and 15 cm depths.

From Figs. 354-365 we observe that the time of attainment of maximum temperatures at 15 cm depth lagged that at 7.5 cm by approximately 4 hrs. This time tended to be constant. The time of attainment of soil temperature minima for at 15 and 7.5 cm depths differed by 1-3 hrs. The fact that these times were different shows that other factors other than sky conditions were involved.

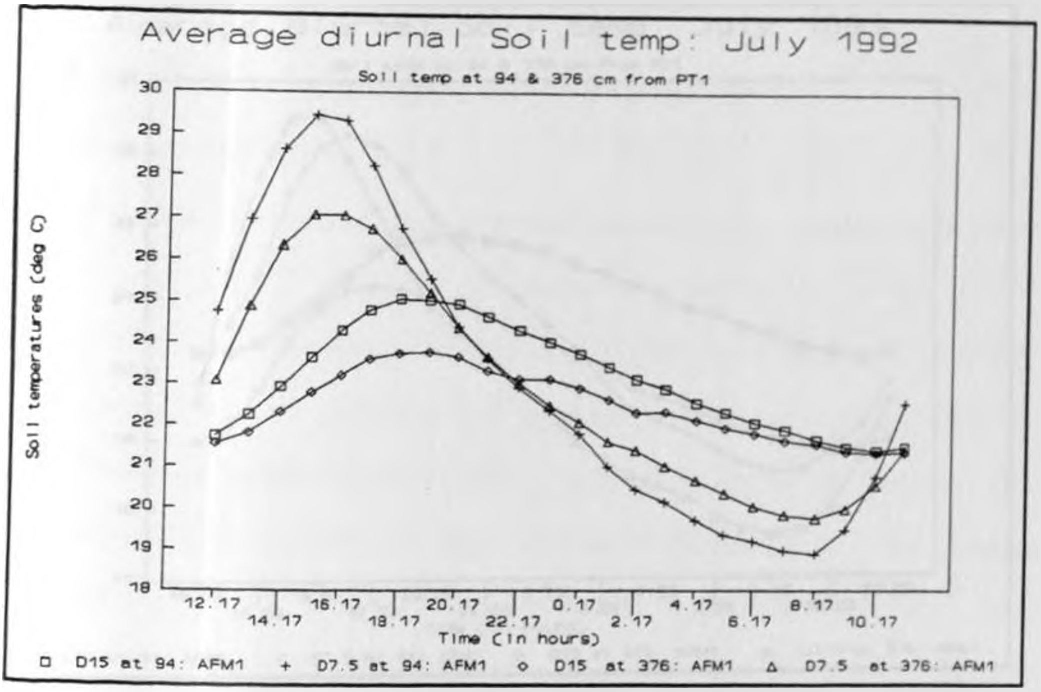

Fig. 362. Monthly diurnal patterns of soil temperatures at 15 and 7.5 cm depths as a function of distances (94 and 376 cm) from pruned PT1 in Mulched plot (AFM1) for July 1992.

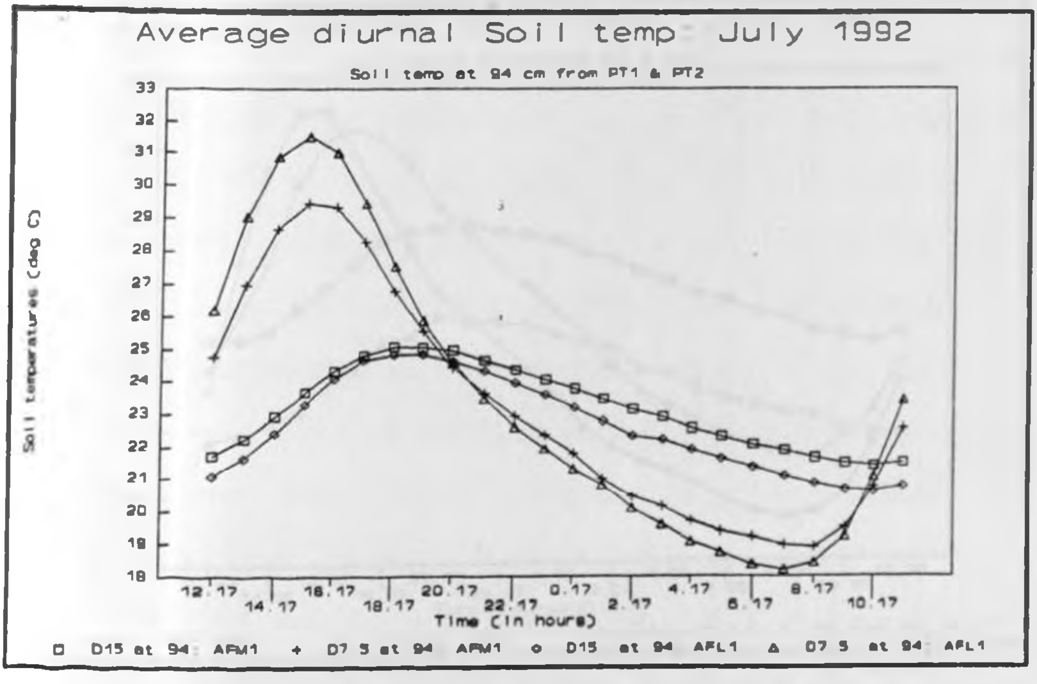

Fig. 363. Monthly diurnal patterns of soil temperatures to show mulch effect in AF at 15 and 7.5 cm depths and a distance of 94 cm from PT1 in AFM1 and PT2 in AFL1 for July 1992.

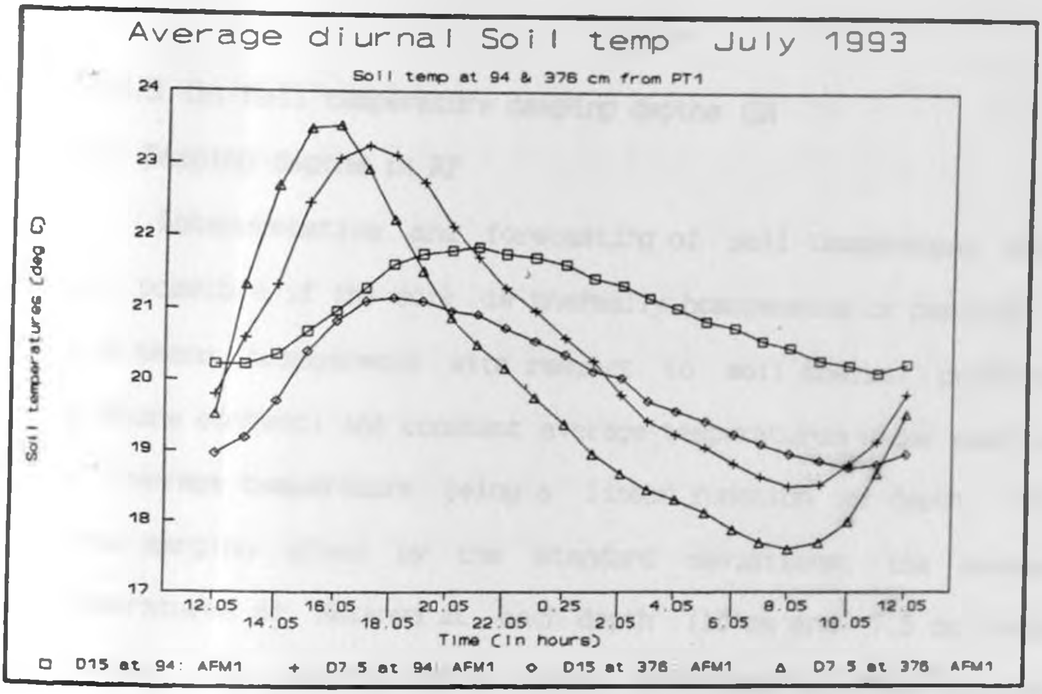

Fig. 364. Monthly diurnal patterns of soil temperatures at 15 and 7.5 cm depths as a function of distances (94 and 376 cm) from pruned PT1 in Mulched plot (AFM1) for July 1993.

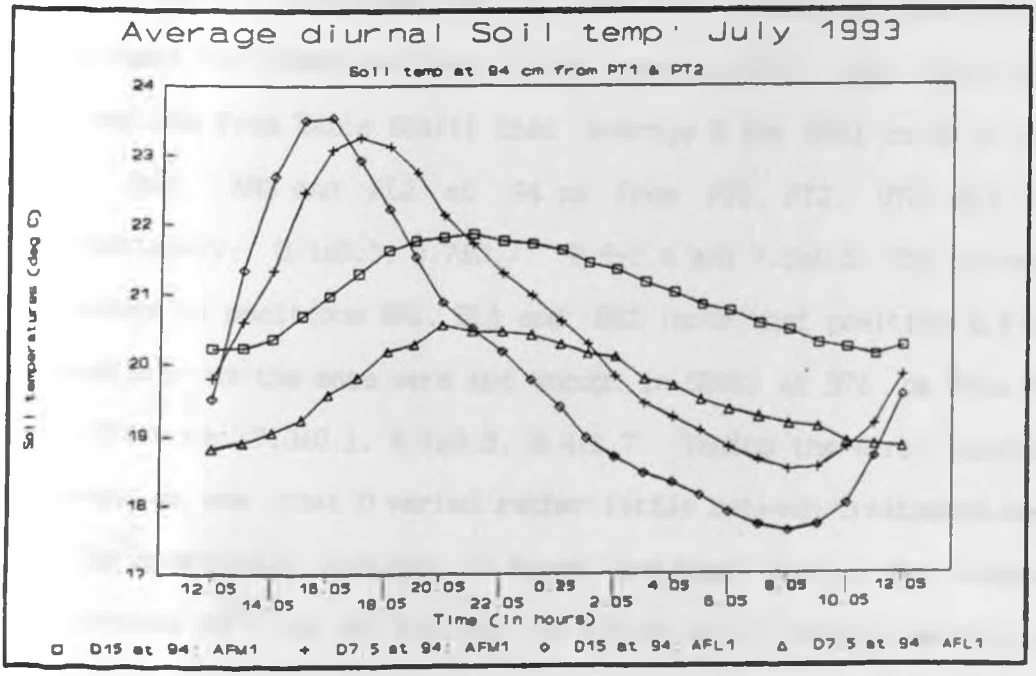

Fig. 365. Monthly diurnal patterns of soil temperatures to show mulch effect in AF at 15 and 7.5 cm depths and a distance of 94 cm from PT1 in AFM1 and PT2 in AFL1 for July 1993.

4.5.3 (b) Soil temperature damping depths (D)

(i) Damping depths in AF

Interpretation and forecasting of soil temperature patterns is only possible if the soil is thermally homogeneous or has such layers. This means homogeneous with respect to soil thermal properties (so moisture content) and constant average temperatures under each treatment or average temperature being a linear function of depth. Within the error margins given by the standard deviations, the average soil temperatures at Matanya at each depth (15 cm and 7.5 cm depths) are constant. The damping depth values presented here are obtained from monthly averaged diurnal temperature patterns under a maize/beans intercrop in an agroforestry system.

Average monthly and seasonal damping depths (D) (e.g. Stigter. 1984c; 1985a) are summarized in Table 80. Table 80 shows D for each treatment for Short and Long Rains seasons: SR91, LR92, LR93 and SR93. We can see from Table 80a(i) that average D for SR91 in AF in positions AM1, AL1, AM2 and AL2 at 94 cm from PT1, PT2, UT4 and UT5 were respectively: 8.1±0.5, 6.7±0.7, 8.6±0.4 and 7.6±0.5. The corresponding D values in positions BM1, BL1 and BM2 (note that position BL2 missed a thermistor as the same were not enough in SR91) at 376 cm from PT1, PT2 and UT4 were 7.3±0.1, 8.6±0.5, 8.4±1.7. Taking the error margins into account we see that D varied rather little between treatments and hence may be considered constant in space and time during SR91 season. The magnitudes of D did not reflect the effect of *G. robusta* shading on soil temperature patterns at 94 cm from the trees compared to 376 cm during SR91, because there is no systematic difference between the two distances.

We can see from Table 80a(ii) that average D for LR92 in AF in positions AM1, AL1, AM2 and AL2 at 94 cm from PT1, PT2, UT4 and UT5 were respectively: 7.0±0.5, 8.9±3.2, 12.7±3.4 and 12.4±2.3. The corresponding D values in positions BM1, BL1, BM2 and BL2 at 376 cm from PT1, PT2, UT4 and UT5 were 9.7±2.2, 11.4±1.8, 6.5±0.6 and 6.9±3.5. Here we see a pattern where the D values at 94 cm from pruned trees (PT1 and PT2) are smaller than the D values at 376 cm and these 94 cm values are larger for unpruned trees at 94 cm (UT4 and UT5), but the values at 376 cm at the unpruned trees are smallest of all. With respect to soil surface cover D values in pruned mulched at 94 cm from PT1 (position AM1) are smaller than those in pruned Local (position AL1) and the same applies at position BM1 compared to BL1. Similarly in unpruned plots D values in unpruned Mulched (position AM2) are smaller than those in unpruned Local (position AL2). We observe here that mulch cover reduced D, but only below pruned trees.

Table 80a(iii) shows that average D for LR93 in AF in positions AM1, AL1, AM2 and AL2 at 94 cm from PT1, PT2, UT4 and UT5 were respectively: 6.9±0.2, 8.7±0.4, 10.8±0.4 and 6.9±0.4. The corresponding D values in positions BM1, BL1, BM2 and BL2 at 376 cm from PT1, PT2, UT4 and UT5 were 9.2±1.5, 10.1±2.6, 4.3±0.9 and 8.7±2.1. Again we see a pattern where the D values at 94 cm from pruned (PT1 and PT2) and unpruned (UT5) trees are smaller than the D values at 376 cm. Unpruned tree (UT4) then had a malfunctioning thermistor at 15 cm, that was later replaced, so the value 4.3 is not used. Again with respect to soil surface cover, D values in pruned mulched at 94 cm from PT1 (position AM1) were found to be smaller than those in pruned Local (position AL1). The same applies at 376 cm. Similarly in unpruned plots D values in unpruned Mulched (position AM2) for 376 cm are smaller than those in unpruned Local (position AL2). Here again the effect of mulch cover in reducing D was observed.

Table 80a(iv) shows that average D for SR93 in AF in positions AM1, AL1, AM2 and AL2 at 94 cm from PT1, PT2, UT4 and UT5 were respectively: 10.5±1.2, 8.6±0.5, 10.9±1.9 and 10.0±0.9. The corresponding D values in positions BM1, BL1, BM2 and BL2 at 376 cm from PT1, PT2, UT4 and UT5 were: 7.9±0.1, 7.5±0.5, 6.4±0.3 and 10.2±1.3. SR93 did not seem to have any definite pattern in D values with respect to distance from the trees and the effect of mulch cover as did LR92 and LR93. If any trend, D values tended to be higher at 94 cm than at 376 cm and also higher in mulched than in Local treatments, which is appropriate to the LR seasons. D varied between 6.4±0.3 and 10.9±1.9 and had an overall average of 9.0±1.5.

(ii) Damping depths in NAF

We can see from Table 80b(i) that average D for SR91 in NAF in the Mulched control (M), Local control (L) and Bare Soil (BS) plots were respectively 9.3±0.3, 9.2±2.8 and 9.3±0.8. The old control plots were used for soil temperature measurements during preliminary exercises and then the measurements were transferred to the new control plots for LR92 and later seasons. The D values in SR91 were nearly the same, except for the larger error margin for L than either BS and M plots. This proves that the soil in NAF was homogeneous.

Table 80b (ii) shows average D for LR92 in NAF in the new control plots. The D values for Mulched control (M), Local control (L) and Bare Soil (BS) were respectively 14.4±2.3, 12.9±3.4 and 9.4±0.3. The D values for LR92 for the bare soil was still the same as for SR91. However, high D values were found for the newly opened control plots. The soil of the newly opened control plot had a lot of humus and was still easy to work. The BS site had been opened up earlier in the experimental period in SR91 and since the surface was kept bare it settled easily. The soil of the newly opened control plot was still dispersed due to a lot of humus. Hence homogeneity was still observed in the new plots, but they were different from the old ones.

Table 80b (iii) shows that average D for LR93 in NAF in the new control plots: Mulched (M) control, Local control (L) and Bare Soil (BS) were respectively 7.7±1.3, 18.5±8.5 and 8.3±0.5. The D values for LR93 for the bare soil had not changed much from the SR91 and LR92 values. The soil under the mulch in the newly opened up plots had settled quite first, giving relatively lower D than previously. However, the control plot still had very high D values.

Table 80b (iv) presents average D for SR93 in NAF in the new control plots. D values for M, L and BS were respectively 8.1±1.5, 7.5±0.3 and 5.3±0.9. The D values for SR93 for the bare soil had dropped a bit from the SR91, LR92 and LR93 values. The soil under the control plots had now settled and were proving to be thermally homogenous. Their values were in the same order of magnitude (between 8 and 10) as the soil in the agroforestry plot.

The drop of D in the BS may be due to extreme dryness of very bare soil which received direct solar heating and very high evaporative losses while NAF and AF had vegetative cover during this time of the year.

4.5.3 (c) Phase shifts

Table 81 presents phase shifts (ϕ) of monthly diurnal soil temperature waves during SR91-SR93. We see in Table 81a (i) that the ϕ values for SR91 range from 3.4±0.9 to 4.7±1.2 hours. We did not notice

Table 80. Damping depth (D) in cm for each treatment and each month during SR91, LR92, LR93 and SR93. D was calculated by the method of reducing amplitudes of the temperature wave between 7.5 and 15 cm depths in the soil.
(a) agroforestry. (b) non-agroforestry plots.

(a) Agroforestry: Mulched and Local AF plots

	PT1		PT2		UT4		UT5	
Plots:	AFM1		AFL1		AFM2		AFL2	
Positions:	AM1	BM1	AL1	BL1	AM2	BM2	AL2	BL2
	94	376	94	376	94	376	94	376
(i) SR91: All plots similarly treated								
Oct	8.0	7.5	7.2	9.3	8.4	10.5	8.2	-
Nov	8.7	7.3	7.2	8.1	9.1	8.4	7.6	-
Dec	7.6	7.2	5.8	8.5	8.3	6.3	7.0	-
Average	8.1	7.3	6.7	8.6	8.6	8.4	7.6	-
	±0.5	±0.1	±0.7	±0.5	±0.4	±1.7	±0.5	-
(ii) LR92 - From this season plots treated differently								
Mar	7.7	12.4	9.1	10.4	10.0	6.9	11.3	-
May	6.6	10.1	6.8	9.6	16.7	7.0	12.9	5.2
Jun	6.2	11.6	14.9	14.9	17.0	5.4	16.7	13.0
Jul	7.1	6.9	6.6	11.0	10.1	6.4	10.9	5.1
Aug	7.2	7.6	6.9	11.3	9.7	6.7	10.1	4.4
Average	7.0	9.7	8.9	11.4	12.7	6.5	12.4	6.9
	±0.5	±2.2	±3.2	±1.8	±3.4	±0.6	±2.3	±3.5
(iii) LR93								
Apr	6.8	11.7	7.9	13.8	10.2	5.8	6.2	10.7
Jun	7.2	8.1	9.0	9.1	11.2	4.2	7.3	10.9
Jul	6.7	8.8	8.9	6.8	11.0	3.7	7.2	6.3
Aug	7.0	8.2	8.8	10.8	10.7	3.5	7.0	6.9
Average	6.9	9.2	8.7	10.1	10.8	4.3	6.9	8.7
	±0.2	±1.5	±0.4	±2.6	±0.4	±0.9	±0.4	±2.1
(iv) SR93								
Oct	11.7	7.8	9.1	7.0	8.8	6.7	9.0	11.4
Nov	9.3	8.0	8.1	7.9	12.7	6.1	10.9	8.9
Aver.	10.5	7.9	8.6	7.5	10.9	6.4	10.0	10.2
	±1.2	±0.1	±0.5	±0.5	±1.9	±0.3	±0.9	±1.3

(b) Non-agroforestry: Mulched and Local control plots

(i) SR91: All plots similarly treated

Plots:	L	M	BS
Oct	8.8±2.7	8.8±0.1	8.5±0.1
Nov	9.6±2.9	9.8±0.7	10.0±0.2
Average	9.2±2.8	9.3±0.3	9.3±0.8

Plots:	L	M	BS
(ii) LR92 - From this season plots treated differently, also different control plots			
Jun	13.7±4.8	14.9±5.5	9.8±0.2
Jul	12.7±4.9	13.9±5.1	9.1±0.1
Aug	12.1±6.0	11.5±0.8	9.4±0.4
Average	12.9±3.4	14.4±2.3	9.4±0.3
(iii) LR93			
Plots:	L	M	BS
Apr	19.6±9.6	9.8±3.5	7.9±0.4
Jun	19.0±8.4	7.3±1.1	9.1±0.5
Jul	17.9±8.0	7.1±1.1	7.8±0.1
Aug	17.5±8.1	6.5±0.5	8.3±0.2
Average	18.5±8.5	7.7±1.3	8.3±0.5
(iv) SR93			
Plots:	L	M	BS
Oct	7.0±1.4	6.2±0.4	6.6±0.5
Nov	7.7±1.5	8.2±1.6	4.8±0.7
Dec	7.8±1.8	9.8±1.7	4.6±0.8
Average	7.5±0.3	8.1±1.5	5.3±0.9

any pattern related to eventual differences in tree shading. We likewise did not find a pattern related to mulch cover because all had same cover in SR91. Table 81a (ii) shows that ϕ values LR92 range from 4.0±0.4 to 4.6±1.5. Table 81a (iii) shows that ϕ values LR93 range from 3.4±1.0 to 4.9±0.3 while those for SR93 range from 3.8±0.4 to 4.3±0.3 (Table 81a(iv)). In all these seasons we did not notice any pattern related to tree shading nor mulch cover. The AF ϕ values were comparable to the NAF values (Tables 81b(i), (ii), (iii) and (iv)) indicating thermal homogeneity of the vertisols in the control and AF plots at Matanya. It could perhaps be observed that the high variability (error margins) of the phase shifts point towards large irregular interventions of either clouds or other changing shades over the plots, in long term and short term periods.

Table 81. Phase shift (ϕ) in hours for each treatment during SR91, LR92, LR93, SR93, LR94 & SR94. ϕ was calculated by knowing the time the temperature wave attains its maximum and minimum temperatures at 7.5 and 15 cm depths in the soil. (a) agroforestry, (b) non-agroforestry plots (see Fig. 13)

(a) Agroforestry: Mulched and Local AF plots

Plots:	PT1 AFM1		PT2 AFL1		UT4 AFM2		UT5 AFL2	
Positions:	AM1	BM1	AL1	BL1	AM2	BM2	AL2	BL2
	94	376	94	376	94	376	94	376
(i) SR91: All plots similarly treated								
Average	4.7	4.6	3.4	3.8	3.9	4.0	3.9	-
	±1.2	±0.9	±0.9	±0.8	±0.8	±3.8	±0.9	-
(ii) LR92 – From this season plots treated differently								
Average	4.6	4.4	4.0	4.3	4.1	4.3	4.1	4.6
	±0.4	±0.4	±0.8	±0.5	±0.5	±1.4	±0.2	±1.5
(iii) LR93								
Average	4.9	4.3	4.3	4.0	3.9	3.9	3.9	3.4
	±0.3	±0.4	±0.9	±0.6	±0.5	±2.0	±0.4	±1.0
(iv) SR93								
Average	4.1	4.3	4.1	3.8	4.3	4.2	3.9	4.1
	±0.4	±0.3	±0.7	±0.4	±0.8	±0.9	±0.7	±0.7

(b) Non-agroforestry: Mulched and Local control plots

(i) SR91: All plots similarly treated

Plots:	L1	L3	M1	M3	BS
Average	5.1	4.9	3.9	4.3	4.4
	±0.5	±0.8	±0.6	±0.8	±0.7

Plots:	AL4	BL4	AL5	BL5	AM4	BM4	AM5+BM5	BS
(ii) LR92 – From this season plots treated differently								
Average	4.1	4.1	4.4	3.9	4.5	4.5	4.5	4.4
	±0.4	±0.6	±0.7	±0.3	±0.7	±0.5	±0.4	±0.5
(iii) LR93								
Average	3.7	3.8	4.1	4.4	3.9	4.2	3.8	4.4
	±0.4	±0.4	±0.6	±1.2	±0.9	±0.7	±0.2	±0.7
(iv) SR93								
Average	4.8	3.7	4.0	4.1	3.9	4.1	3.9	3.8
	±0.2	±0.3	±0.6	±0.9	±0.7	±0.9	±1.1	±1.3

4.5.3 (d) Stigter's ratios (R_{sti})

Stigter's ratios as calculated from Eq. 20 were used to estimate the thermal effect induced by intercrop residue mulch and *G. robusta* canopy shading that altered soil temperature amplitudes and averages, hence the intercrop response to these changes. The monthly diurnal soil temperatures used for calculating R_{sti} were chosen according to Stigter *et al*. (1984): temperature differences in the bare soil and the test plot at the same depth must be larger than 1°C although in our cases evaporation from the soil was not negligible as per the second requirement, even not in mulched soil, because (i) maize stalks mulch used was more effective in run-off control rather than evaporation form the soil; (ii) soil temperature data used covered strong winds season which increased evaporation from the soil. Only the data for 7.5 cm depth satisfied this criterion for all the seasons chosen. The data for 15 cm depth did not, hence we did not use them.

(i) Stigter's ratios (R_{sti}) in Mulched AF (AM1, AM2) and control Mulched (M) plots

Table 82a(i) presents average R_{sti} values for SR91 in Mulched plots (AFM1 & AFM2) in AF. Average R_{sti} in position AM1 at 94 cm from PT1 was smaller than the R_{sti} in position BM1 at 376 cm from the same tree. Similarly average R_{sti} in position AM2 at 94 cm from unpruned UT4 was smaller than the R_{sti} in position BM2 at 376 cm from the same tree. Here *G. robusta* tree canopies must have influenced R_{sti}.

Table 82a(ii) presents average R_{sti} values for LR92 in Mulched plots (AFM1 & AFM2) in AF. Again R_{sti} in position AM1 at 94 cm from pruned PT1 was smaller than the R_{sti} in position BM1 at 376 cm from the same tree. However this time in average R_{sti} in position AM2 at 94 cm from unpruned UT4 was larger than the R_{sti} in position BM2 at 376 cm from the same tree. Again *G. robusta* tree canopies had influence on average R_{sti}.

Table 82a (iii) presents average R_{sti} values for LR93 in Mulched AF plots (AFM1 & AFM2) in AF. Again R_{sti} in position AM1 at 94 cm from pruned PT1 was significantly smaller than the R_{sti} in position BM1 at 376 cm from the same tree. Again in average R_{sti} in position AM2 at 94 cm from unpruned UT4 was larger but not significantly than the R_{sti} in position BM2 at 376 cm from the same tree. Again *G. robusta* tree canopies must had influence on average R_{sti}. The SR93 results present the same picture as the SR91 although the surface cover for the two seasons was different as the plots during the latter season were equally treated while for the latter were differently treated.

The relative magnitudes of R_{sti} with distance from trees show that tree canopy shade can be significant in modifying soil temperatures closest to the trees. R_{sti} values were higher in SR93 than in previous seasons studied. Tables 83b (i-iv) for mulched NAF plots also show higher average R_{sti} than the previous seasons studied with the highest of 3.23±0.95 being comparable to that of AF in position AM1 at 94 cm from PT1 of 3.04±0.59. This was due to higher soil moisture in SR93 than in the other seasons as more rainfall was received in the latter than in the previous seasons studied and higher soil moisture conserved nearer to the pruned trees (see in Tables 7 & 8 of section 4.1).

(ii) Stigter's ratios (R_{sti}) in Local AF (AL1, AL2) and control Local (L) plots

Table 83a(i) presents average R_{sti} values for SR91 in Local AF plots (AFL1 & AFL2) in AF. Average R_{sti} for SR91 in position AL1 at 94 cm from PT2 was smaller than the R_{sti} in position BL1 at 376 cm from the same tree. This was also true for LR92 but not for LR93 and SR93. In SR91 the average R_{sti} in position AL2 at 94 cm from unpruned UT5 was relatively larger than the R_{sti} in position BL2 at 376 cm from the same tree. The same picture was seen in LR92 and LR93 while in SR93 R_{sti} at 94 cm from UT4 was smaller than at 376 cm away although not significantly different. Again *G. robusta* tree canopies must had influence on average R_{sti}.

Like for the Mulched case R_{sti} values were higher in SR93 than in previous seasons studied. Tables 83b(i-iv) for Local NAF plots also show higher average R_{sti} than the previous seasons studied with the highest of 2.62±0.94 being 0.06 smaller than the highest in AF of 2.68±0.94 experienced in position BL2 at 376 cm from UT5. Again as pointed out above higher rainfall in SR93 caused this difference.

- The damping depths, in their variations but also in their consistency under same conditions, confirm the modifications due to the treatments as well as the differences due to earlier induced and natural inhomogeneity (e.g. slope etc.) of the AF plots and the change in control plots. Although certain consistent differences between seasons may be due to the difficulty to determine shallow depths in worked soil surfaces, differences in soil moisture are clearly the most determining factor for between season and within season differences in damping depths. Another factor confusing the picture is variable shading as far as it does not average out as an environmental constant over longer periods. Many factors were met in the previous section that induced such changes, such as mulch blown over plots, wind induced movement of tree crowns and crops, as well as the annual growth of the latter.

Table 82. Thermal effect of *G. robusta* canopy shades and crop residue mulch plus minimum tillage as estimated from Stigter's ratios R_{sti}: $R_{sti} = D_{Ts}/D_{Tm}$ where D_{Ts} and D_{Tm} are differences between the monthly and actual averages of diurnal temperature pattern at the same depth for bare soil and the Mulched soil respectively. (a) agroforestry (b) non-agroforestry Mulched plots, and the bare soil.

(a) Agroforestry: Mulched AF plots (AFM1 & AFM2)

Position	R_{sti} = BS/AFM1 AM1 (94 cm)	BM1 (376 cm)	R_{sti} = BS/AFM2 AM2 (94 cm)	BM2 (376 cm)
(i) SR91 - All plots similarly treated				
October	0.99±0.07	0.81±0.06	0.77±0.14	0.82±0.13
November	0.96±0.05	1.36±1.08	0.74±0.22	0.78±0.19
Average	**0.98±0.02**	**1.09±0.28**	**0.76±0.01**	**0.80±0.02**
(ii) LR92 - From this season plots treated differently				
March	0.88±0.48	0.77±0.39	0.99±0.41	1.07±0.42
June	1.13±0.17	1.27±0.31	1.28±0.45	0.72±0.81
July	1.09±0.91	1.30±0.84	1.58±0.76	1.20±0.82
August	1.19±0.38	1.17±0.63	1.51±0.93	1.29±0.73
Average	**1.07±0.12**	**1.13±0.21**	**1.34±0.23**	**1.07±0.21**
(iii) LR93				
April	0.98±0.51	1.33±0.54	1.20±0.57	0.88±0.41
June	0.87±0.19	0.99±0.26	0.90±0.17	0.67±0.50
July	0.96±0.09	0.92±0.30	0.99±0.09	0.54±0.26
August	1.00±0.30	0.92±0.31	1.21±0.27	2.06±0.92
Average	**0.95±0.05**	**1.04±0.15**	**1.08±0.13**	**1.04±0.60**
(iv) SR93				
October	2.45±0.83	2.00±0.87	1.74±0.87	1.97±0.84
November	3.63±1.52	2.87±1.04	2.50±1.19	2.83±1.04
Average	**3.04±0.59**	**2.44±0.44**	**2.12±0.38**	**2.40±0.43**

(b) Non-agroforestry: Mulched control plots

Position	BS/M
(i) SR91 - Old control plots	
October	-
November	0.80±0.05

Plots treated differently from LR92 to SR93

(ii) LR92	BS/M	(iii) LR93	
March	-	April	1.36±0.41
June	1.96±0.56	June	1.68±0.73
July	-	July	1.50±0.62
August	1.17±0.15	August	1.43±0.59
Average	1.67±0.30	Average	1.49±0.12

(iv) SR93	
October	1.95±0.09
November	3.52±0.21
December	4.22±0.43
Average	**3.23±0.95**

Table 83. Thermal effect of *G. robusta* canopy shades and not mulching plus deep tillage estimated from Stigter's ratios R_{sti}: $R_{sti} = D_{Ts}/D_{TL}$ where D_{Ts} and D_{TL} are differences between the monthly and actual averages of of diurnal temperatures patterns at the same depth for bare soil and the Local plot respectively.
(a) agroforestry (b) non-agroforestry Mulched plots, and the bare soil.

(a) Agroforestry: Mulched AF plots (AFM1 & AFM2)

Position	R_{sti} = BS/AFL1 AL1 (94 cm)	 BL1 (376 cm)	R_{sti} = BS/AFL2 AL2 (94 cm)	 BL2 (376 cm)
(i) SR91 - All plots similarly treated				
October	0.50±0.10	0.78±0.10	0.65±0.07	0.34±0.07
November	1.04±0.98	0.94±0.16	0.63±0.24	0.61±0.40
Average	**0.77±0.27**	**0.86±0.08**	**0.64±0.01**	**0.48±0.14**
(ii) LR92 - From this season plots treated differently				
March	0.85±0.50	0.96±0.57	0.69±0.34	0.63±0.43
June	1.33±0.18	0.91±0.58	1.84±0.84	0.93±0.58
July	1.00±0.98	2.25±0.83	1.03±0.88	1.16±1.05
August	0.93±0.21	2.06±0.88	0.70±0.11	0.63±0.47
Average	**1.03±0.18**	**1.55±0.61**	**1.07±0.47**	**0.84±0.22**
(iii) LR93				
April	1.00±0.51	1.27±0.78	1.14±0.39	0.73±0.45
June	1.06±0.23	1.04±0.69	1.61±0.18	0.75±0.47
July	1.14±0.10	0.60±0.26	1.31±0.26	0.47±0.22
August	1.54±0.18	0.73±0.64	1.65±0.46	0.46±0.28
Average	**1.19±0.21**	**0.91±0.26**	**1.43±0.21**	**0.60±0.14**
(iv) SR93				
October	2.00±0.93	1.58±0.76	1.85±0.75	2.04±0.78
November	2.39±0.98	2.75±1.87	2.58±1.11	3.31±1.45
Average	**2.20±0.20**	**2.17±0.59**	**2.22±0.37**	**2.68±0.64**

(b) Non-agroforestry: Local control plots

(i) SR91 - Old control plots	R_{sti}: BS/L
October	1.06±0.20
November	0.61±0.02
Average	0.84±0.23

New control plots used from LR92 to SR93

R_{sti}: BS/L

(ii) LR92		(iii) LR93	
March	-	April	0.89±0.19
June	1.14±0.23	June	1.11±0.39
July	-	July	0.95±0.35
August	1.26±0.27	August	1.01±0.17
Average	1.20±0.60	Average	0.99±0.08

(iv) SR93	
October	1.40±0.23
November	2.78±0.38
December	3.69±0.16
Average	**2.62±0.94**

It is these fluctuations and variations that somewhat spoil the use of Stigter's ratio as an indicator of thermal efficiency af 'mulches' under shade. However, the strong reaction of the R_{sti}: values under moisture, as shown in SR93, is revealing, but with this trend in mind the difference between pruned and unpruned plots cannot be understood. The difference between Mulched and Local plots should give lower values for the non-mulched plots, which is fully true for SR91; where R_{sti} reveals residual effects from former use, of which the existence is this way independently confirmed. It is true for LR92 for the unpruned situation only, and for LR93 only for the 376 cm in the same situation. For SR93, however, it is only true for the pruned situation. For the NAF plots it is true everywhere, apart from SR91 where it is equal and no different residual effects occur. The fact that NAF plots and SR91 give R_{sti} values that can be understood, while the other seasons give changing variations, indeed points to local factors, residual as well as environmental, that influence the values too much in an unknown way. In combination with the earlier mentioned fluctuations and variations this leads to inconsistencies that cannot be explained from other data that we took. The inconsistency is larger in Local plots, which is very understandable because the "mulch" is the deep tillage treatment and inhomogeneity with depth and horizontally occurs. The data obtained from Mulched plots are much more consistent, particularly under dry conditions for which R_{sti} was developed. Under the latter conditions the relatively little variation between seasons. even more so under pruned situations. reveals that even our mulches even with our tree canopy treatment differences. contributed together with pruning, to a thermal homogenization not found in other plots. This is an important finding.

CHAPTER FIVE

5 Discussions and conclusions

5.1 Maize and beans intercrops

5.1.1 Comparison within and between seasons

Table A2.1 shows that for the equal treatments of SR91, a rather dry season apart from the very beginning, the future mulched control plot (M) had 0.34 t/ha more maize yields than the future Local (L) control plots and 0.27 t/ha and 0.36 t/ha more than future pruned AFM1 (for SR91: AFM1 plus AFL1) and future unpruned AFM2 (for SR91: AFM2 plus AFL2), for yields in the order of 1 t/ha. These differences, themselves, similar within the error margins, were bigger than any standard deviation error margins associated with each mean yield, but the lower error margin of M was either close to or just within the upper error margins of the other. For bean seeds a rather similar yield picture occurred with only the pruned plots doing better than in the case of maize, now coming halfway the mulched controls and the others, with its lower error margin only just lower than the lowest two averages. The better results in beans for plots with pruned trees is due to competition of maize and neighbouring fruit trees till SR92 inclusive.

The differences between M and L control plots are due to their history as respectively mulched and unmulched treatments, under which they were placed by the host institution prior to our experiments and in which role they continued. In the AF plots the differences must be due to pruning versus unpruning of *Grevillea robusta* trees plus, possibly, inhomogeneous climatic parameters associated with agroforestry systems such as ours.

As early as SR91, when trees were still young, results from UT1 show that shading was mainly concentrated in NW. This, and the roots from the neighbouring fruit trees, may have slightly contributed to reduction in yields in AF plots in contrast to the control plots. The tunnelling effect of the mainly strong southerly winds by the deliberate gap in the southern hedge (SH) for LR92 had not yet been introduced. The SH was planted in LR92 and the problem of tunnelling effect came only when the hedge had grown taller (by SR93). Termite infestation also may have exacerbated the problem but was less severe than these other factors. However, pruning is likely to be the most important factor within the AF plots.

Maize and beans yield measurements for LR92, which was the driest (in total rainfall) of the seven growing seasons of the study period, gave lowest yields for all seasons throughout the control plots, as indicated in review Table A2.1 (a). This table also shows that the minimum tilled pruned mulched plot (AFM1) had the highest maize biomass yield closely followed by Local control (L) while the minimum tilled unpruned mulched plot (AFM2), the deep tilled pruned Local and the Mulched control had the lowest. This driest season is the only one where the Mulched control maize gives substantial lower yields than the Local control although also have lower and upper error margins that overlap.

This coincides with the only season in which beans biomass and seed yields are both substantially higher for the mulched plots than for the Local plots, be it that also these yields are the lowest of all the seasons. It is very likely that beans took much of the early falling precipitation but then also relatively failed. That is why beans biomass yields are substantially higher than seed yield. The Mulched control plot had the highest bean seed and biomass yield shared in beans seed yields by the mulched pruned plots. while AFM2 had the lowest among AF plots (see Table A2.1 (b)). In beans biomass Local control shared these low yields while the bean seed yields were far the lowest of all the Local control. In NAF more moisture was conserved in the mulched control plot than in the Local control. This difference between M and L was substantial and was apparently soil moisture driven. This led to a bit more seed yields but less maize yields.

Yield comparisons between upper and lower halves of the AF plots in LR92 indicated consistently higher values. from 20% to 25% higher in pruned plots till 35% to 45% higher in unpruned plots. the higher values belonging to the mulched plots. the error margins being in the order of magnitude or smaller than the differences. We will come to the causes of these differences later on.

The conclusions to be drawn from the above results in the driest season of all suggest that in soil moisture conservation by the two methods of mulching and root pruning. only one was operatively effective in LR92. that is mulching in NAF beans and in pruned AF maize and beans. in the latter for seed only. For LR92 pruning was not yet operatively effective in the quality of AF yields. pruned and unpruned. while only mulch gave a difference between pruned and unpruned. In the NAF mulching in maize was not effective because of competition from beans. Competition (in this season between beans and maize) may induce water stress to which bean plants are not tolerant: as stomates close at a moderate leaf moisture deficit of -0.5 MPa (Norman *et al*.. 1984). An additional effect of radiative heating may be suggested by the very low value of bean seed yield in NAF Local plot. Results show that a high biomass may not necessarily produce a higher seed yield as under these drying up conditions more dry matter may remain in the vegetative phase than may go to fruit (or seed) parts. Norman *et al.* (1984) contend that more leaf area (or increased biomass) does indeed not necessarily increase seed yield. Seed yield is correlated with the number of pods per plant and number of plants surviving to maturity (Norman *et al.*, 1984), both negatively influenced by increasing water stress.

For SR92, the wettest of the seven growing seasons of this study, apart from the very beginning, the results of maize biomass and grain yields, and bean biomass and seed yields presented in Table A2.1 (a) show that with no exception the AF yields were the highest obtained, only in AFL1 shared for beans with SR94. The effect on maize and beans biomass yield and grain respectively, bean seed yields of mulching existed, although only large for maize biomass and perhaps for beans biomass in unpruned AF as well as for grains and seeds in NAF control plots.

If we may infer a pruning effect from the comparison of Local yields, for maize biomass the effect is opposite to that for bean biomass and perhaps of maize grain and bean seed yield, but all effects are small compared to the error margins. It seems that under the wetter conditions again mulching is more operative than pruning, but the latter additional effects. This is confirmed by the comparison of mulched AF plots.

The results of the weights of cobs in AF (see Table 19) show that low weights obtained for cobs from plants next to unpruned trees also suggest that there was some competition for soil water between unpruned *Grevilleas* and maize plants during the period of adequate rainfall like SR92.

The effect of mulch on water conservation are well known (see chapter 2). The competition for soil moisture between trees and crops brought about by the overlapping of depletion zones (**root system** sorption zone and **root surface** sorption zone) of the intercrop and tree root systems. The '**root system** sorption zone' refers to the volume of soil occupied by roots as determined by using a segment of a sphere with a mean radius of root spread and depth of rooting (Armson, 1977). This gives a quantitative approximation of the total soil volume of root exploitation. '**Root surface** sorption zone' is the volume of soil within one centimeter of any root surface determined by calculating the volume of soil associated with root lengths by diameter classes. This is an indirect measure of rooting intensity. This according to, for example, Palaniappan (1985) may cause over-crowding of the roots (from the two systems) in the soil where the surface area of the root system becomes larger than that of the shoot, resulting in higher competition for soil resources. The uptake of water and nutrients by the roots from the soil establishes a concentration gradient along which these substances diffuse or move by mass flow to the roots. These movements soon depletes the soil around the roots of these substances resulting in slowed down growth. Experience has learnt that the depletion zone for water for a single root extends to a radius of 25 cm. This applies to the "additional effect" of pruning that we observe. Root pruning, which affects 30 cm of the upper soil layer only, helps to reduce lateral competition within these layers. However, when roots have to go beyond 30 cm in search of soil resources, this depth becomes too shallow to be effective.

The results of the measurements of the per cent yield components of maize (i.e. cob, grain and biomass weights) for SR92 in both AF and

NAF suggest that the ratio by weight of cob, grain and biomass in the total weights produced per row were on the average nearly 1:3:6. The cob and grain weights per row were directly related to each other and inversely related to the biomass weights. An increase in stover biomass tends to result in a corresponding reduction in the weights of cob and grain components. The cob weights per row tended to be more stable around their mean values than the grain and biomass weights. This and a quantitative idea of the enormous fluctuations in yields in AF plots per row and within rows were among the most important results obtained from SR92 data and could be used to model maize yields for the semi-arid areas from weather parameters.

Results for LR93, which was particularly dry in the first two months, maize biomass and bean biomass and seed yields presented in Table A2.1 show that there was more of each yield in the NAF than in AF plots. This will repeat itself from now onwards in all seasons. The effect is now more substantial because of root pruning of the neighbouring fruit trees from LR93 onwards. Within the NAF plots yields were more or less equal, given the error margins and the differences concerned. If anything, a slight depression in maize biomass is noticed for the mulched plot, but this does not repeat itself in the seasons of the same kind. This may have been due to physical damage by termites which reside in and eat mulch materials and sometimes small roots of the intercrop plants during the time when there is little moisture available even for the termites. The first two months were relatively drier in LR93 than in the other two seasons. The termites were often absent in unmulched plots and in mulched plots during rainy periods.

The fruit trees comprising loquats and guavas were bordering the pruned mulched plot (AFM1) on one long side and by the pruned Local

(AFL1) on the other side. We demonstrated this by digging during land preparation for LR93. We dug 50 cm deep trenches at the borders between AFM1 and the fruit trees and between AFL1 and AFM2 to exclude the roots from the *loquat* and *guava* fruit trees and unpruned *Grevilleas* in the adjacent plots from invading the pruned *Grevilleas* area of the AF plot.

In AF plots pruned mulched with minimum tillage (AFM1) had most maize and bean yields. Only for maize biomass this will repeat itself in all further coming seasons. differences becoming more and more substantial with time. They show the trend and cumulative advantage of mulch application and pruning with time (tree roots becoming more and more developed) to increase yields. be it initially small. whose cumulative effects makes such increases important. For maize the effect of pruning on the Local control plots appears not to remain as strong as in LR93 but a depressive effect in the mulched unpruned plots is also returning in all the seasons after LR93. This has slowly built up from the beginning of the experiments and was for example also already visible in maize grain yields of the previous season. It occurs also in bean yields. be it not always as strong as in LR93 and there it occurs particularly in bean seed yields. The reasons for this yield depression in AFM2. that particularly occurs in the upper half of plots may be due to aging of trees that expand their roots (which decrease relative yields in both AFM2 and AFL2) and the effect of higher turbulence and wind. The latter effect comes from two sources effective in the upper half of plots. The increased turbulence due to the environment outside the AF plots visually disturbs plant growth particularly in AFM2. during LR where this effect was largest. This combined more and more with the effect of the growing southern hedge (that was planted early in the experiment (LR92), the gap in which increasingly negatively influenced the upper parts of both AFM2 and AFL2. It also should be recalled that from LR93 onwards AFM1 and to a lesser extent AFL1 yields increase because of root pruning of the neighbouring fruit trees. For SR seasons it must be the same increased wind/turbulence effects acting before sowing, decreasing the available soil moisture before the rainy season actually starts. In AFM2 an effect of termites adds to the above, but given the results in AFM1, they must in that case have had more influence on otherwise weakened plants. In both unpruned AF plots a bit more shading may also be an additive factor but the difference between Local plots do not confirm this. Throughout the last four growing seasons, pruning has very little effect on bean seed production and only occasionally on bean biomass production. Also the influence of mulching on bean biomass and seed yields reduces after LR93. This appears to be a prove that in AF conditions maize competition is effective in the upper layer, where most bean roots are. That this competition apparently occurs less in NAF plots, given the overall higher yields there throughout, must be due to the higher soil moisture in NAF plots. Apparently, although all indications give higher yields due to more soil moisture (and other effects) in the lower parts of AF plots, there is still soil moisture running off the AF plots, after which less is left for which competition between beans and maize is particularly strong.

From the results of LR93 and all seasons beyond we can also conclude that competition between the intercrop (maize and beans) and the AF trees with increased root growth for soil moisture, resulting in overall lower yields in AF than in NAF, is evident during a season with less rainfall. Plant residue mulching as applied is more effective in pruned and minimum tilled soil than in NAF in particularly the driest seasons. which must be due to the slope of the AF land. After new control plots were added any residual effects appeared small.

The SR93 season is covered by the above. Results for LR94 maize biomass yields as presented in Table A2.1 show this time exceptionally large differences in maize biomass within the NAF themselves. where M had more than twice more biomass than L. The differences within NAF plots showed how the NAF yields in Matanya can fluctuate even within the seasons themselves. It is indeed particularly the mulched control that is out of tune in the between season and within season comparisons. It is clear from Table A2.1 that both last seasons. LR94 and SR94. are the better ones after SR92. which is confirmed by the rainfall data. Mulching in NAF plots therefore becomes overwhelmingly important. The picture for the other treatments. in AF. remains relatively the same for these two seasons as before. with mulching not effective for beans in AF plots in SR94.

The decrease in bean yields over the last three seasons due to strong competition with maize and related water stress may have been due to plant mortality and failure of flowers to produce mature pods. due to this water stress which occurred at different stages of their development as reported in the phenology sections of this thesis. This may have resulted in abscission of flowers and failure to set and fill pods (Norman et al. 1984). Also here tree roots from farms or woodlot may cause interference in neighbouring farms. For soil water conservation measures to succeed. one should try to exclude the threat of invasion of tree roots from the neighbouring plots.

From the monitoring of phenological phases of maize hybrid H511 we used in this study. we can only draw conclusions from the SR92 results. For the remaining six other seasons the maize crop failed and therefore full phases were not reached. SR92 was a good year although plant growth was interrupted in the earlier stages as rainfall disappeared only to come late and salvage the intercrop. The ground was wet and the atmosphere was cold. The plants, which were planted on 4th October were harvested 176 days later on 23th March when the LR92 crop would have been in the ground. This interfered with land preparations for the LR92 season although even here rainfall came rather late. In this regard perhaps hybrid H511 is not appropriate as it takes too long before reaching maturity when conditions such as experienced in SR92 prevail. The periods from planting to harvesting of beans (Table A1) ranged from 104 days for LR93 and LR94 to 110 days for SR91 and generally tended to be somewhat longer during SRs than during LRs. However these differences were agronomically not marked.

In the on-farm situations the small-scale farmers try other hybrids such as H626 which they do dry-plant one (or two) month(s) before the main rains in the hope that should such conditions as SR92 come the crop will mature just before the onset of the next season. They often lose their seed through such trial and error methods.

A conclusion to be drawn from these overall results is that well planned water abstraction and rain water harvesting would be a solution for limited irrigation to grow maize varieties that require less rainfall and can grow faster than the H511 that is currently being used.

It has been pointed out in Chapter 2 that water stress in maize influences both vegetative and reproductive growth resulting in limitation of maize yield. Even with more abundant vegetative growth, drought can prevent grain yields to occur. It should also be considered that where water stress cannot be avoided maize should be replaced by sorghum and pearl millet. the two crops which according to Norman *et al.* (1984) have lower water requirements than maize. The problem, however, with such a statement is that food habits will for the time being prevent such changes.

5.1.2 Comparisons of on-station and on-farm results

5.1.2 (a) On-farm results

(i) Kiahuko-A

The results for Kiahuko-A on-farm for SR93, the comparison of the biomass yields in the pruned part of *Coleus barbatus* live-fence with the unpruned part, show that closest to the fence pruning accounted for 10% increase in biomass yields. which increase though small as far as relief measures are concerned, may provide the farmer in such a dry environment as Matanya a bonus to his livestock or provide mulching materials. The biomass yields in the open General Control plot (GC) were lower than closer to the live-fence due to exposure to the aerodynamic and evaporative effects in this part of the field which has no windbreak effect. Additionally competition for water between maize and a mature *Eucalyptus* tree growing nearby may have affected the yields negatively.

The maize biomass yields for SR94 were much lower than for SR93 due to less rainfall received during early crop establishment in SR94 than SR93. However the same trends are observed. Comparing SR94 maize biomass closest to the live-fence in pruned and unpruned fence, we see that pruning accounted for 34.2% increase in biomass yields, which is a substantial increase, although error margins strongly overlap. The farmer would be very pleased with such an increase, although he would still need grains to avert hunger. The GC obtained the highest biomass yields although it had shorter plants: which according to Norman et al. (1984) is due to dry matter distribution within the crop and to the sensitivity to water stress of both net photosynthesis and partitioning of assimilates.

(ii) Kiahuko-B

The results of the comparisons of maize biomass yields in pruned and unpruned plots with those in mulched control plots for SR93 and LR94 give substantial yield reductions attributable to shading by the *Grevillea robusta* trees in the Kiahuko-B on-farm (see Table A2.2), which made root pruning appreciably less effective under such conditions and competition for water between the unpruned trees and the crop less operative.

Similarly comparisons of Local plots in AF with the Local control give yield reductions which again we attribute to heavy shading which reduced the effect of other factors such as pruning and mulching.

The same conclusions can be drawn for LR94 seasons as shading by the trees became heavier with the age of the trees. pruning and mulching became less effective.

SR94 as the only season that produced some maize grain was again affected by shading. which reduced the yield differences between different treatments thus nullifying the positive effects of these treatments in both AF and the control plots (see Table A2.2). The error margins indeed overlap although the differences are always in the same direction. Only the effect of mulching seems fully nullified by the heavy shading. but the effect of pruning. although numerically appreciable and within the large error limits. is certainly diminished and does not bring sufficient relief (see Table A2.2).

The same conclusions hold for the bean seeds and biomass yields as there were no yields in AF plots due to strong shading and no substantial differences among treatments in NAF plots.

5.1.2 (b) **On-farm and on-station comparisons**

A comparison of the effect of **Grevillea robusta** tree root pruning at Matanya (Table A2.1) with that at Kiahuko-B (Table A2.2) for SR93 indicate that the differences between two mulched plots was less than its error margins, which showed that the two plots had equal yields. In unpruned mulched plots Kiahuko-B produced more biomass than Matanya. The differences in the pruned and unpruned Local plots show that the two locations produced equal maize biomass yields given their large error margins, with the tendency for higher biomass in on-farm conditions.

In LR94 the differences in pruned and unpruned mulched plots, and pruned and unpruned Local plots in the two locations show that Matanya produced markedly higher maize biomass than the Kiahuko-B on-farm, where the lower yields in the latter was attributed to heavy shading (see Tables A2.1 & A2.2). The differences in maize biomass in mulched control and Local control in the two locations were not negligible, which infers with certainty that Matanya overtook Kiahuko-B in biomass production in LR94 because of heavy shading in the latter AF plot. The yields in AF in Kiahuko-B were proportionally much smaller than in Matanya because the heavy shade factor in the former caused the lower yields. The situation for LR94 was opposite that for SR93, due to rainfall variations over a small distance of a few kilometres which in turn manifests in variations in biomass in Laikipia district.

Comparisons of different treatments in Matanya AF (Table A2.1) and Kiahuko-B AF (Table A2.2) show that in SR94, a supposedly good season at Kiahuko-B, shade reduced the biomass yields in the on-farm to a level where it equalled the biomass yields in Matanya. The biomass yields differences in the control plots at the two locations were clearly in favour of the on-farm yields. Only Kiahuko-B on-farm maize gave actual grain yields of paramount importance to the farmer.

The on-farm results compared to the simultaneously obtained on-station results for yields therefore show that appreciable differences may occur between the control plots at the different sites. For the best on-farm season (SR94) heavy shading in Kiahuko-B reduced these differences and for the worst on-farm season the already bad on-farm results were clearly worsened by this heavy shading. One may therefore conclude that with the shading reduced the remarkable biomass and other yield differences observed over very short distances would have come out in AF plots as well.

5.2 Soil moisture

Results from the calibration of neutron probes at Matanya show that on average there was a higher scatter of dry bulk density at lower values of volumetric soil moisture content, VSMC (θ), than at higher values, which was due to contraction of the Verto-luvic phaeozem soils on drying, thereby forming shrinkage cracks and lumps (clods) which get filled with air, thus inducing heterogeneity in dry seasons and becoming relatively more homogeneous under wet conditions. The conclusion that may be drawn from this is that in the dry season, when the vertic soils become too dry, such that they form shrinkage cracks, the neutron probe may not measure soil moisture accurately as the radius of sphere of importance of the meter becomes very large. The cracks also exposed somewhat deeper soil to desiccating strong winds during the LRs and strong radiative heating which depleted the soil of moisture in the upper layers even more. as shown by soil moisture results during dry seasons and in LRs more than in SRs. for example LR92. when top soil layers had less moisture than the deeper layers.

From results of soil moisture measurements from gravimetric samples for 1992 we learn that the soil surface (at 7.5 cm depth) became very dry during the cool dry season (CD) and very wet during SR92 that followed. The control plots were drier than the AF plots during CD but became wetter during SR92. The dryness was caused by strong winds which desiccated the top soil in the unsheltered control plots.

Results for VSMC near pruned and unpruned AF trees show that during the seasons of maize crop failures (all seasons except SR92) the soil water was mainly confined to the deeper layers. Deeper percolation occurred during a short number of days that the whole profile was above field capacity. which was followed by direct evaporation at the very top of the profile and through plants. The periods between rainfall occurrences were large and allowed enough time for the water to be used up in the layers holding the roots. The wetter season had more permanently higher VSMC values nearer the surface. when rainfall distribution was not skewed. than the drier seasons (or wetter seasons with skewed rainfall distribution). Hence the six seasons could not produce maize yields. making SR92 stand out as the only season that gave maize grain yields.

Average VSMC measurements with the neutron probe during SR92 indicated more soil moisture than during LR92 at all the depths and distances from the *Grevilleas*. The 30 cm depth had most pronounced soil moisture amounts during both LR92 and SR92. The marginal differences in average VSMC during SR92 between pruned plots (AFM1 & AFL1) and unpruned plots (AFM2 & AFL2) and M and L were in the AF plots amplified in small yield differences between the treatments, with pruned Mulched minimum tilled plot (AFM1) and unmulched deeply tilled Local plot (AFL2) having the highest maize biomass and in the former the highest beans biomass and beans seed yields of the AF plots in SR92, as indicated in Table A2.1. The yield differences are higher in beans because the top soil has highest fluctuations of and competition for soil moisture, particularly between maize and beans, of which the latter are susceptible. AFM1 and AFL1 are almost equally wind protected during strong winds which occur in the course of LRs.

Results of agronomically important deviations of soil moisture from averages and differences between access tubes of different agronomically important depths show that soil moisture in the AFM1 had generally highest positive deviations while AFL2, our supposed worst case, particularly for beans, had generally highest negative deviations, although rather some deviations were too small to be of agronomic value. It may be noted that soil moisture averages over the full soil profile till 170 cm, over the full season gave for example in LR93 and SR94 values that indicate that maize varieties with deeper roots would have had more chance to yield grain as sufficient water still was available in layers beyond the present rooting depths. The results of agronomically important differences of soil moisture show that in SR92 between up-slope and down-slope in the agronomically important layers there are not very remarkable differences. Overall, at the three distances from trees trends are certainly not identical but any existing trends give more moisture in the Mulched pruned plots and. up-slope. more moisture closer to the trees. Again a confirmation of somewhat more yields in AFM1 as influenced by increased moisture due to pruning. mulching and minimum tillage in AFM1, although the roots of the fruit trees have certainly reduced these effects because these roots were only pruned in the LR93 season.

We therefore conclude here that crop residue mulch was more effective as a water conservation method when applied in the somewhat sloping AF plots that had been root pruned and minimum tilled. Apparently as combination of minimum tillage, mulching and root-pruning this method is ideal for soil moisture conservation in semi-arid agroforestry systems. However, for the last four seasons the depressing effects of maize on bean yields in AF plots (and in NAF this applied also to SR92 for beans) and the higher yields in all NAF plots show that with the small amount of crop residue that we used soil moisture was still lost through run off beyond the AF plots.

We can conclude from the results of analysis of equivalent access tubes for LR92 and SR92 that at the three distances from the trees due to gravity more soil moisture was found down-slope in the lower half of AF than in the upper half and within AF this phenomenon was stronger in mulched plots than in the Local plots. Up-slope more soil moisture is found closer to the trees. There was surprisingly very little difference in soil moisture trends between the driest season (LR92) and the wettest season (SR92).

From the results of soil moisture trends with the distance from the pruned *Grevilleas* (PT1 & PT4) in the Mulched and minimum tilled plot

(AFM1) we observe a general decrease of soil moisture with the distance from the trees between 94 cm and 188 cm and then an increase between 188 cm and 376 cm in the agronomically important layers (i.e. 18-90 cm depths) for both LR92 and SR92. Soil moisture trends with distance from the trees (PT2 and PT5) in the pruned Local plot (AFL1) show that soil moisture increased between 94 cm and 188 cm and then decreased beyond 188 cm. with most striking increase being at 30 cm depth. For unpruned cases the soil moisture was lowest closer to the trees and increased with the distance from the trees although very inconsistently so in the layers of agronomic significance. Integrating these opposite trends it would support the finding that low yields were found closer to the unpruned trees where moisture was low and high yields closer to the pruned trees where moisture was rather high. the differences in seasonal distribution notwithstanding.

The LR94 and SR94 results for the on-farm live-fence experiment at Kiahuko-A show that competition for soil moisture between crop and fence roots may be substantially reduced by root pruning. There was similarity between places for different seasons among pruned and unpruned respectively within the treatments like for the *Grevilleas* in the on-station. All tubes closest to the live-fence in the unpruned area showed that there was least soil moisture at 90 cm from the unpruned live-fence compared to the other two distances away from it.

The conclusion on our hypothesis with respect to the soil moisture will be given after the yields results are also concluded on.

The LR94 and SR94 results for the on-farm *Grevillea* experiment at Kiahuko-B show that pruning on the on-farm was marginally important agronomically as the trees were very close together. The small spacing between adjacent *Grevillea* rows and within such rows enabled the canopies to close up and almost completely shade the ground, thereby reducing plant photo-synthesis, direct evaporation from the ground and soil temperature gradients, aided by leaf mulches that fell on all plots, thus making the effect of our intervention with mulch ineffective. The soil moisture in the agroforestry plots was appreciably less than that in the control plots but mulch did not improve the control situation. Also here within season distributions could change the picture but given the canopy influence this is not very likely here.

The application of our hypothesis for soil water conservation implied that increased final yields could be obtained by application of crop residue mulch at 3 t/ha, by pruning of agroforestry trees and live-fence and by minimum tillage. This was proved wrong for all but the driest and the wettest seasons, in the latter only the maize grains although the AFM1 plot, which was minimum tilled and mulched and had trees that were pruned, had higher final yields than the other AF plots (AFL1, AFM2 and AFL2). The combination of the mentioned relief measures resulted in higher yields in the NAF plots for those seasons. Remaining competition for water must be the spoiling factor in our set-up. However, for maize grain in the wettest season SR92 high and low yields are comparable in AF and NAF plots and the same applies to maize biomass in LR92. And for beans biomass (lowest values) and bean seeds (highest values) in LR92.

5.3 Strong winds at Matanya

It is important that we could conclude from the three calibration exercises that no corrections were necessary to individual electrical cup anemometers during periods between or otherwise close to the times of calibrations. because the instruments did not deteriorate with time during experimental periods at Matanya.

We may conclude from the results of wind direction studies for the period of strong winds (June–September), that these winds blow over Matanya from mainly southerly direction. and have rather small south-easterly and southwesterly components.

From the results of protective effects of the elements in the AF we find that according to the criteria of Heisler and Dewalle (1988), Seginer (1975) and Sturrock (1969), only crops in the lower part of AF (row 1) were effectively protected as the protective effect of the hedge. E, was measured to be greater than 0.2 there (i.e. $E \geq 0.2$). The sheltering effects of the *Coleus barbatus* hedge. assisted by *Grevillea* stems and canopies and the roughness of other maize plants. cumulatively decreased in AFM1 wind speeds from the first tree line (i.e. west to east from near SH) downwind to the last tree. This may partly explain the differences in biomass yields in AF for 1993 and 1994. The LR maize crops in the lower half of AF were taller and yielded more biomass than in the upper half. We learn from the results presented here that the crops were progressively protected from the southerly and south-easterly winds. The crops on the leeward side of each row of *Grevillea* were additionally and progressively protected by tree stems and canopies. but that influence appears to have only little difference among the places monitored.

The results from normalized wind speeds (Rsd) in AF show that the highest fluctuations were experienced in the protected areas. depending on the degrees of protection. with the highest Rsd observed for the positions with the highest protection and therefore lowest wind speeds. Many things mechanically influence daily average wind speeds with trends that increase the Rsd-values: increasing biomass of the protective elements, that is increasing biomass of hedge, the canopies and maize plants during rainy periods, when there is increase in foliage, change biomass influence with wind speed and wind angle.

It is important that results for the use of Piche evaporimeters as auxiliary anemometers gave very high correlation coefficients (r) between wind speed reduction ratios and Piche evaporation reductions. The over-all picture is that calculated values of wind speeds were very close to the measured values, thus confirming the Piche as a cheap alternative for wind speed extrapolation and interpolation in semi-arid agroforestry systems. Differences between the calculated and measured wind speeds were mostly less than 5%, even in what appeared as the worst case, without point (0,0). The results also show that the method of using a reference point in an open area (like cup 55) was for a sufficient sample inferior to using one of the positions in the AF as reference (like cup 38 position A7), which had similar micro-climatic conditions of air temperature and air humidity as most other Piches.

The application of our hypothesis for protection of the AF plot from strong winds implied that AF trees and live-fence (and nearby structures) provided sufficient protection to cropped land and hence increased intercrop yields. This could be proved although yields was higher in the well protected lower part of AF and in the areas occupied by AFM1 and AFL1, where protection from the strong June–September winds was adequate. It is, however, very likely that without root competition wind protection would have shown up as being effective.

5.4 Solar radiation

It is important that the tube solarimeters between themselves and in comparison with two Kipp solarimeters were very close to one another with correlation coefficients of nearly 100%, although the tube solarimeters appeared more sensitive to low amounts of radiation in their off-set values than the Kipp solarimeters.

From the results on solar radiation received by the intercrop we learn that the degree of canopy shade concentration was well reflected in the relative magnitude of the fractional radiation recorded. The magnitude and direction of concentration of tree canopy shade of course follows the sun's declination (position of the sun with respect to the equator).

Prior to LR94 UT1 canopy shade was measured, in LR94 PT2 canopy shade during the SRs, the region of heaviest canopy shading affected particularly NW and NE sectors of the tree canopy with the former getting the highest degree of shading. This picture was clear in SR92, where differences were a lot smaller, while in SR93 and SR94 the SW sector had also a lot of shade, in SR94 even most of all sectors. During LRs the region of heaviest UT1 canopy shading affected SW and SE sectors of the tree canopy somewhat more in LR92, but in LR93 (June only) and LR94 the shade distribution was more even, with the SW having more shade in LR94. As to relative shade with distance to the stem, from SR91 till LR93 inclusive, shade was overall highest at 188 cm, shared with in LR93 by 94 cm and in LR93 by 376 cm. From SR93 onwards 94 cm took over as being the distance where most shade occurred. The PT2 canopy shading was lighter than the UT1 shading, so more radiation was received by the inter-crop under root pruned conditions. This shows that pruning enhances radiation reaching the inter-crop, which may benefit from radiative enrichment by increasing PAR resulting in higher maize biomass yields. if other limiting factors do not interfere. close to the yields received in NAF plots, which had higher maize biomass yields most of the seasons. Of course less wood comes from pruned trees.

From the results of biomass yields (YLD) correlated with fractional radiation received by maize plants. we learn that YLD decreased with decrease in fractional radiation until about a fraction of 0.60 till 0.65. below which dry matter production virtually stopped. In SR92 there was higher YLD produced at higher radiation levels because rainfall was adequate to produce maize biomass and grain yields. We also learn that gradients and intercepts of the regression lines for the three distances from the trees were conservative, suggesting that the dry matter produced per unit increase in intercepted radiation was a conservative quantity. The conversion efficiency, e. in which other limiting factors radiation are hiding as well, was much higher during SR than during LR. The SRs crops produced more dry matter per unit of radiation intercepted than the LRs crops.

We may conclude from the results of comparing of yields in AF and NAF, that for Matanya low radiation loads below a fraction of about 0.6 of the open area total radiation were more harmful to maize plants in AF than high radiation loads with a fraction above this value. The application of our hypothesis for plant protection by shade from AF trees implied success only with no reduction of final yields by cutting of PAR. This could not be proven right or wrong although the NAF control plots (particularly Mulched control, M) gave consistently higher yields than the AF plots, suggesting the shade level was too high. However, matching of PAR and available nutrients only comes in if soil moisture is adequate. Therefore management aspects of pollarding and lopping may increase yields by increasing the PAR that falls on the intercrop canopy only in cases of adequate soil moisture and nutrients.

5.5 Soil temperature

We may conclude from the results of the analysis of extreme temperatures that although mulching at 3 t/ha was light it was useful in moderating extreme soil temperatures by affecting the temperature amplitudes and time to respond (phase shifts). The canopy differences, especially closer to the trees, and higher wind speeds in the course of the LRs, which results in changes in soil water status, were all involved to produce differences in soil temperatures of at least ±2.0° C. This might have brought about differences in the number of tillers produce per plot, which in turn could have influenced grain filling (Norman et al., 1984). However, because such influences are superimposed on direct soil moisture effects, it is unlikely that temperature has been of influence in other than extreme cases such as in the occurring (cumulative) drought periods.

Earlier work on mulches at Matanya indicated that 3 t/ha mulching rate did not have significant influence on the average soil temperature although it significantly influenced infiltration and soil moisture status (Liniger, 1991). Given the above, this depends on whether the soil was wet or dry and on the apparent albedo of that surface. It also depends on tree/hedge shading, which reduced the effects of additional mulch and air movement. It is likely that the temperature effect for shaded relatively wet soils was small and the mulch effect of run-off diminishing was appreciably more important.

The damping depths confirm the modifications due the treatments as well as the differences due to earlier induced (residual) and natural inhomogeneity of the AF plots and the change in control plots. The fluctuations and variations that the damping depth values show are also somewhat spoiling the use of Stigter's ratio. However, the R_{sti} values independently confirm the existence of non-negligible differences in residual effects. The fact that NAF plots and SR91 give R_{sti} values that can be understood confirm the damping depths results. It is nevertheless possible to draw one important conclusion, mulching as well as pruning, even with our mulches and tree canopy differences, induce strong thermal homogenization effects not found in other plots.

Soil temperature changes at Matanya as obtained from our study may well be managed through the relief measures proposed in the weather advisory (section 5.6). The application of our hypothesis for seedling protection by crop residue mulch and tree shade, through moderating soil temperature thereby resulting in better plant performance, could be proved right for mulch. The plants in Mulched NAF plots and AFM1 grew taller and had higher yields as well compared to their unmulched variants. It is likely that it would be proven right for tree shade as well in case of ample water in AF plots.

5.6 Weather advisories and further research

5.6.1 Weather advisories

Weather advisories are policy recommendations for actual farming conditions issued as results of the identified weather related problems that are solved through field research.

From the scientific point of view most parts of Laikipia district including Matanya area are not suitable for agriculture. But the small-scale farmers moved in to this area because of land scarcity in the high potential areas where they originated. They do not want to move again and our role is therefore to help them through scientific research to survive on their parcels of land.

Given the cropping systems that the farmers of the area know well, and the relatively low temperatures during good rainy seasons, for the time being no alternatives will be easily introduced, unless supplementary irrigation would be available. In any design within the limits of the system we researched, it will ne necessary:

- to root prune agroforestry trees and hedges;
- to plant agroforestry trees with suitable economic returns and with canopy spacings and crown densities (after pruning of roots and eventually branches) that compromise between crop protection through shading from too strong solar radiation and throughfall of sufficient light to match in the best rainy seasons the rate of photosynthesis allowed by the fertility of the farmer's plots. Our data indicate that well spread shade of 30 to 40% would be optimal. Pruning should have more influence on soil moisture improvement than shading (other than from mulch);
- to prevent run off by all means: which points to more conservation on steeper slopes, even when we talk about slopes smaller than 10%;
- to use (residue) mulch, of preferably more than 3 t/ha, for soil moisture improvement, particularly on somewhat sloping land, where runoff prevention appears essential. More mulch would also mean a higher contribution for soil fertility;
- to combine mulching with minimum or low tillage to improve physical soil properties near the surface;
- to design hedge and tree configurations that maximize wind protection preferably ≥ 35%, and do not introduce tunnelling through gaps. The plot environments should not generate turbulence that can harm the

crops and/or hedges and trees:

- to utilize the observed spatial differences in seasonal rainfall over short distances (of a few kilometres):
- to try drought resistant maize varieties with shorter growing seasons. that are acceptable to the local farmers.
- to try maize varieties with higher rooting depths that would use percolated water in deeper layers in seasons with irregular rainfall.

5.6.2 Further research

In the context of the weather advisories developed. the following future research will be necessary together with as many participating farmers as possible:

- to find more suitable agroforestry trees. in addition to the suitable *Grevilleas*. that combine economic returns from their products with optimal properties for root and branch pruning to obtain the shading compromise we indicated to be necessary:
- to find ways of obtaining additional mulch from outside the system or other means to prevent run off (and soil evaporation where the shade is low) and moderately improve soil fertility:
- to find the most suitable tillage method for improvement of top soil physical conditions in combination with different levels of mulching:
- to find hedges that optimize wind protection while root pruned and do not contribute to forming of harmful turbulence. Hedges with additional economic advantages should be tried out first:
- to find strategies. to utilize the observed spatial differences in seasonal rainfall over short distances. of either a community type or an individual land distribution type. Also improved storage or

marketing systems could be part of such strategies.

- to find ways of on-farm research in the region in which the history of yield variations of plots can play its own positive role, without attempts to nullify such differences at the beginning of experiments.
- to find drought resistant maize varieties, with shorter growing season, that can withstand cold conditions in the study area during growing seasons and are acceptable to the local farmers.

References

Abrecht, D.G., and Bristow, K.L., 1990. Maize seedling response to soil environment at varying distance from a mulched soil-bare soil boundary. Soil & Tillage. 15: 205-216.

Acland, J.D., 1971. East African crops. Longman Group Limited: 252 pp.

Allen, L.H., Sinclair, Jr., T.R. and Lemon, E.R., 1976. Radiation and microclimate relationship in multiple cropping systems. In: R.I. Papendick, P.A. Sanchez and G.B. Triplett (Eds). Multiple cropping. Amer. Soc.Agron., Crop Sci. Soc. Amer. and Soil Sci. Soc. Amer., Wisconsin, U.S.A.

Armson, K.A., 1977. Forest soil: Properties and processes. Toronto: University of Toronto Press, 390 pp.

Baldy, C.H., 1963. Cultures associate'es et productivite' de l'eau. In: Ann. agron., 14(4): 489-534.

Bean, A., Alperi, R.W., and Federer, C.A., 1975. A method of categorizing shelter porosity. Agric. meteorol., 14: 417-312

Bennett, J.M., Jones, J.W., Zur., B. and Hammond, L.C., 1986. Interactive effects of nitrogen and water stresses on water relations of field-grown leaves. Agron. J., 78: 273-280.

Berger, P., 1989. Rainfall and agroclimatology of the Laikipia plateau, Kenya. Geographica Bernensia. African study series, A7. Berne: 47: 102 pp.

Blacklow, W.M., 1972. Influence of temperature on germination and elongation of the radicle and shoot of corn (*Zea mays*, L.). Crop Science, 12: 647-650.

Bohn, H., B. McNeal and O'connor, G., 1979. Soil chemistry. John Wiley and sons, Inc. 329 pp.

Bowden, L., 1979. Development of present dryland farming systems. In: A.E. Hall, G.H. Cannell and H.W.Lawton (Eds.). Agriculture in Semi-arid environments. Ecological Series 34; New York: 45-72 pp.

Braun, H.M.H., 1980. Exploratory soil map and agro-climatic zone map of Kenya. Ministry of agriculture, Nairobi, 30 pp.

Bristow, K.L., 1988. The role of mulch and architecture in modifying soil temperatures. Aust. J. Soil Res., 26: 269- 280

Bristow, K.L., and Abrecht, D.G., 1989. The physical environment of two semi-arid tropical soils with partial surface cover. Aust. J. Soil Res., 27: 577-587.

Brown, D.M., 1976. Response of maize to environmental temperatures: A review. In: Proc. Symp. Agromet. maize (corn) crop WMO No. 481, Iowa state Univer. Ames, Iowa U.S.A 5-9 July 1976: 15-26.

Budelman, A., 1988. The performance of the leaf mulches of Leucaena leucocephala, Flemingia macrophylla and Gliricidia sepum in weed control. Agroforestry Systems, 6(2): 137-145.

Budelman, A., 1989. The performance of selected leaf mulches in temperature and soil moisture conservation in the upper soil stratum. Agroforestry Systems, 8: 53-56.

Burley, J., 1985. Global needs and problems of the collection, storage and distribution of multipurpose tree germplasm. ICRAF Science and Practice of agroforestry 2, 179 pp.

Bussiere, F., and Cellier, P., 1994. Modification of the soil temperature and water content regimes by a crop residue mulch: experiment and modelling. Agric. For. Meteorol., 68: 1-26.

Campbell Scientific Ltd., 1990. CR10 measurement and control module. Operator's manual. Koenders Instruments, England.

Chepil, W.S., and Woodruff, N.P., 1963. The physics of wind erosion and its control. Adv. Agron., 15: 211-302.

Chepil, W.S., 1965. Transport of soil and snow by wind. In: Meteorological monographs, 6: 123-132.

Chui, J.N., and Nadar, H.M., 1983. Effect of spatial arrangement on the yield and other agronomic characters of maize and legume intercrops. E.A. agric. For. J. (special issue). 44: 137-146.

CIAT, 1978. Annual Report. 1977. Bean program. Cali, Colombia: Centro International de Agricultura Tropical, 85 pp.

CIAT, 1979. Annual Report. 1978. Bean program. Cali, Colombia: Centro International de Agricultura Tropical, 75 pp.

Connor, D.J., 1983. Plant stress factors and their influence on production of agroforestry plant associations. In: P.A. Huxley, ed.)., Plant research and agroforestry, ICRAF, Nairobi.

Cunningham, R.A., 1988. Genetic improvement of trees and shrubs used in windbreaks. Agric. Ecosystems Environ. 22/23: 483-498.

Da Costa, J.M.N., Rosenberg, N.J., and Verma, S.B., 1986. Joint influence of air temperature and soil moisture on CO_2 release by a soybean crop. Agric. For. Meteorol., 37: 219-227.

Davies, J.M., 1975. Mulching effects on plant climate and yield. WMO Tech. Note No. 136, WMO, Geneva: 92 pp.

Davis, J.H.C., and Garcia, S., 1987. The effects of plant arrangement and density on intercropped beans (*Phaseolus vulgaris L.*) and maize. I. Traits related to dry matter and seed productivity. Field Crops Res., 16: 105-115.

Davis, J.H.C., Roman, A., and Garcia, S., 1987. The effects of plant arrangement and density on intercropped beans (*Phaseolus vulgaris L.*) and maize. II. Comparison of relay intercropping and simultaneous planting. Field Crops Res., 16: 117-128.

Davis, J.E., and Norman, J.M., 1986. Effects of shelter on plant water use. Agric. Ecosystems Environ., 22/23: 393-402.

Delta - T Devices. 1984. Tube solarimeters manual. Delta-T Devices Ltd.

Delta-T Devices Ltd., U.K. 1988. The Decagon sunfleck ceptometer user manual. CEP-UM-8.

Delta-T Devices Ltd. 1989. Instruments for environmental science. Delta T Devices Ltd., U.K.

Denmead, O.T., and Shaw, R.H., 1960. The effects of soil moisture stress at different stages of growth on the development and yield of corn. Agron. J., 52: 272-274.

Desaules, A., 1986. The soils of Mt. Kenya semi-arid Northwest Footzone and their agricultural suitability. Ph.D. thesis. University of Berne, Switzerland.

Dhyani, S.K., P. Narain and Singh, R.K., 1990. Studies on root distribution of five multipurpose tree species in Doon Valley, India. Agroforestry systems. 12(2): 149-161

Doran, J.W., W.W., Wilhelm, and Power, J.F., 1984. Crop residue removal and soil productivity with no-till corn, sorghum, and soybean. Soil Sci. Soc. Am. J., 48, (3): 640-645.

Duin, R.H.A., 1956. On the influence of tillage on condition of heat diffusion of air and infiltration of water in the soil. Wageningen. Versl. Landbouwk. onderz. 62 pp.

Eastin, J.A., 1969. Leaf position and leaf function in corn: Carbon-14 labelled photosynthate. In: Proceedings of the 24th Annual Corn and sorghum Research conference American Seed Trade Association: 181-189.

EUROCONSULT (Eds.). 1989. Agricultural compendium: For rural development in the tropics and subtropics. The Netherlands Ministry of Agriculture and Fisheries, The Hague, Amsterdam. 740 pp.

FAO. 1979. A provisional methodology for soil degradation assessment: FAO, Rome (person. comm.): 143 pp.

Finch, S.J., 1988. Field windbreaks: Design criteria. Agric.Ecosystems Environ. 22/23: 215-228.

Flury, M., 1986. Semi-arid Highlands of Laikipia (Kenya): Small-scale farmers in marginal environment. Change of land-use and contribution of applied research to adapted development planning. African Mountain Workshop (Ethiopia): 18-27 October. 13 pp.

Flury, M., 1987. Rain-fed agriculture in the central division of Laikipia district, Kenya: suitability, constraints and potential for providing food. Geographica Bernensia. Vol. 6, Berne, Switzerland.

Flury, M., 1988. Precipitation, growing periods, agro-ecological suitability for small-scale rain-fed farming (Laikipia district, Kenya). Working paper WP5. Laikipia Research Programme, Nanyuki, Kenya.

Freebairn, D., 1992. Improving the storage and use of rainfall Less tillage - Less Risk. Conservation farming information centre and Dalby /Wamboand Jondaryan Landcare Warra and Mt. Tyson, 13-14 July 4-22.

Gachathi, F.N., 1989 Kikuyu dictionary of plant names and uses. University of Nairobi, Nairobi, Kenya.

Gardner, E.A., 1988. Soil water. In: Understanding soils and soil data. Australian society of soil science Inc., Brisbane, Australia.

Gates, D.M., 1965. Radiant energy, its receipt and disposal. In: Agric. Meteorol. Monographs, 6(28): 26 pp.

Gerald, C.J., Sexton, P., and Shaw, R.H., 1982. Physical factors influencing soil strength and root growth. Agron. J., 74: 875-879.

Gilbert, E., 1995. The meaning of the maize revolution in sub-Saharan Africa: Seeking guidance from past impacts. Agricultural administration (Research and Extension) Network. Network paper 55. Odi : 52 pp.

Gloyne, R.W., 1955. Some effects of shelterbelt and windbreaks. Met mag., 84 (999): 272 - 281.

Goodman, M., 1976. Maize. *Zea mays* (Graminae-Maydeae). In: N.W. Simmonds (ed.). Evolution of crop plants. Longman London: 128-136.

Gosh, K.L., and Rao, V.S., 1972. Chemical constituents of *Grevillea robusta* bark. Indian Forester, 98: 32-35.

Grace, J., 1977. Plant response to wind. Academic Press Lond.: 204 pp.

Grace, J., 1985. The measurement of wind speed. In B. Marshall and F.I. Woodward (Ed.): Instrumentation for Environmental Physiology. Society for experimental Biology, Seminar series 22, Cambridge University Press, Lond.

Grace, J., 1988. Plant response to wind. Agric. Ecosystems Environ. 22/23: 71-88.

Greacen, E.L. (Ed.), 1981. Soil water assessment by the neutron method. CSIRO. Divsion of Soils. Adelaide: 1-140 pp.

Griffiths. J.F., 1972. Climates of Africa. In: J.F.Griffiths (ed.). World Survey of climates. 10: 604 pp.

Hall, A.E., Foster, K.W. and Wanes, J.G., 1979. Crop adaptation to semi-arid environments. In: A.E. Hall. G.H. Cannell and H.W.Lawton (Eds.). Agriculture in Semi-arid environments. Ecological Series 34: New York: 148-179 pp.

Halverson. H.G., and Smith. J.L., 1974. Controlling solar light and heat in a forest by managing shadow sources. USDA Forest Service Research Paper PSW-102.

Hanway, J.J., 1963. Growth stages of corn. Agron. J., 55: 487-492.

Harder. H.J., Carlson, R.E., and Shaw. R.H. 1982. Yield, yield components and nutrient content of corn grain as influenced by post-silking moisture stress. Agron. J., 74: 275-278.

Harrison, P., 1987. The greening of Africa: Breaking through in the battle for land and food. An intern. Instut. Environment and Development-EARTHCAN STUDY: 380 pp.

Harrison-Murray, R.S., and Lal, R., 1979. High soil temperature and the response of maize to mulching in the lowland humid tropics. In: R. Lal and D.J. Greenland (eds.). Soil physical properties and crop production in the tropics. Wiley. New York: 285-304.

Hartfield. J.L., 1976. Light response in maize: A review. In: Proc. Symp. Agromet. maize (corn) crop WMO No. 481, Iowa state Univer. Ames. Iowa U.S.A 5-9 July 1976: 199-206.

Harwood, C.E. (ed.), 1989. Grevillea robusta: an annotated bibliography. ICRAF/CSIRO/ACIAR. 123 pp.

Harwood, C.E., 1992. Natural distribution and ecology of Grevillea robusta. In: C.E. Harwood (ed.): Grevillea robusta in agroforestry and forestry. Proc. Intern.Workshop. ICRAF/CSIRO/AIDAB/ACIAR: 21-28.

Hazra, C.R., 1985. Forage and seed yield of crops under agroforestry production systems-Radiation and temperature relations. Journ. Agron. & Crop Sci., 155: 186-192.

Heisler, G.M., and Dewalle. D.R., 1988. Effects of windbreak structure on windflow. Agric. Ecosystems Environ, 22/23: 41-69

Hesketh, H.E., 1972. Understanding and controlling air pollution. Ann Arbor Science Publishers, Inc., Michigan.

HMS. 1956. Handbook of meteorological instruments. Part 1 Instruments for surface observations. London: 458 pp.

Hofstra. G.. and Nelson. C.D.. 1969. The translocation of photosynthetically assimilated ^{14}C in corn. Canadian J. Botany. 47. 1435-1442.

Huxley. P.A.. Akunda. E.. and Repollo. A. 1987. Climate and plant response: the use of phenological data to match with the choice of woody species for agroforestry systems. In: W.S. Reifsnyder and T.O. Darnhofer (eds.).Meteorology and agroforestry. Proc. Intern. Workshop on Application of meteorology to Agroforestry systems planning and management 9-13 Feb.. Nairobi: 99-113.

Ibrahim. A.A.. Stigter. C.J.. Adeeb. A.M.. Adam. H.S. and Jansen. A.E.. 1989. Development and validation of a shaded Piche evaporimeter for the tropics to replace humidity and wind speed data in the aerodynamic term of the Penmann equation. In: Proceedings of the Fourth Technical Conference on instrumentsand Methods of Observation (TECIMO IV), Instruments and Observing Methods Report No. 35, WMO/TD No. 303, Geveva: 147-152.

Ibrahim. A. A.. 1992. Water use efficiency of dura and groundnut under traditional and non-traditional irrigation practices in the Gezira Scheme, Sudan. Ph.D thesis University of Gezira: 395 pp.

Jackson. I.J.. 1989a. Climate, Water and Agriculture in the tropics. Longman Scientific & Techn. John Wiley & sons Inc. New York: 377pp.

Jackson. J.E.. 1983. Light climate and crop-tree mixtures. In: P.A. Huxley (ed.). Plant Research and Agroforestry. ICRAF: 365-378.

Jackson. J.E.. 1989b. Tree and crop selection and management to optimize overall system productivity, especially light utilization. in agroforestry. In: Meteorology and Agroforestry. Reifsnyder. W.S. and Darnhofer. T.O. (eds.): 163 - 173.

Jackson. J.E.. and Palmer. J.W.. 1989. Light availability at the tree / crop interface. In: Meteorology and Agroforestry. Reifsnyder. W.S. and Darnhofer. T.O. (eds.): 391 - 400.

Jama. B.. Getahun. A.. and Ngugi. D.N.. 1991. Shading effects of alley cropped *Leucaena leucocephala*. on weed biomass and maize yield at Mtwapa. Coast Province. Agroforestry systems, 13: 1-11.

Jatzold. R.. and Schmidt. H.. (eds.). 1983. Farm management handbook of Kenya. vol. II/B, Central Kenya: Nairobi and Trier.

Jeffrey. C.. 1973. Biological nomenclature: Special topics in biology series. 5 pp.

Jeffrey. C.. 1982. An introduction to plant taxonomy (second edition). Cambridge University Press. 63 pp.

Jensen. M.. 1954. Shelter effect. Investigations into the Aerodynamics of shelter and its effects on climate and crops. The Danish Technical Press. Copenhagen: 263 pp.

Jerrard, H.G., and McNeill, D.B., 1972. A dictionary of Scientific units. Chapman and Hall, London (3rd edition), 212 pp.

Jones, J.W., Zur, B., and Bennett, J.M., 1986. Interactive effects of water and nitrogen stresses on carbon and water vapor exchange of corn canopies. Agric. For. Meteorol., 38: 113-126.

Kainkwa, R.R.M., 1983. Shortwave radiation effects of shading with a review of shade use in Tanzania farming. M.Sc. Thesis, University of Dar-es-Salaam, Department of Physics, Tanzania.

Kainkwa, R.R.M., 1991. Shelter efficiency of some traditional windbreaks in Tanzania. A Ph.D. thesis, University of Dar es Salaam. 300 pp.

Kainkwa, R.R.M., and Stigter, C.J., 1994. Wind reduction downwind from a savanna woodland edge. Netherl. J. Agric. Sci. 42-2: 145-157.

Kay, D.E., 1979. Food legumes. Lond: Tropical Products Instit., 435pp.

Keating, B.A., and Carberry, P.S., 1993. Resource capture and use in intercropping: solar radiation. Field crops research.34: 273-301.

Kerkhof, P., 1988. Agroforestry manual for Taita-Taveta district, Kenya. DANIDA/Kenya Forest Department /Ministry of Agriculture. 151 pp.

Kerkhof, P., 1990. Agroforestry in Africa: In: G. Foley and G. Barnard, (eds.), A survey of project experience: 216 pp.

Kiniry, J.R., Jones, C.A., O'Toole, J.C., Blanchet, R., Cabelguenne, M., and Spanel, D.A., 1989. Radiation-use efficiency in biomass accumulation prior to grain-filling for five grain-crop species. Field crop Res., 20: 51-64.

Kipp and Zonen, 1977. Solarimeter for outdoor installation. Kipp & Zonen, The Netherlands.

Kipp and Zonen, 1988. User manual solar integrator CC12 (8802).

Kohler, T., 1987. Landuse in transition, aspects and problems of small-scale farming in a new environment: the examples of Laikipia district, Kenya. Geographica Bernensia, African studies, vol. A5, Berne, Switzerland.

Konate, M., 1984. Climate of sorghum and millet cultivation zones of the semi-arid tropical regions of west Africa. In: ICRISAT, Agrometeorology of sorghum and millet in the tropics: Proc. of the Intern. Symposium, 15-20 Nov 1982, ICRISAT center, India Patancheru.

Konstantinov, A.R., 1966. Evaporation in nature. Translated from Russian by Israel Program for Scientific Translation. Natl. Sci. Found., Washington, DC.: 523 pp.

Krishnan, A. and R.S. Kushwaha, 1972. Study of average heat fluxes in various layers of the soil and their seasonal variations in Jodhpur, India. Arch. Met. Geoph. Biokl. Ser. B., 22: 247-256.

Jerrard, H.G., and McNeill, D.B., 1972. A dictionary of Scientific units. Chapman and Hall, London (3^{rd} edition), 212 pp.

Jones, J.W., Zur, B., and Bennett, J.M., 1986. Interactive effects of water and nitrogen stresses on carbon and water vapor exchange of corn canopies. Agric. For. Meteorol., 38: 113-126.

Kainkwa, R.R.M., 1983. Shortwave radiation effects of shading with a review of shade use in Tanzania farming. M.Sc. Thesis, University of Dar-es-Salaam, Department of Physics, Tanzania.

Kainkwa, R.R.M., 1991. Shelter efficiency of some traditional windbreaks in Tanzania. A Ph.D. thesis, University of Dar es Salaam, 300 pp.

Kainkwa, R.R.M., and Stigter, C.J., 1994. Wind reduction downwind from a savanna woodland edge. Netherl. J. Agric. Sci. 42-2: 145-157.

Kay, D.E., 1979. Food legumes. Lond: Tropical Products Instit., 435pp.

Keating, B.A., and Carberry, P.S., 1993. Resource capture and use in intercropping: solar radiation. Field crops research.34: 273-301.

Kerkhof, P., 1988. Agroforestry manual for Taita-Taveta district, Kenya. DANIDA/Kenya Forest Department /Ministry of Agriculture, 151 pp.

Kerkhof, P., 1990. Agroforestry in Africa: In: G. Foley and G. Barnard, (eds.), A survey of project experience: 216 pp.

Kiniry, J.R., Jones, C.A., O'Toole, J.C., Blanchet, R., Cabelguenne, M., and Spanel, D.A., 1989. Radiation-use efficiency in biomass accumulation prior to grain-filling for five grain-crop species. Field crop Res., 20: 51-64.

Kipp and Zonen, 1977. Solarimeter for outdoor installation. Kipp & Zonen, The Netherlands.

Kipp and Zonen, 1988. User manual solar integrator CC12 (8802).

Kohler, T., 1987. Landuse in transition, aspects and problems of small-scale farming in a new environment: the examples of Laikipia district, Kenya. Geographica Bernensia, African studies, vol. A5, Berne, Switzerland.

Konate, M., 1984. Climate of sorghum and millet cultivation zones of the semi-arid tropical regions of west Africa. In: ICRISAT, Agrometeorology of sorghum and millet in the tropics: Proc. of the Intern. Symposium, 15-20 Nov 1982, ICRISAT center, India Patancheru.

Konstantinov, A.R., 1966. Evaporation in nature. Translated from Russian by Israel Program for Scientific Translation. Natl. Sci. Found., Washington, DC.: 523 pp.

Krishnan, A. and R.S. Kushwaha, 1972. Study of average heat fluxes in various layers of the soil and their seasonal variations in Jodhpur, India. Arch. Met. Geoph. Biokl. Ser. B., 22: 247-256.

Jerrard, H.G., and McNeill, D.B., 1972. A dictionary of Scientific units. Chapman and Hall, London (3rd edition), 212 pp.

Jones, J.W., Zur, B., and Bennett, J.M., 1986. Interactive effects of water and nitrogen stresses on carbon and water vapor exchange of corn canopies. Agric. For. Meteorol., 38: 113-126.

Kainkwa, R.R.M., 1983. Shortwave radiation effects of shading with a review of shade use in Tanzania farming. M.Sc. Thesis, University of Dar-es-Salaam, Department of Physics, Tanzania.

Kainkwa, R.R.M., 1991. Shelter efficiency of some traditional windbreaks in Tanzania. A Ph.D. thesis, University of Dar es Salaam. 300 pp.

Kainkwa, R.R.M., and Stigter, C.J., 1994. Wind reduction downwind from a savanna woodland edge. Netherl. J. Agric. Sci. 42-2: 145-157.

Kay, D.E., 1979. Food legumes. Lond: Tropical Products Instit., 435pp.

Keating, B.A., and Carberry, P.S., 1993. Resource capture and use in intercropping: solar radiation. Field crops research.34: 273-301.

Kerkhof, P., 1988. Agroforestry manual for Taita-Taveta district, Kenya. DANIDA/Kenya Forest Department /Ministry of Agriculture. 151 pp.

Kerkhof, P., 1990. Agroforestry in Africa: In: G. Foley and G. Barnard, (eds.), A survey of project experience: 216 pp.

Kiniry, J.R., Jones, C.A., O'Toole, J.C., Blanchet, R., Cabelguenne, M., and Spanel, D.A., 1989. Radiation-use efficiency in biomass accumulation prior to grain-filling for five grain-crop species. Field crop Res., 20: 51-64.

Kipp and Zonen, 1977. Solarimeter for outdoor installation. Kipp & Zonen, The Netherlands.

Kipp and Zonen, 1988. User manual solar integrator CC12 (8802).

Kohler, T., 1987. Landuse in transition, aspects and problems of small-scale farming in a new environment: the examples of Laikipia district, Kenya. Geographica Bernensia, African studies, vol. A5, Berne, Switzerland.

Konate, M., 1984. Climate of sorghum and millet cultivation zones of the semi-arid tropical regions of west Africa. In: ICRISAT, Agrometeorology of sorghum and millet in the tropics: Proc. of the Intern. Symposium, 15-20 Nov 1982, ICRISAT center, India Patancheru.

Konstantinov, A.R., 1966. Evaporation in nature. Translated from Russian by Israel Program for Scientific Translation. Natl. Sci. Found., Washington, DC.: 523 pp.

Krishnan, A. and R.S. Kushwaha, 1972. Study of average heat fluxes in various layers of the soil and their seasonal variations in Jodhpur, India. Arch. Met. Geoph. Biokl. Ser. B., 22: 247-256.

Krishnan, A. and G.G.N. Rao. 1979. Soil temperature regime in the arid zone of India. Arch. Met. Geoph. Biokl. Ser. B. 27: 15-22.

Kristensen, K.J., 1973. Depth interval and top soil moisture measurement with the neutron probe. Nordic hydrology. 4: 77-83.

Lal, R., 1979. Physical characteristics of soils of the tropics, determination and management. In: R. Lal and D.J.Greenland (Eds.). Soil physical properties and production in the tropics. John Wiley, Chichester. Ch. 1.2, 7-44.

Lal, R., 1987. Managing the soils of subsaharan Africa. Science, 236: 1069-1076.

Lawrence, E.N., 1955. Effects of a windbreak on the speed and direction of wind. Met mag., 84 (998): 244 -251.

Lawson, T.L., and Kang, B.T., 1984. Resource use in alley cropping. In: IITA Annual Report, 1983, Ibadan, Nigeria: 181-182.

Lawson, T.L., and Kang, B.T., 1990. Yield of maize and cowpea in alley cropping system in relation to available light. Agric. For. Meteorol., 52: 347 - 357.

Lind, E.M., and Tallantire, A.C., 1975. Some common flowering plants of Uganda. Oxford University press, 2nd ed., Nairobi.

Liniger, H.P., 1991. Water conservation for rainfed farming in the semi -arid Footzone northwest of Mt. Kenya (Laikipia highlands). Consequences on the water balance and the soil productivity. Laikipia - Mt. Kenya papers, D-3, Ser. D, discussion papers: 174 pp.

Liptay, A.M. and Tiessen, H. 1970. Influences of polyethylene-coated paper mulch on soil environment. J. Amer. Soc. Hort. Sci., 95: 395-398.

Lomas, J., and Lewin, J., 1977. Water use efficiency of maize and its response to physical parameters of the environment. In: Proc. Symp. Agromet. maize (corn) crop WMO No. 481. Iowa state Univer. Ames, Iowa U.S.A 5-9 July 1976: 156-173.

Long, I.F. and French, B.K., 1967. Measurement of soil moisture in the field by neutron depth probe. J. Soil Sci., 18(1): 149-166.

Lundgren, B.O., 1978. Soil conditions and nutrient cycling under natural and plantation forests in Tanzanian highlands. Reports in forest ecology and forest soils No. 31. Sweden Univers. Agric. Sci., Uppsala, Sweden, 426 pp.

Lundgren, B.O., and Raintree, J.B., 1983. Sustained agroforestry. Agricultural Research for Development. Potentials and Challenges in Asia. The Hague ISNAR, ICRAF, reprint No. 3: 26 pp.

Lyles, L., 1988. Basic wind erosion processes. Agric. Ecocsystems Environ., 22/23: 91-101.

MacHattie, L.B., and Schneile, F., 1974. An introduction to agrotopoclimatology. Tech. Note No: 133. WMO: Geneva: 131 pp.

McArthur, J.D., 1976. Some general characteristics of farming in a tropical environment. In: H. Ruthenberg. Farming systems in the tropics. Clarendon Press-Oxford: 19-27.

McNaughton, K.G., 1988. Effects of windbreaks on the turbulent transport and microclimate. Agric. Ecosystems Environ. 22/23: 17-39.

McTaish, G.H., Rose, C.W., Okach, G.E., and Palis, R.G., 1992. Water and wind erosion similarities and differences. In: H. Hurn, and K. Tato (Eds.). Erosion conservation and small - scale Farming, 6th Intern. soil conserv. conf. of the ISCO Ethiopia and Kenya 6 - 18 Nov. 1989: 107 - 119.

Moges, A., 1991. Water conservation and production under two agroforestry systems: A Laikipia district case study. M.Sc.thesis. University of Nairobi. 136

Mongi, H.O. and Huxley, P.A., 1979. Soils research in agroforestry.Proc. Expert Consultation.ICRAF: 584 pp.

Monsi, M., and Saeki, T., 1953. On the light factor in plant communities and its significance for dry matter production. Jap. J. Bot., 14: 22-52.

Monteith, T.L., 1977. Climate and the efficiency of crop production in Britain. Phil. Trans. R. Soc. Lond., b 218: 277 - 294.

Monteith, T.L., and Unsworth, M.H., 1990. Principles of environmental physics: 36-100.

Muchena, F.N., 1979. Use of soil physical characteristics for land evaluation. In: R. Lal and D.J. Greenland (Eds.). Soil physical properties and crop production in the tropics. 427-437.

Mugah, J.O., 1983. Rooting characteristics of water extraction by Katumani maize composite B maize under varying moisture regimes. E.A. agric. For. J. (special issue). 44: 80-87.

Mungai, D.N., 1991. A micrometeorological investigation of yield differences in alley cropping trials in the semi-arid areas of Machakos district, Kenya. Ph.D. Thesis, University of Nairobi: 404 pp.

Mungai, D.N. and Stigter, C.J., 1994. The use of weather and climate information in planning and production in Africa under conditions of increasing climate variability. African Meteorol. Soc. (special issue): 596-600.

Mutinda, M. N., 1995. The influence of an agroforestry system on light competition , biomass production and nutritive value for sheep. M.Sc. University of Egerton (under preparation).

Mwampaja, A.R., 1983. Soil temperature effects of mulching and an example of soil temperature under mulched tea in Kericho, Kenya. M.Sc. thesis, Physics Department, University of Dar es Salaam.

Nadar, H.M., 1983. Intercropping and intercrop component interaction under varying rainfall conditions in East Kenya. I: maize/bean intercrop. E.A. agric. For. J. (special issue). 44: 166-175.

Nadar, H.M., and Faught, W. A., 1983. Maize yield response to different levels of nitrogen and phosphorus fertilizer application: A seven-season study. E.A. agric. For. J. (special issue). 44: 147-156.

Nagaeli, W., 1953. The braking effect of a forest on wind. Intern.Union. Forest. Res. and Organ., 11th Conf., Rome, section 11: 12 - 17.

Nair, P.K.R. 1984. Soil productivity aspects of agroforestry. Science and practice of agroforestry 1. ICRAF, Nairobi, 85 pp.

Nair, P.K.R., 1988. Agroforestry and firewood production. In: D.O. Hall and R.P. Overend. R.P. (eds.), Biomass. John Wiley & Sons Ltd.: 367-386.

Neumann, I.F., 1983. Use of trees in small-holder agriculture in tropical highlands. In: W. Lockertz, (ed.), Environmentally sound agriculture, New York: 351-376.

Nicoullaud, B.; King, D. and Tardieu, F., 1994. Vertical distribution of maize roots in relation to permanent soil characteristics. Plant and soil, 159: 245-254.

Norman, M.J.T., Pearson, C.J. and Searle, P.G.E., 1984. The ecology of tropical food crops. Cambridge University Press, London. 369 pp.

Oke, T.R., 1987. Boundary layer climates. Methuen, Lond. 435 pp.

Ong, C.K. 1989. Interaction of light, water and nutrients in agroforestry systems. In: M.E. Avery, M.G.R Cannell and C.K. Ong.(eds.), Biophysical Research for Asian agroforestry; Winrock Intern., USA & S. Asia books, USA: 107-124.

Ongugo, P.O., 1992. Place of *Grevillea robusta* in National Agroforestry and Wood production Policies and Plans. In: C.E. Harwood (ed.). *Grevillea robusta* in Agroforestry and Forestry. Proc. Intern. Workshop, ICRAF. 29-36.

Onyewotu, L.O.Z., Ogigirigi, M.A., and Stigter, C.J., 1994. A study of competitive effects between a *Eucalyptus camaldulensis* shelterbelt and an adjacent millet (*Pennisetum typhoides*) crop. Agric. Ecosyst. and Environ., 51: 281-286.

Oteng'i, S.B.B., 1982. The reliability of pentad rainfall in Kenya. IMTR research report No. 2/82: 41 pp.

Oteng'i, S.B.B., 1994. Maize straw and agroforestry influence on the micrometeorology of maize/beans intercrop on the western footzone of Mt. Kenya. The Second National workshop on Meteorological Research Applications and Services, 5 - 9th Dec., Nairobi: 17 pp.

Oteng'i, S.B.B., Ng'ang'a, J.K., Mungai, D.N., Stigter, C.J., and Liniger, H.P., 1995. An investigation of the effect of mulching and agroforestry systems on the microclimatic conditions affecting soil moisture for maize/bean intercrop: In: C.J. Stigter, F.J. Wang'ati, J.K. Ng'ang'a, and D.N. Mungai (eds). The TTMI-Project and the 'PICNIC model: An evaluation of approaches and results and of prospects for TTMI-units. 124-135.

Othieno, C.O., Stigter, C.J., and Mwampaja, A.R., 1985. On the use of Stigter's ratio expressing the thermal efficiency of grass mulches. Expl. Agric., 21:169-174.

Owino, F., 1992. Trends in growing and utilization of Grevillea as an exotic. In: C.E. Harwood (ed.): Grevillea robusta in agroforestry and forestry. Proc. Intern. Workshop. ICRAF/CSIRO/AIDAB/ACIAR: 17-19.

Paez, M.L. and Rodriguez, R., 1992. Erosion and conservation assessment on arable lands in Venezuela. In: H. Hurn and K.Tato (Eds.). Erosion conservation and small - scale Farming: 6th Intern. soil conservation conf. of the ISCO Ethiopia and Kenya 6 - 18 Nov. 1989: 39-49.

Palaniappan, S.P., 1985. Cropping systems in the tropics: Principles and management. Wiley East. Ltd (New Delhi) & Tamil Nadu Agricultural Univers. (Coimbatore). 215 pp.

Papendick, R.I., Lindstorm, M.J., and Cochran, V.L., 1973. Soil mulch effects on seedbed temperature and water during fallow in eastern Washington. Soil Sci. Soc. Amer. Proc., 37: 307-314.

Parkes, M.E., and Siam, N., 1979. Errors associated with measurements of soil moisture by neutron probe. J. agric. Eng. Res., 148-166.

Pearcy, R.W., 1989. Radiation and light measurements. In: R.W. Pearcy, J. Ehleringer, H.A. Mooney and P.W. Rundel (Eds.). Plant physiological Ecology: Field methods and instrumentation. Chapman and Hall, London: 97-116.

Pearcy, R.W., Tumosa, N. and Williams, K., 1981. Relationships between growths, photosynthesis and competitive interactions for a C_3 and a C^4 plant. Oecologia, 48: 321-326.

Pereira, H.C., 1979. Hydrological and soil conservation aspects of agroforestry. In: H.O. Mongi and P.A. Huxley (Eds.).Soil research in agroforestry: 315-326. ICRAF. Nairobi.

Quashu, H.K. and Evans, D.D., 1967. Effect of black granular mulch on soil temperature, water content and crusting. Soil Sci. Soc. Amer. Proc., 31: 429-435.

Quesada, F., Somarriba, E., and Vargas, E., 1989. Simulation of tree shadows in agroforestry systems. In: W.E. Reifsnyder and T.O.Darnhofer (eds.).Meteorology and agroforestry. Proc.Intern. Workshop on Application of meteorology to Agroforestry systems planning and management 9-13 Feb., Nairobi: 157-161.

Rachie, K.O., 1983. Intercropping tree legumes with annual crops. In: Plant Research and Agroforestry, ICRAF: Huxley, P.A. (ed.).

Radke, J.K., and Hagstrom, R.T., 1976. Strip intercropping for wind protection. In: R.I. Papendick, P.A. Sanchez, G.B. Triplett (Eds.): Multiple cropping. ASA Special Publication No. 127. Madison, U.S.A.

Rao, M.R., 1986. Cereals in multiple cropping. In: C.A. Francis (ed.). Multiple cropping systems. Macmillan Publishing Company New York: 96–132.

Ratliff, L.F., Ritchie, J.T., and Cassell, D.K., 1983. A survey of field measured limits of soil water availability and related laboratory measured properties. Soil Sci. Soc. Am. J., 47: 770–775.

Reddy, A.N.Y., 1992. Grevillea robusta in coffee plantations of Karnataka. In: C.E. Harwood (ed.), *Grevillea robusta* in Agroforestry and Forestry. Proc. Intern. Workshop, ICRAF: 59–65.

Reifsnyder, W.E., 1989. Control of solar radiation in agroforestry practice. In: W.E. Reifsnyder and T.O. Darnhofer (eds.). Meteorology and agroforestry. Proc. Intern. Workshop on Application of meteorology to Agroforestry systems planning and management 9–13 Feb., Nairobi: 141–156.

Reijntjes, C., Haverkort, B., and Waters-Bayer, A., 1992. Farming for the future: An introduction to low-external-input and sustainable agriculture. ILEIA. Macmillan. Netherlands: 250 pp.

Republic of Kenya, 1981. On National Food Policy. Kenya Government Printers.

Republic of Kenya, 1983. Development Plan 1984–1988. Kenya Government Printers.

Republic of Kenya, 1986. Sessional Paper No. 1. On Economic Management for Renewed Growth: 177 pp.

Republic of Kenya, 1994a. Sessional Paper No. 2. On National Food Policy. Kenya Government Printers: 56 pp.

Republic of Kenya, 1994b. National Population Census Statistics of 1989. Kenya Government Printers.

Rocheleau D., Weber, F. and Field-Juma A. 1988. Agroforestry in dryland Africa. Science and practices of agroforestry, 3: 311 pp.

Ross, P.J., Williams, L., and McCown, R.L., 1985a. Soil temperature and energy balance of vegetative mulch in the semi-arid tropics. I. Static analysis of radiation balance. Aust. J. Soil Res., 23: 493–514.

Ross, P.J., Williams, L., and McCown, R.L., 1985b. Soil temperature and energy balance of vegetative mulch in the semi-arid tropics. II. Dynamic analysis of the total energy balance. Aust. J. Soil Res., 23: 515–532.

Ruthenberg. H.. 1976. Farming systems in the tropics.: Clarendon press -Oxford. 366 pp.

Russell. E.E.. 1961. Soil conditions and plant growth. English Language Book Soc. Longmans Green and Co. Ltd.

Russel. M.B.. 1980. Profile moisture dynamics of soil in Vertisols and Alfisols. ICRISAT. In: Proc. Intern. Workshop on the Agroclimatological Research needs of the semi-arid tropics. 22-24 Nov.. 1978, Hyderabad. India.

Saffell. R.A.. Campbell. G.S.. and Campbell. E.C.. 1979. An improved micropower counting integrator. Agricultural meteorology, 20: 393-396.

Seginer. I.. 1975. Flow around a windbreak in oblique wind. Boundary-Layer meteorol.. 9: 323-333.

Shaw. R.H.. 1977. Water use and water requirements of maize. In: Proc. Symp. Agromet. maize (corn) crop WMO No. 481. Iowa state Univer. Ames, Iowa U.S.A 5-9 July 1976: 119-134.

Sinclair, T.R.. and Horie. T., 1989. Leaf nitrogen. photosynthesis. and crop radiation use efficiency: a review. Crop sci.. 29: 90-98.

Skidmore. E.L.. Layton. J.B.. Armbrust. D.V.. and Hooker. M.L.1986. Soil physical properties as influenced by cropping and residue management. Soil Sci. Soc. Am. J., 50(2): 415-419.

Smartt. J.. 1969. Evolution of American Phaseolus under domestication. In: P.J. Ucko & G.W. Dimbleby (eds). The dometstication and exploitation of plants and animals. London: Duckworth: 451-462.

Smith. H.. 1995. Success in the shade. SPORE 54 page 12.

Sombroek. W.G., and Braun. H.M.H.. 1974. The soils of the Area: Properties and water resources. In: WMO: Agroclimatology of the highlands of East Africa. Proc.Tech. Conf. 1-5 Oct.. 1973,Nairobi: 96-96.

Spiers. N. and Stewart. M.. 1992. Use of Grevillea robusta in Embu and Meru districts of Kenya. In: C.E. Harwood (ed.): Grevillea robusta in agroforestry and forestry. Proc. Intern. Workshop. ICRAF/CSIRO /AIDAB/ACIAR: 37-48.

Squire. G.R.. Ong. C.K.. and Monteith. J.L.. 1987. Crop growth in semi-arid environments. In: Proceedings of the International pearl millet workshop, 7-11 April, 1986. Hyderabad. India: ICRISAT: 219-231.

Stewart. J.I.. 1982a. Research on rainfall and yield responses to water and nitrogen in different environment for guiding crop selection and farm practices in semi-arid areas of Kenya. In: Proc. Intern. Symp. Semi-arid tropics. Olinda. Pernambuco: Aug. 16-20.

Stewart. J.I.. 1982b. Crop yields and returns under different soil moisture regimes. 3rd FAO/SIDA Seminar on Field crops in Africa and the Near East. Nairobi, Kenya 6-12 June: 19 pp.

Stigter, C.J., 1984a. Traditional use of shade: a method of microclimate management. Arch. Meteorol. Geoph. Biocl. B. 34: 203-210.

Stiger, C.J., 1984b. Shading: a traditional method of microclimate manipulation. Neth. J. agric. Sci., 32: 81-86.

Stigter, C.J., 1984c. Mulching as a traditional method of microclimate management. Arch. Meteorol. Geoph. Biocl. B. 35: 147-154.

Stigter, C.J., 1985a. Physics of mulching with particular emphasis on grass mulches. Intern. Colloqium on energy flux at the soil/atmosphere interface. Trieste, Italy, ICTP: 11 pp.

Stigter, C.J., 1985b. Wind protection in traditional microclimate management and manipulation - examples from East Africa. Effects of shelter on the physiology of plants and animals. In: Grace, J., (ed.): Progress in biometeorology, 2: 145 - 154.

Stigter, C.J., 1987. Mulching with organic materials: Knowledge is power. ILEIA Newsletter, 3(3): 10-11.

Stigter, C.J., 1988. Microclimate management and manipulation in agroforestry. In: K.F. Wiersum (Ed.), Viewpoints on Agroforestry. Agricultural University Wageningen, The Netherlands: 145 - 168.

Stigter, C.J., 1990. On some experience within the TTMI-Project. ODI Agricultural Administration (Research and Extension) Network Newsletter: 9 pp.

Stigter, C.J., 1994a. Management and manipulation of micro- climate. In: Griffiths (Ed.) Handbook of agricultural meteorology, Oxford University Press: 273 - 284.

Stigter, C.J., 1994b. Conditions, requirements and needs for outdoor measurements in developing countries: The case of Agrometeorology and Agroclimatology. Invited Paper presented at the WMO Technical Conf. on Instruments and Methods of Observation. TECO-94, WMO, Geneva. Extended Abstract in Instruments and Observational Methods. Report No. 57, WMO/TD-No.588: PP. 1-2.

Stigter, C.J., 1995. The "PICNIC" model and TTMI research: Successes, failures and development consequences of two innovative approaches in third world university research education. In: C.J. Stigter, F.J. Wang'ati, J.K. Ng'ang'a and D.N. Mungai (Eds.). The TTMI-project and the "PICNIC"-model: an internal evaluation of approaches and results and of prospects for TTMI-Units. Wageningen Agricultural University.

Stigter, C.J., and Darnhofer, T.O., 1989. Quantification of microclimate near the soil surface. In: J.M. Anderson and I.S. Ingram (eds.), Tropical biology and soil fertility. A Handbook of methods. IUBS/UNESCO (MAB), C.A.B.International, Wallingford (UK): 144-157.

Stigter, C.J. and Baldy, Ch.M., 1994. Manipulation of the microclimate by intercropping: Making the best of services rendered. Presented at the Intern. Meeting on Ecophysiology in Tropical Intercropping, Gudeloupe, December 1993, INRA Antilles

-Guyana. 13 pp.

Stigter, C.J., Mjungu, Y.B., and Waryoba, J.M., 1984a. Out door demonstration experiment on the effects of soil albedo on soil surface temperatures. Am. J. Phys., 52(28): 742-744.

Stigter, C.J., Darnhofer, T.O., and Herrera, S.H. , 1989. Crop protection from very strong winds: recommendations from a Costa Rican agroforestry case study. In: Meteorology and Agroforestry. In: W.E. Reifsnyder and T.O.Darnhofer (eds.),Meteorology and agroforestry. Proc. Intern. Workshop on Application of meteorology to Agroforestry systems planning and management 9-13 Feb., Nairobi : 521 - 529.

Stigter, C.J., Othieno, C.O., Coulson, C.L and the Kenyan TTMI- team. 1987. Mulching with organic materials: Knowledge is power. Microclimate management. ILEIA, 3(3), 10-11.

Stigter, C.J., Mjungu, Y.B., Lutege, M., Waryoba, J.M., Othieno, C.O. and Mwampaja, A.R., 1984b. Relationships between soil albedos and soil and air temperatures. Neth. J. agric. Sci., 32: 33-42.

Stigter, C.J., Wang'ati, F.K., Ng'ang'a, J.K., and Mungai, D.M., 1995a. The TTMI-Project and the 'PICNIC model: An evaluation of approaches and results and of prospects for TTMI-units.

Stigter, C.J., Mungai, D.N., J.K., Ng'ang'a, Oteng'i, S.B.B., and TTMI-team in Kenya, Nigeria, Sudan and Tanzania, 1995b. Moving research ever closer to rural reality: a comparison of two TTMI-projects phases. Submitted for publication in ILEIA.

Stofella, R.J., Sandsted, R.F., Zobel, R.W. & Hymes, W.L., 1979. Root characteristics of black beans: II. Crop Science, 19: 826-830.

Stoker, R., 1974. Effect on dwarf beans of water staress at different phases of growth. New Zealand Journal of experimental agriculture, 2, 13-15.

Sturrock, J.W., 1969. Aerodynamics studies of shelterbelts in New Zealand: Low to medium height shelterbelts in Mid-Caterbury. N.Z. J. Sci., 12: 754-776.

Sturrock, J.W., 1988. Shelter: Its management and promotion. Agric. Ecosystems and Environ., 22/33 : 1-13.

Swan, D., Brown, D.M. and Coligado, M.C., 1981. Leaf emergence rates of corn (*Zea mays*, L.) as affected by temperature and photoperiod. Agric. Meteorol., 24: 51-73.

Symmons, P.M., 1989. Aspects of biology, behaviour and population dynamics of the absent locust relevant to present activities. FAO plant protection Bulletin, 37: 5-15.

Szeicz, G., Monteith, J.L., and Dos Santos, J.M., 1964. Tube solarimeter to measure radiation among plants. Journ. Appl. Ecol., 1: 169-174.

Szeicz, G., 1974a. Solar radiation for plant growth. Journ.Appl. Ecol., 2: 617 - 636.

Szeicz,G., 1974b. Solar radiation in crop canopies. Journ. Appl. Ecol., 2: 1117 - 1156.

Tanner C.B., Peterson, A.E., and Love, J.R., 1960. Radiant energy exchange in a corn field. Agron. J., 52: 373-379.

Tibke, G., 1988. Basic principles of wind erosion control. Agric. Ecosystems Environ., 22/23: 103-122.

Tieszen, L.L., 1983. Photosynthesis systems: Implications for agroforestry. In: P.A. Huxley (ed.). Plant Research and Agroforestry.ICRAF: 365 - 378.

Todorov, A.V., 1977. Guide-Book for agrometeorological observations. East African Meteorological Department. Nairobi. 151 pp.

Trenbath, B.R., 1976. Plant interactions in mixed crop communities. In: R.I. Papendick, P.A. Sanchez and G.B.Triplett (Eds). Multiple cropping. Amer. Soc. Agron., Crop Sci. Soc. Amer. and Soil Sci. Soc. Amer.,Wisconsin, U.S.A.

Trenbath, B.R., 1986. Resource use by intercrops. In: C.A. Francis (ed.). Multiple cropping systems. Macmillan Publishing Company New York: 57-81.

Trolldenier, G., 1988. Influence of cultivation measures on soil life. Plant research and development, 26: 114-126.

Tyler, D.D., and Overton, J.R., 1982. Non-tillage advantages for soybean seed quality during drought stress. Agron. J., 74, 344-346.

Umaya, G.O., 1991. The spatial and temporal distribution of the active roots of Cassia siamea Lam. and Zea mays L. (cv. Katumani Composite B), in alley cropping under semi-arid conditions in Machakos district, Kenya. M.Sc. thesis, University of Nairobi, Botany Dept.: 98 pp.

Unger, P.L.W., 1987. Possibilities of zero-tillage for small-scale farmers in the tropics. The TTMI-Project: ILEIA, 3(3): 7-8.

Van Bavel, C.H.M., Nixon, P.R., and Hauser, V.L., 1963. Soil moisture measurements with the neutron method. Agric. Res. Serv., U.S.A. Depart. Agric.: 1-38.

Van de Weg, R.F., 1978. Field guidelines for the annotation of the soil profile description form. Kenya Soil Survey, IC17. Nairobi, Kenya.

Vandenbeldt, R.J. and Williams, J.H., 1992. The effect of soil surface temperature on the growth of millet in relation to the effect of *Faidherbia albida* trees. Agric. For. meteorol., 60: 93-100.

Van Eimern, J., Karschon, R., Razumuva, L.A., and Robertson, G., 1964. Windbreaks and shelterbelts. WMO Tech. Note 59: 188 pp.

Van Eimern. J.. 1968. Some experiences obtained in mapping the local wind pattern. In: Proc. the regional WMO training seminar on agrometeorology. WMO and agricultural University of Wageningen.

Van Wijk. W.R..1965. Soil microclimate its creation. observation and modification. In: Meteorol. monographs. 6(28): 59-72.

Van Wijk. W.R.. Larson. W.E.. and Burrows. W.C.. 1959. Soil temperature and early growth of corn from mulched and unmulched soil. Soil Sci. Soc. Amer. Proc.. 31: 428-434.

Van Zyl. W.H.. and De Jager. J.M.. 1987. Estimating evaporation from wheat using weather measurements and carborundum or Piche evaporimeter. Agric. For. meteorol.. 41: 65-75.

Visvalingam. M.. and Tandy. J.D.. 1972. The neutron method for measuring soil moisture content - a review. J.Agric. Sci.. 23(4): 499-511.

Walker. G.K.. and Hartfield. J.L.. 1979. Test of the stress degree-day using multiple planting dates of red kidney beans. Agronomy J.. 71: 967-971.

Warren. W.J.. 1969. Maximum yield potential. In. Proc. VIIth Colloqium. Int. Potash Inst. Bern Switzerland. 34-56.

Webb. L.J.. Tracey. J.G.. and Haydock. K.P.. 1967. A factor toxic to seedlings of the same species associated with living roots of the non-gregarious subtropical rainforest tree *Grevillea robusta*. Journ. Appl. Ecology. 4: 13-25.

Webster. C.C.. and Wilson. P.N.. 1966. Agriculture in the tropics. Tropical agric. series. Longman Lond. 488 pp.

Wiersum. K.F.. 1988. Outlines of agroforestry concepts. In: K.F. Wiersum (Ed.). Viewpoints on Agroforestry. Wageningen Agricultural Univ.. The Netherlands: 1-26 pp.

Willey. R.W.. and Osiru. D.S.O.. 1972. Studies on mixtures of maize and beans (*Phaseolus vulgaris*) with particuiar reference to plant population. Journal of Agricultural Science. 79: 517-529.

Willey. R.W.. Natarajan. M.. Reddy. M.S.. and Rao. M.R.. 1986. Cropping systems with groundnut: resource use and productivity. In: Agrometeorology of groundnut. international symposium proceedings. 21-26 Aug.1986. Niamey. Niger: ICRISAT Sahelian Centre: 193-205.

Wilhelm. W.W.. Doran. J.W.. and Power. J.F.. 1986. Corn and soybean yield response to crop residue management under no-tillage production systems. Agron. J.. 78(1): 184-189.

Wilken. G.C.. 1972. Microclimatic management by traditional farmers. Geogr. Rev.. 62 (4): 544-560.

Wilkes. H.G.. 1967. Teosinte: The closest relative of maize: Cambridge. Mass. Harvard university. The Bussey Institute.

WMO. 1981. Meteorological aspects of the utilization of wind as an energy source. WMO Tech. Note No. 175: Geneva. 180 pp.

WMO. 1983. Meteorological aspects of certain processes affecting soil degradation - especially erosion. WMO Tech. Note No. 178: Geneva. 149 pp.

WMO. 1985. Use of meteorological and hydrological data in the combat against desertification. WMO Special Report. I: WMO Geneva. 24-36

WMO. 1986. Land use and agrosystem management under severe climatic conditions. WMO Techn. Note No. 184: Geneva. 161 pp.

WMO. 1989. Land management in arid and semi-arid areas. WMO Tech Note. No. 186: Geneva. 148 pp.

WMO. 1995. Commission for Agricultural meteorology. Eleven Session. Abridged Final Report with Resolutions and Recommendations. WMO-No. 825. WMO. Geneva. 50 pp.

Young. A., 1987. The potential of agroforestry for soil conservation and sustainable land use. In: J. Kozub (Ed.). Seminar on land and water resources management.Washington, D.C.: Economic Development Institute of The World Bank. 16 pp.

Young. A., 1989. Agroforestry for soil conservation. ICRAF Science and practices of agroforestry 4. C.A.B. International: 276 pp.

Zhou. F.J., Wang. L.K. and Peng Xu. 1992. Wind erosion on a coastal hilly soil in China. In: H. Hurn and K.Tato (Eds.). Erosion conservation and small - scale Farming: 6th Intern. soil conservation conf. of the ISCO. Ethiopia and Kenya. 6-18 Nov. 1989: 121 - 131.

Figures and Tables in Appendix

Figures in Appendix

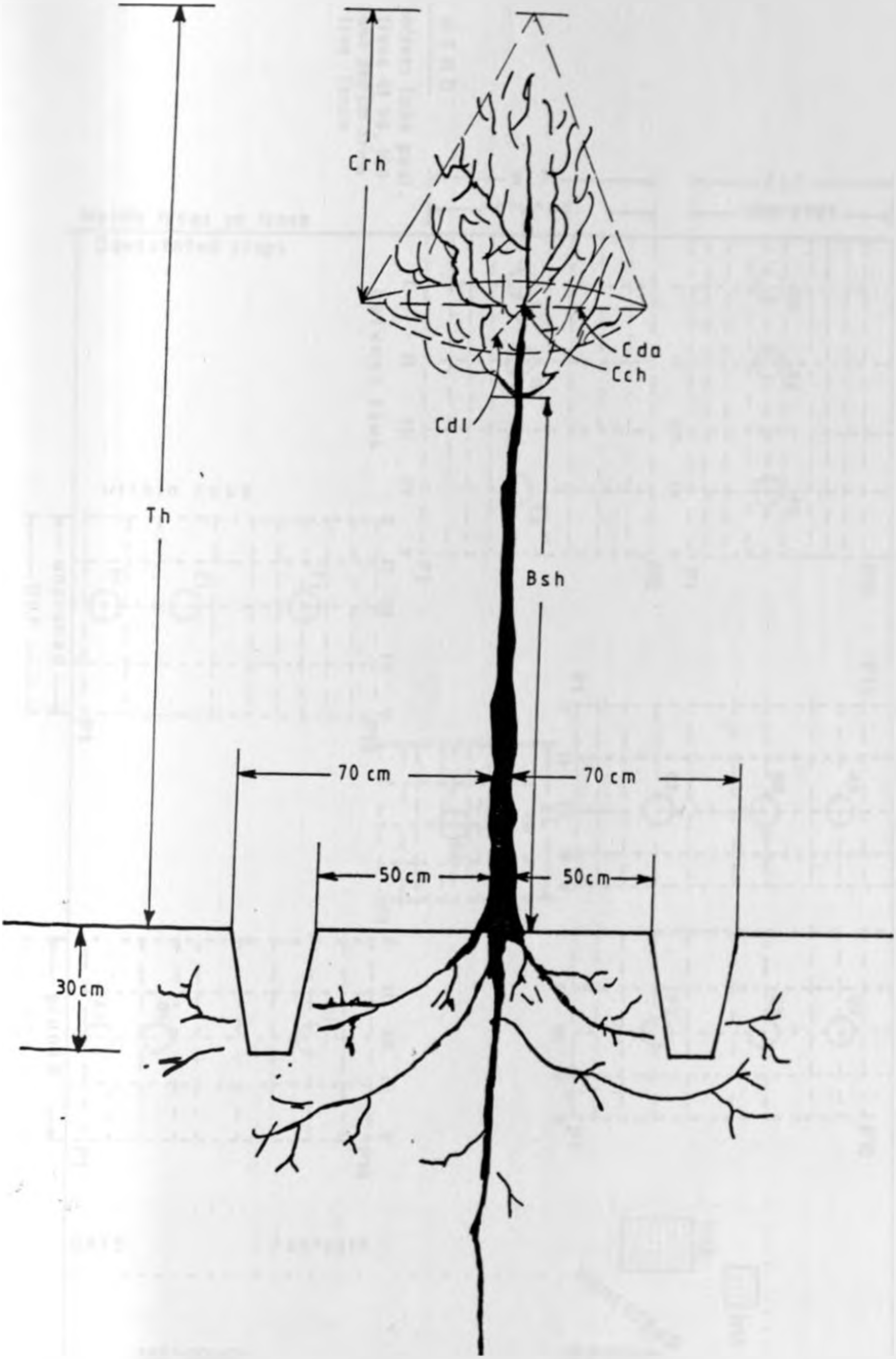

Fig. A1. A sketch of a root-pruned *Grevillea robusta* tree illustrating its geometry including its cone-shaped canopy used in wind protection and radiation shading effects (see Table A8 for meanings of abbreviations used).

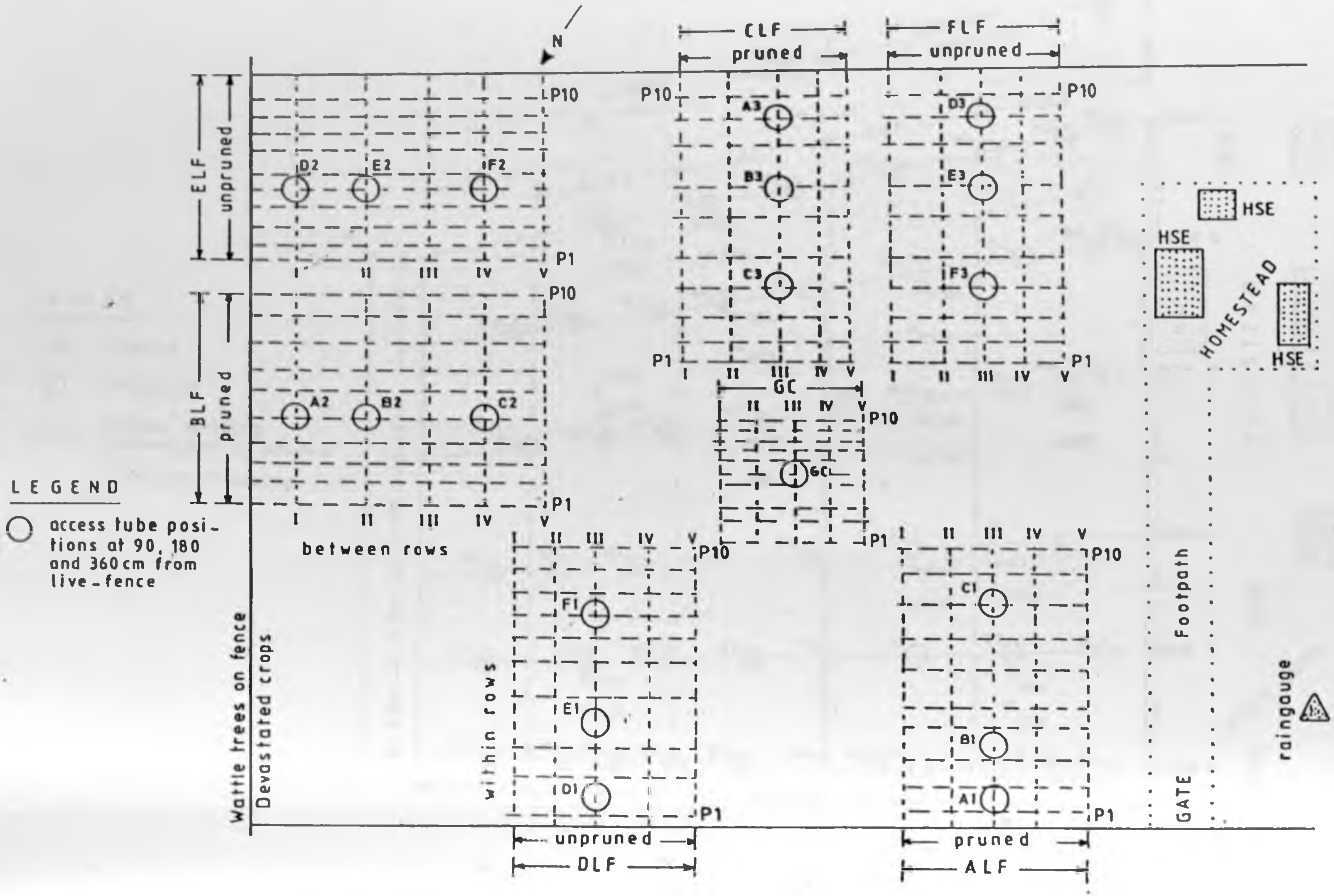

Fig. A2. A layout of on-farm experiment on the effect of live-fence root pruning on soil moisture at Kiahuko-A.

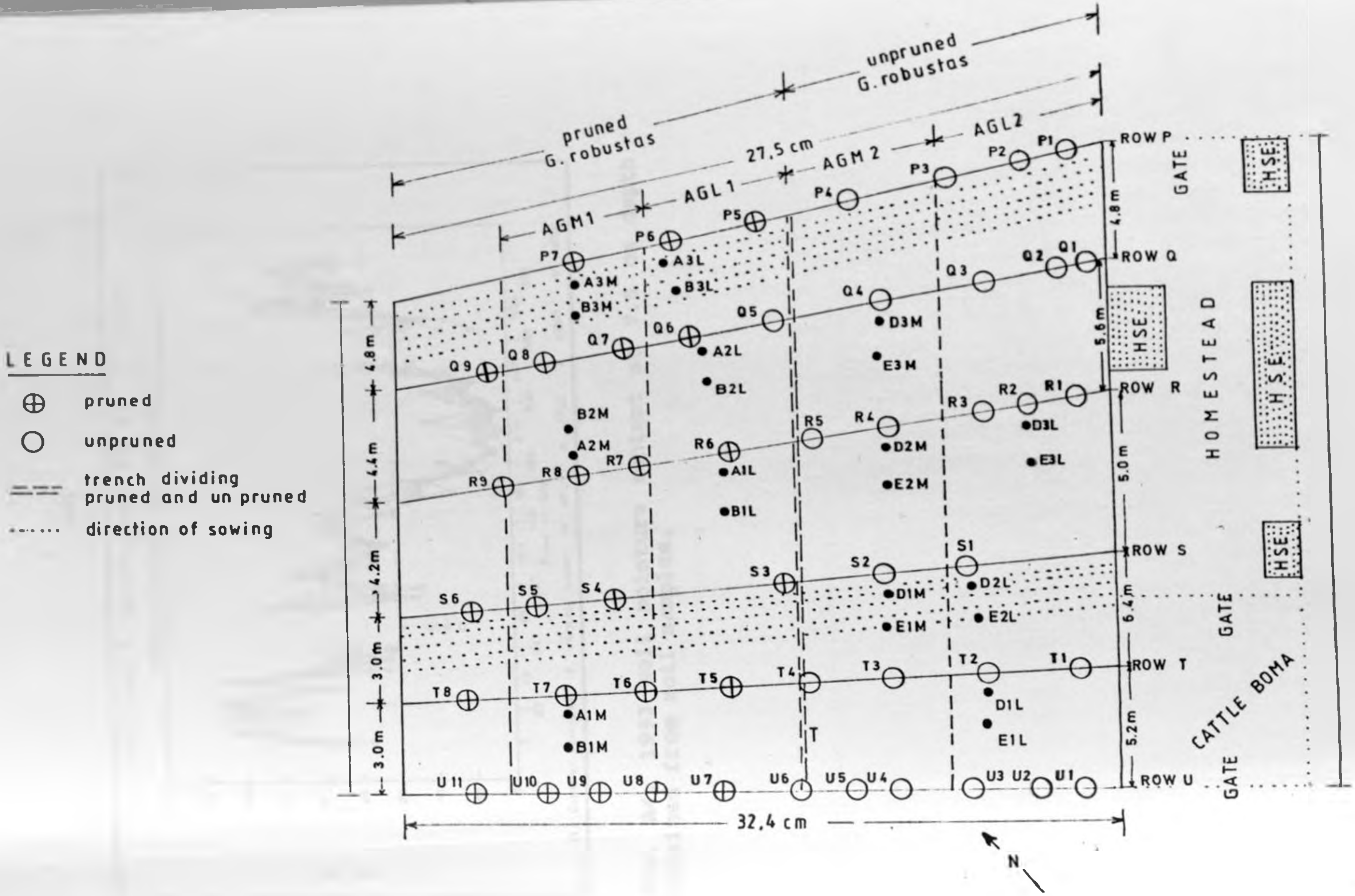

Fig. A3. A layout of on-farm experiment on the effect of Grevillea robusta root pruning and mulching on soil moisture at Kiahuko-B.

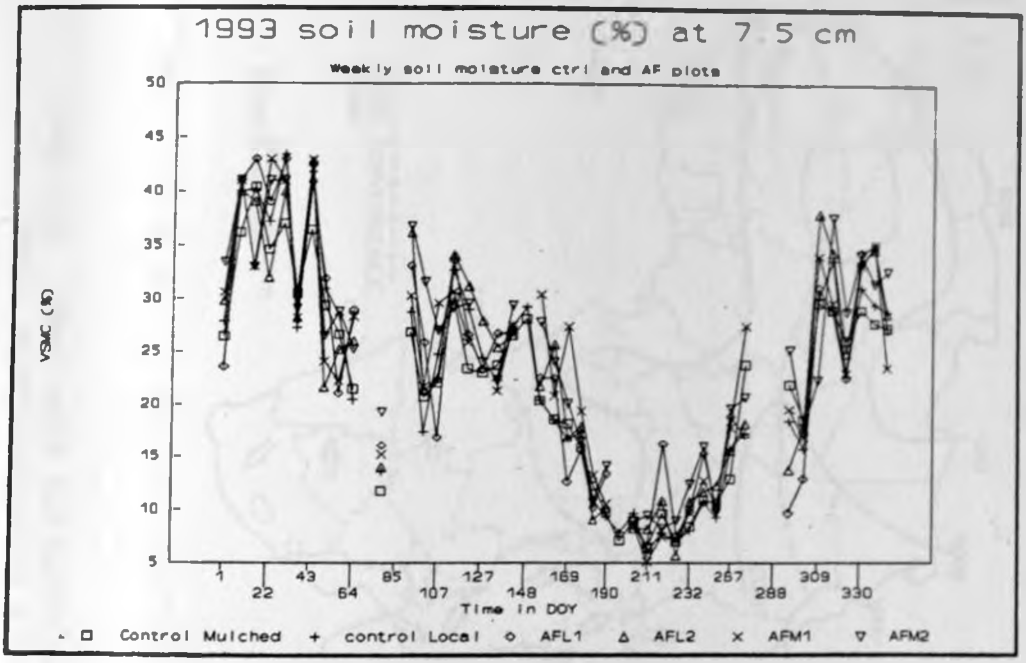

Fig. A4. 1993 soil moisture content at 7.5 cm depth obtained from soil samples.

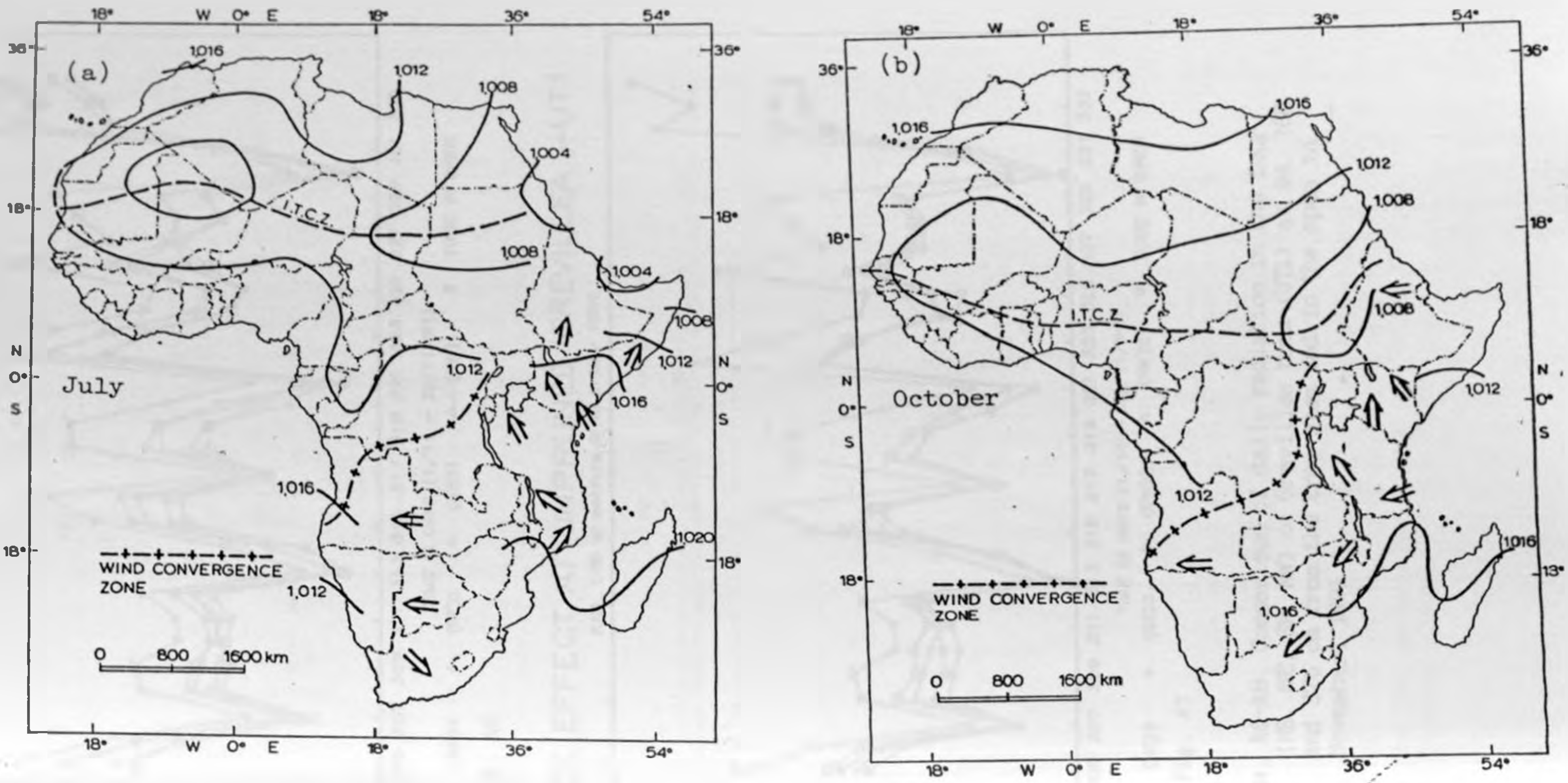

Fig. A5. Mean wind patterns over Africa for July (a) and October (b). Note: North-easterly and south-easterly winds over Kenya during the two months (After Griffiths. 1972).

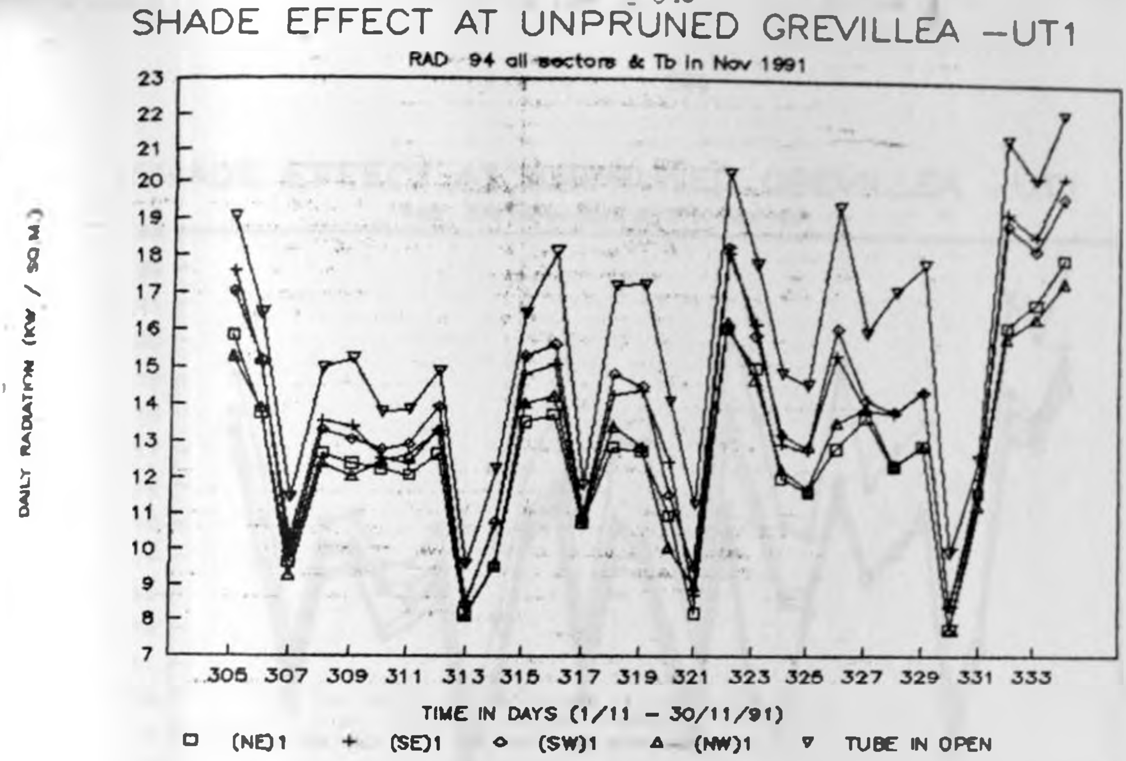

Fig. A6

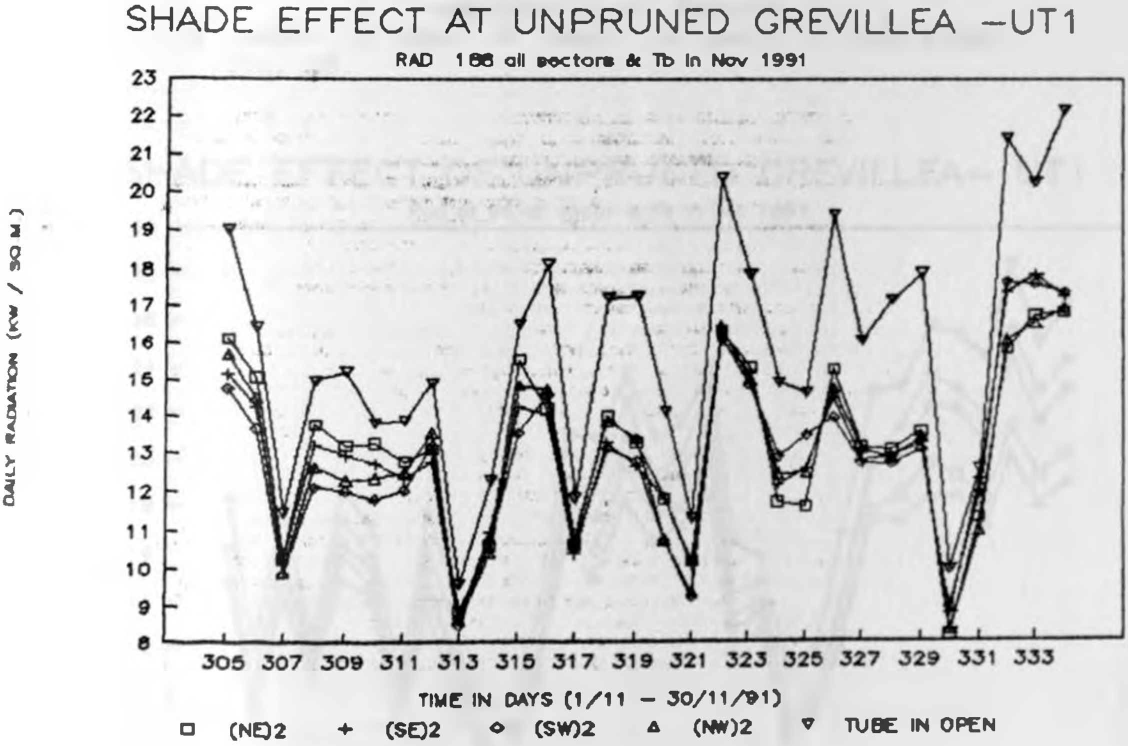

Fig. A7

Figs. A6–A8. Comparison of daily radiation in the four (NE, SE, SW, NW) of Grevillea tree (UT1) at 94, 188 and 376 cm from the tree stem and in the open in November, 1991

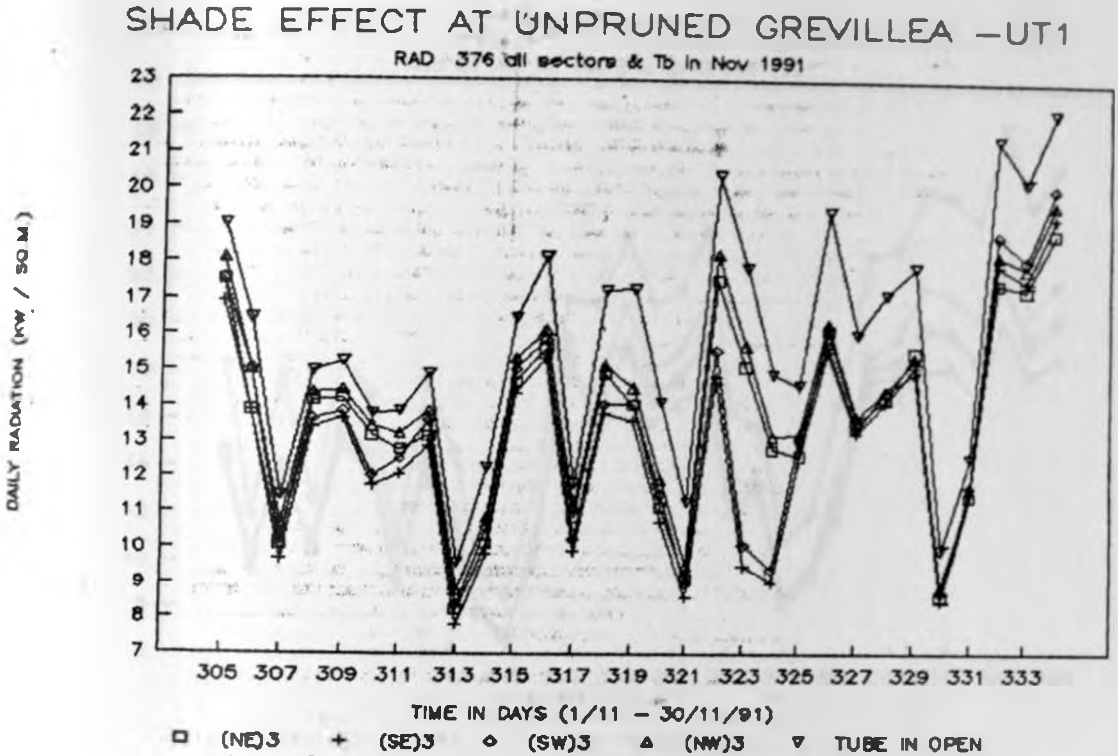

Fig. A8

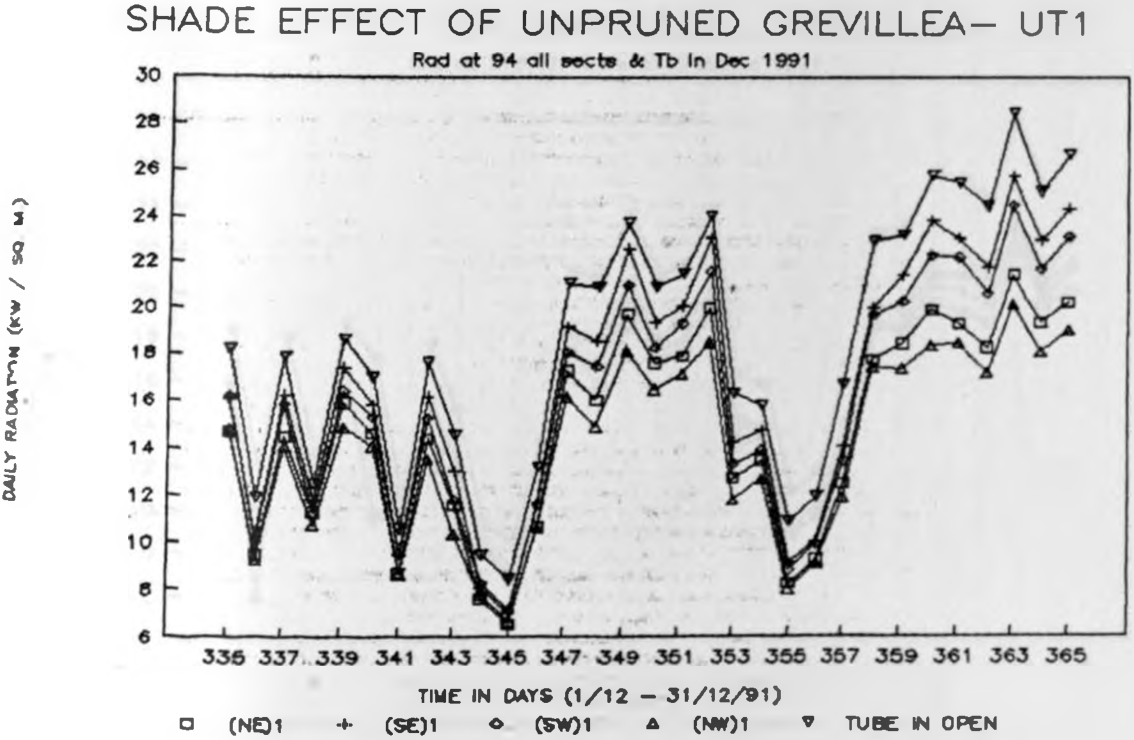

Fig. A9

Figs. A9–A11. Comparison of daily radiation in the four (NE, SE, SW, NW) of Grevillea tree (UT1) at 94, 188 and 376 cm from the tree stem and in the open in December, 1991

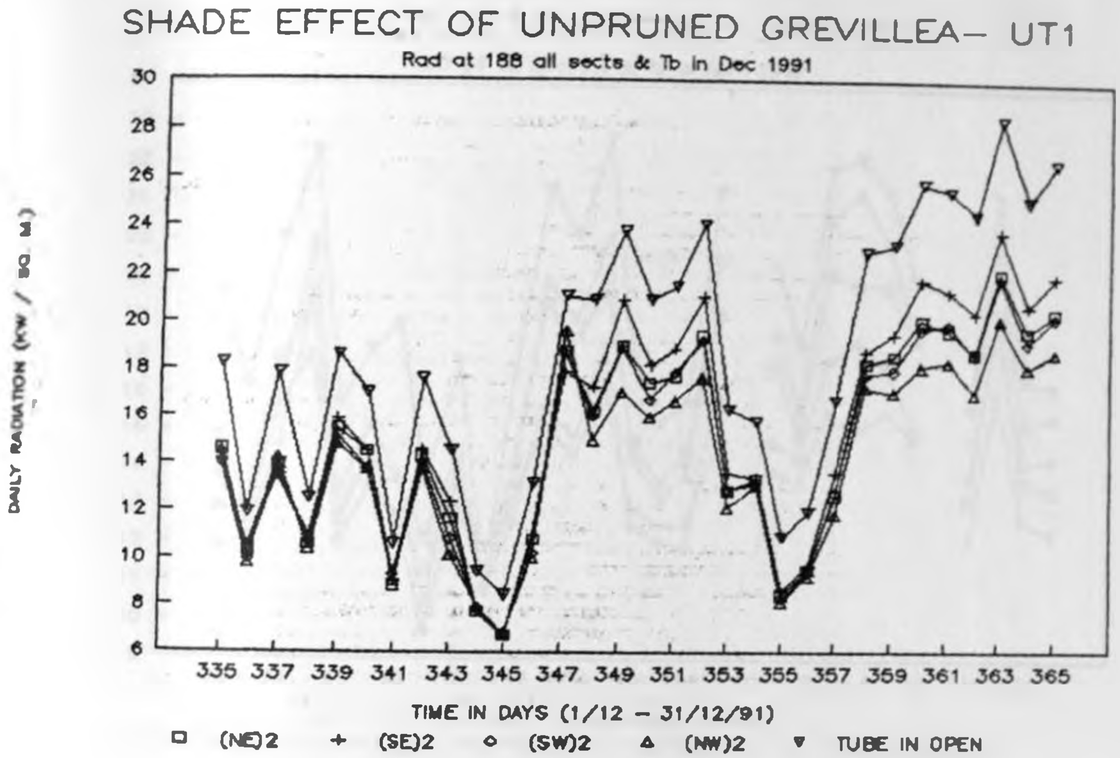

Fig. A10

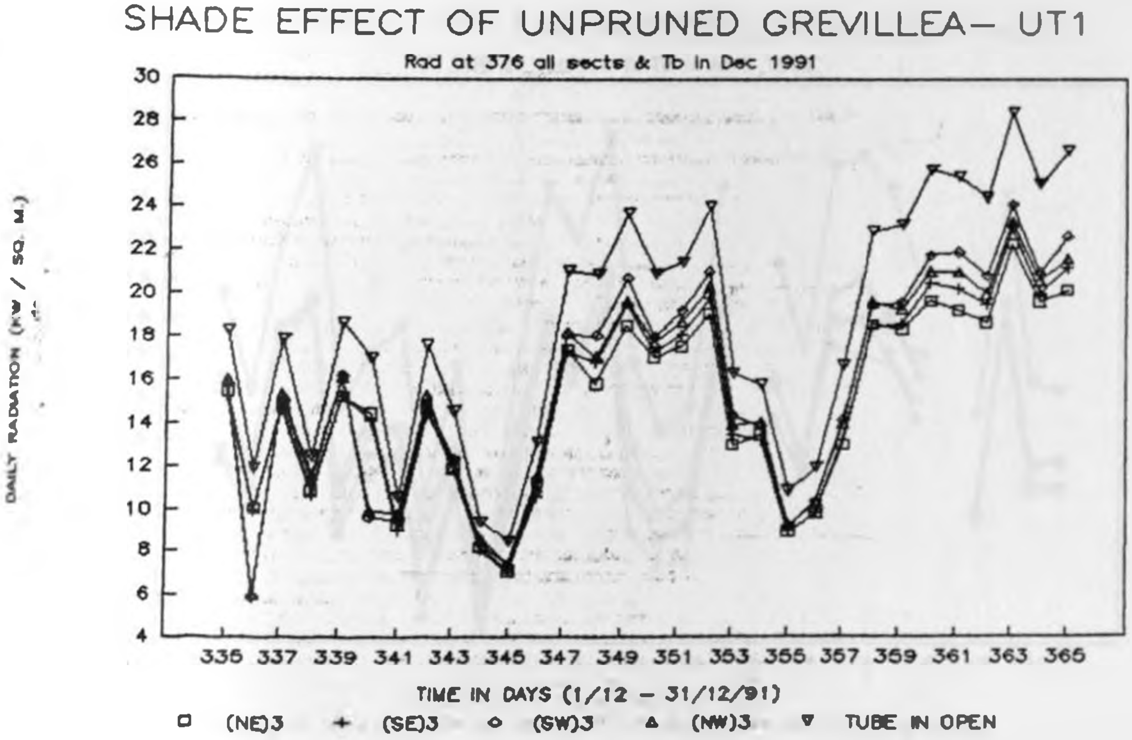

Fig. A11

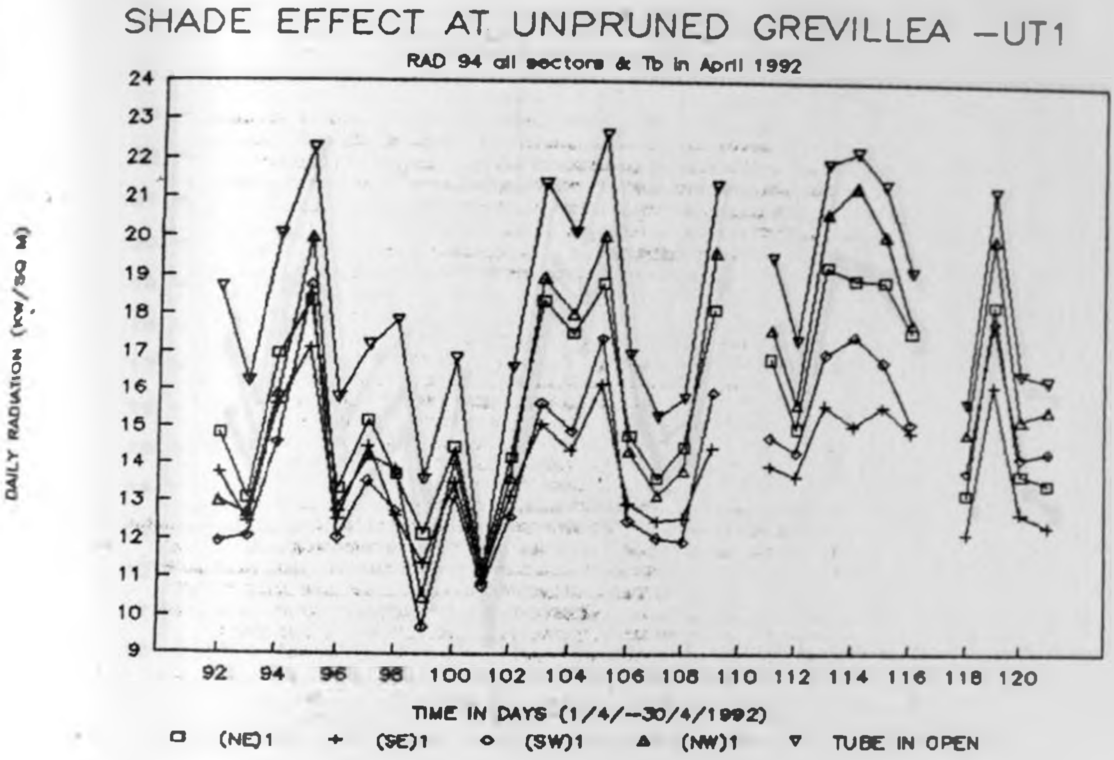

Fig. A12

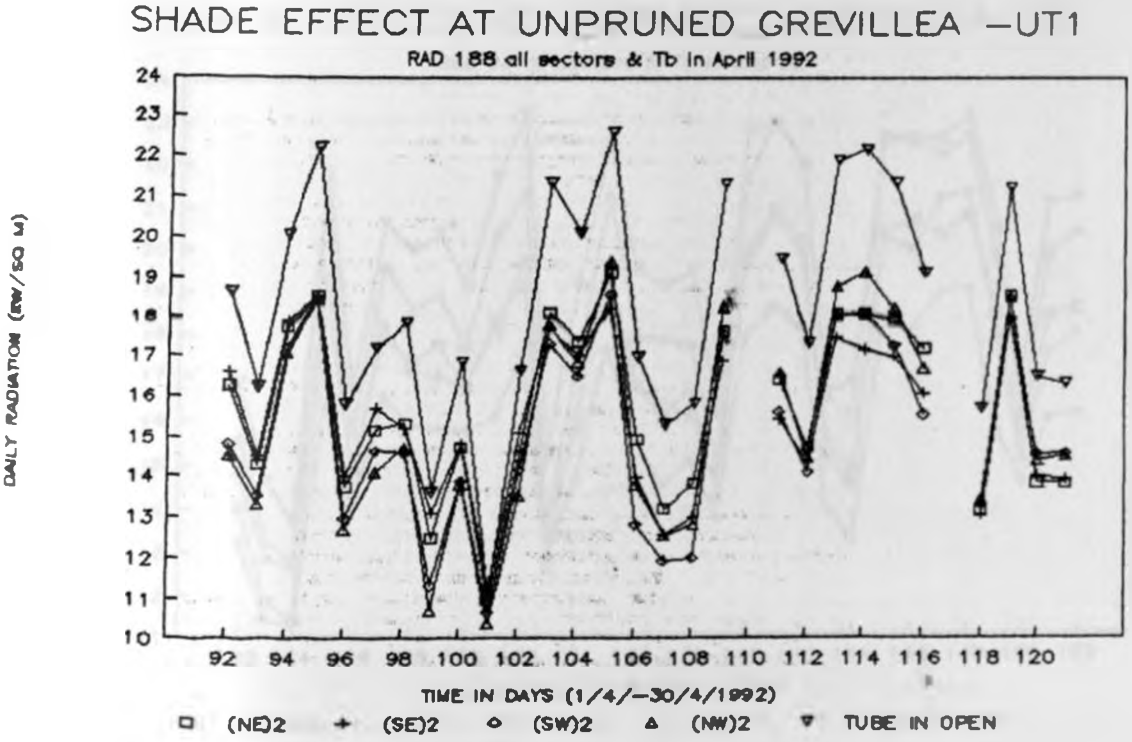

Fig. A13

Figs. A12-A14. Comparison of daily radiation in the four (NE, SE, SW, NW) of Grevillea tree (UT1) at 94, 188 and 376 cm from the tree stem and in the open in April, 1992

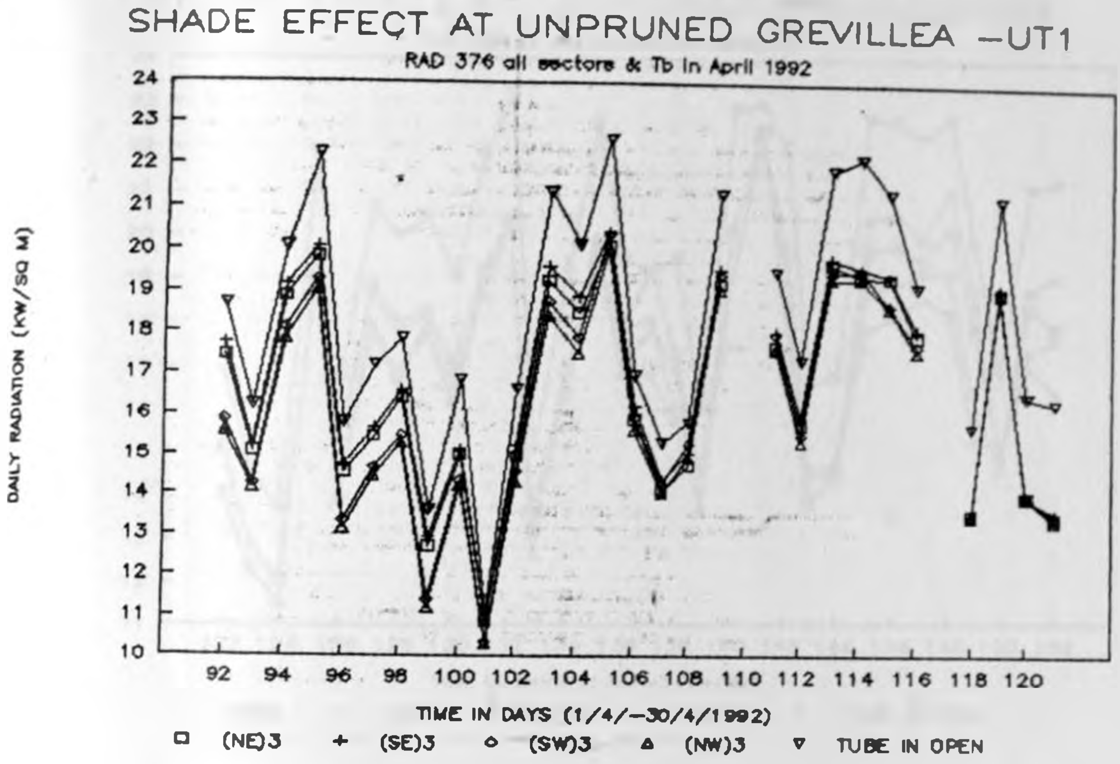

Fig. A14

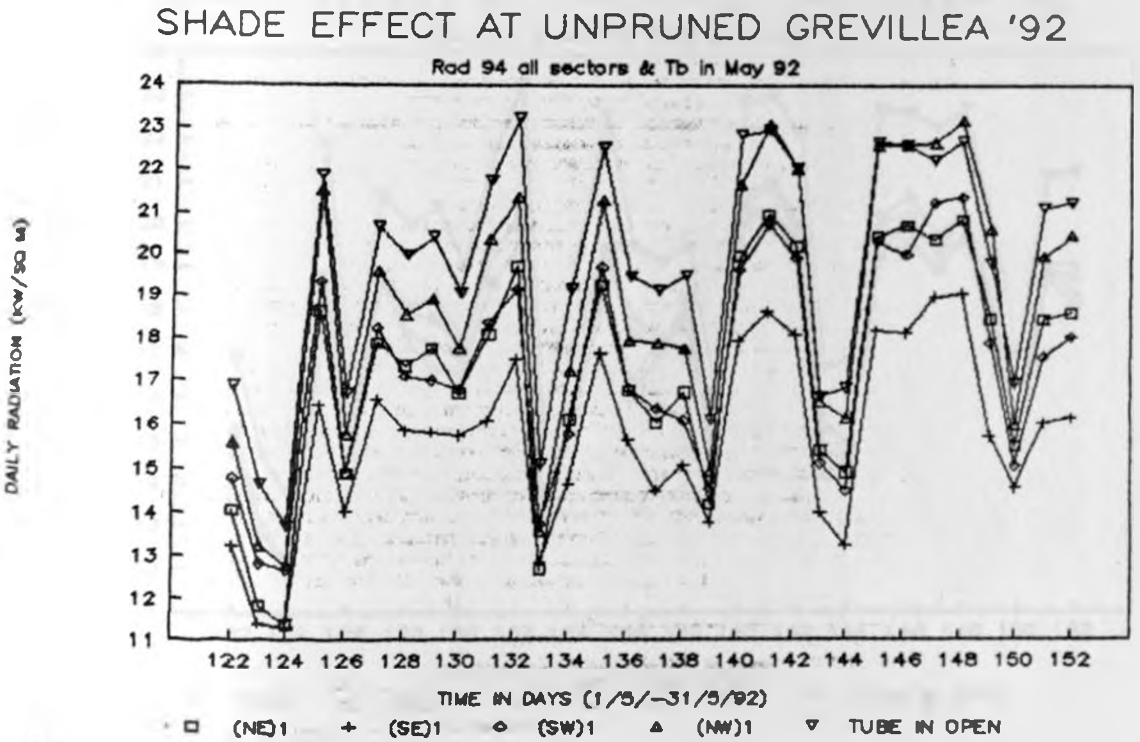

Fig. A15

Figs. A15–A17. Comparison of daily radiation in the four (NE, SE, SW, NW) of Grevillea tree (UT1) at 94, 188 and 376 cm from the tree stem and in the open in May, 1992

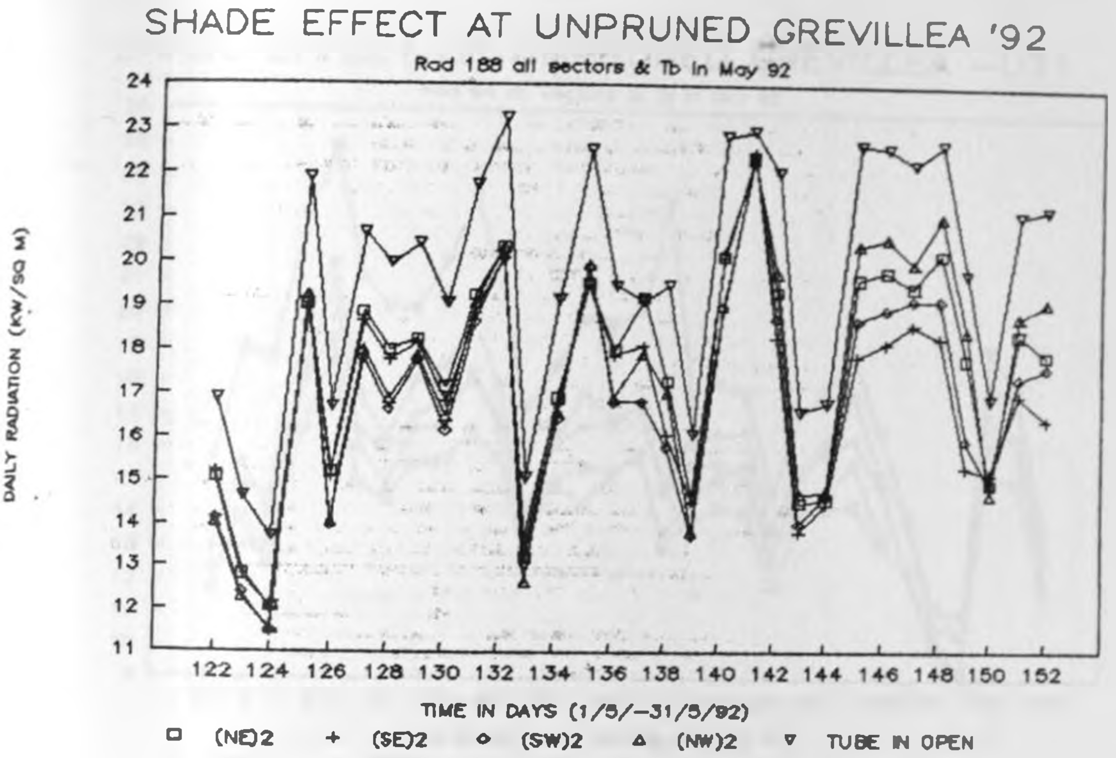

Fig. A16

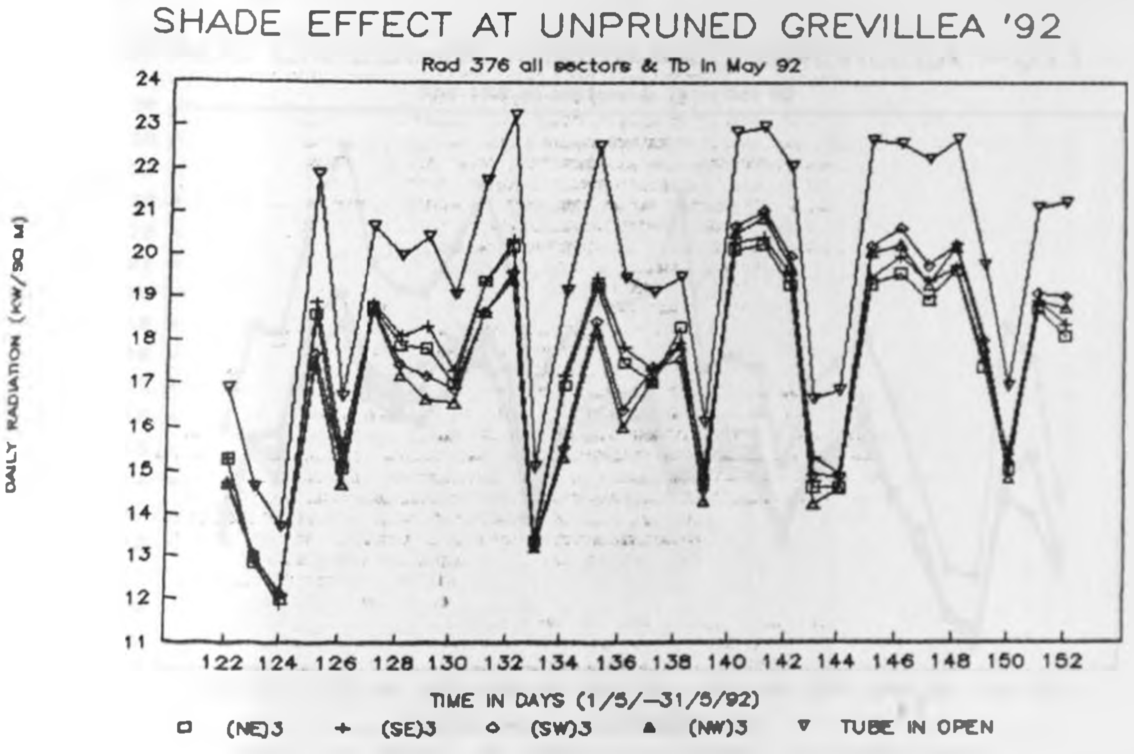

Fig. A17

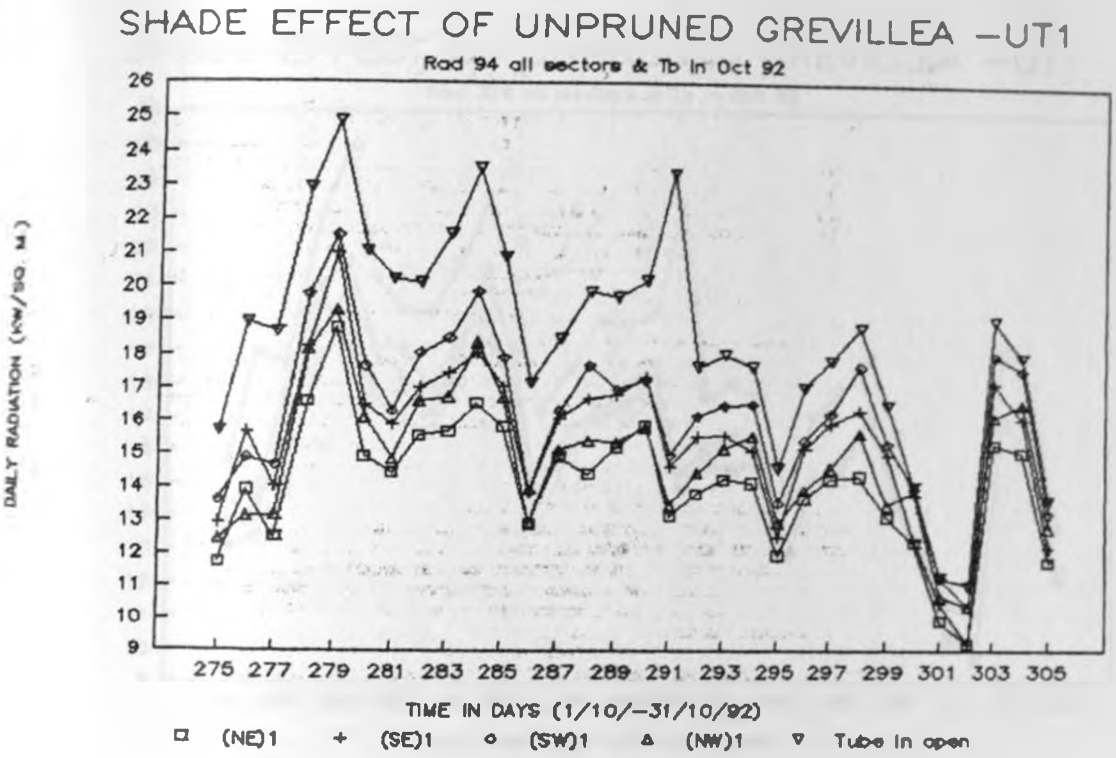

Fig. A18

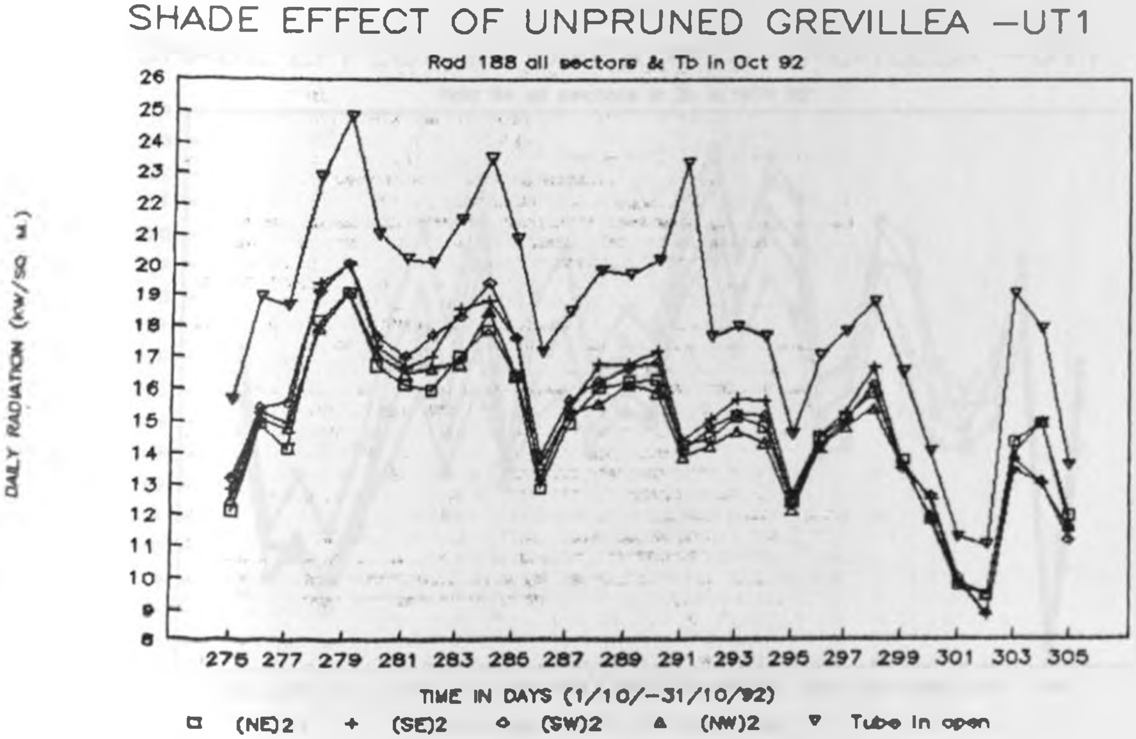

Fig. A19

Figs. A18–A20. Comparison of daily radiation in the four (NE, SE, SW, NW) of Grevillea tree (UT1) at 94, 188 and 376 cm from the tree stem and in the open in October, 1992

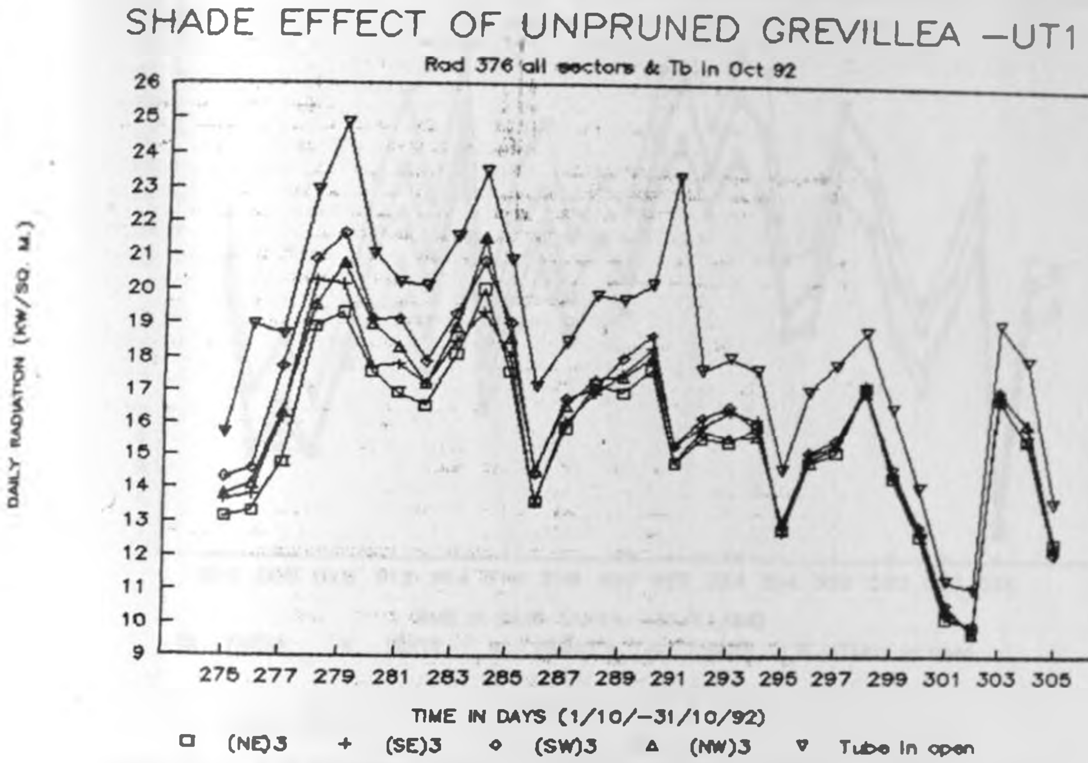

Fig. A20

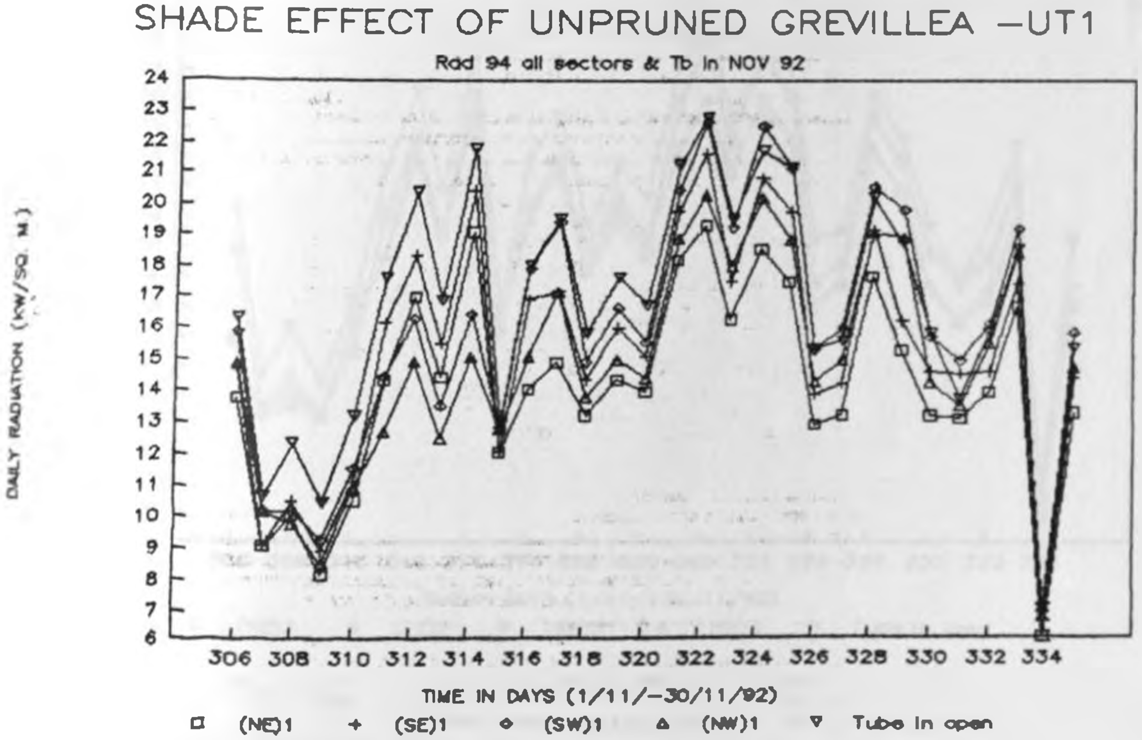

Fig. A21

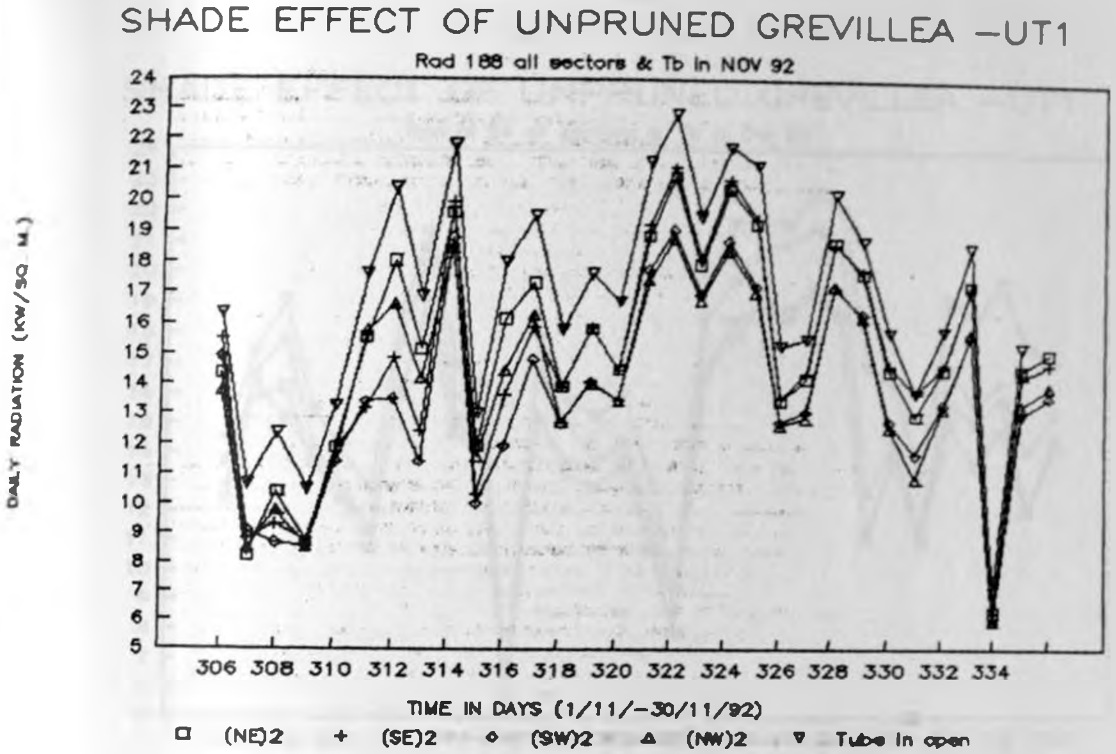

Fig. A22

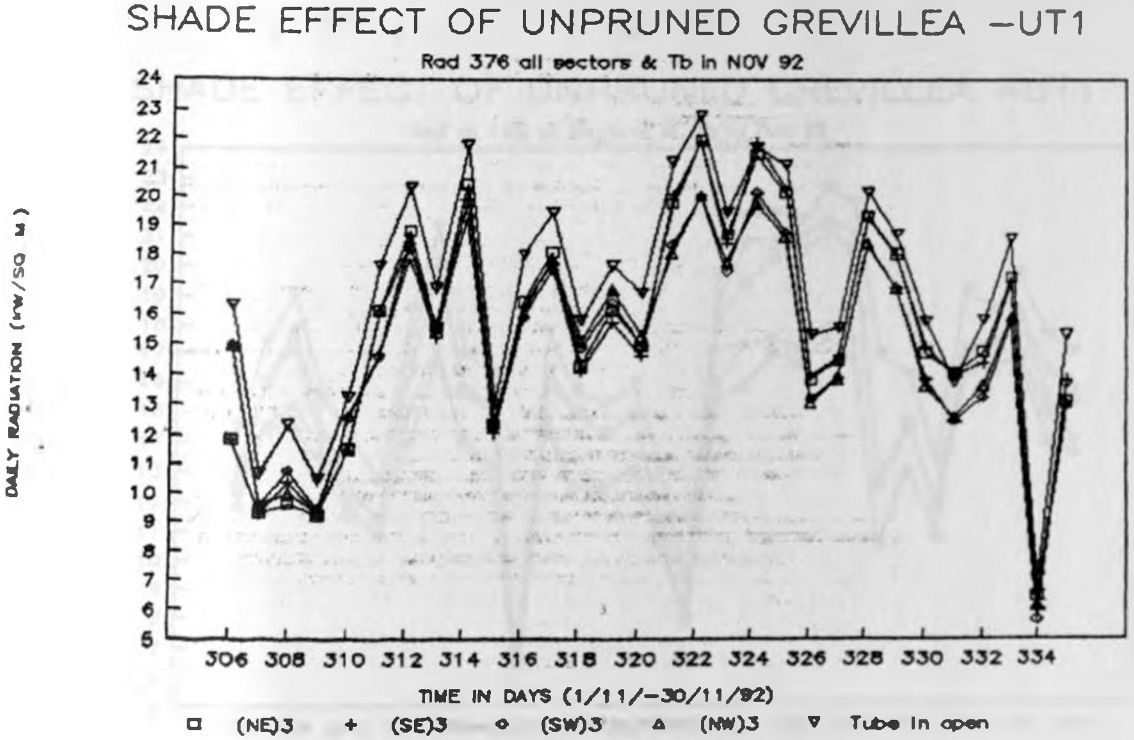

Fig. A23

Figs. A21-A23. Comparison of daily radiation in the four (NE, SE, SW, NW) of Grevillea tree (UT1) at 94, 188 and 376 cm from the tree stem and in the open in Novemer, 1992

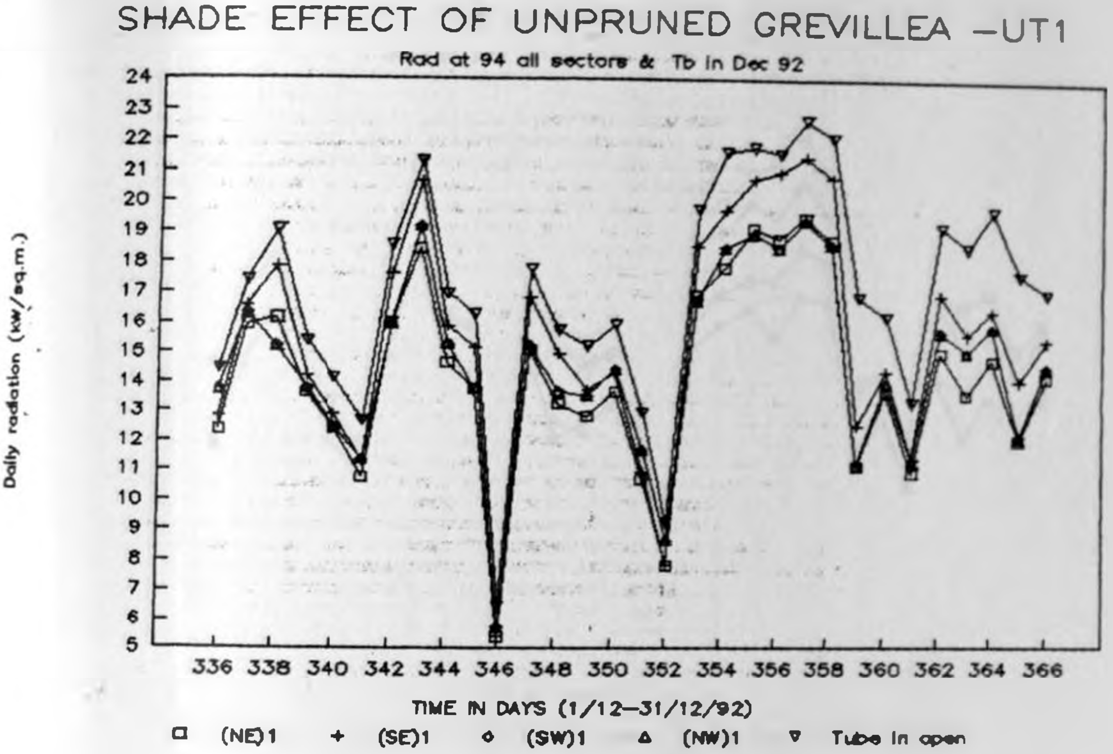

Fig. A24

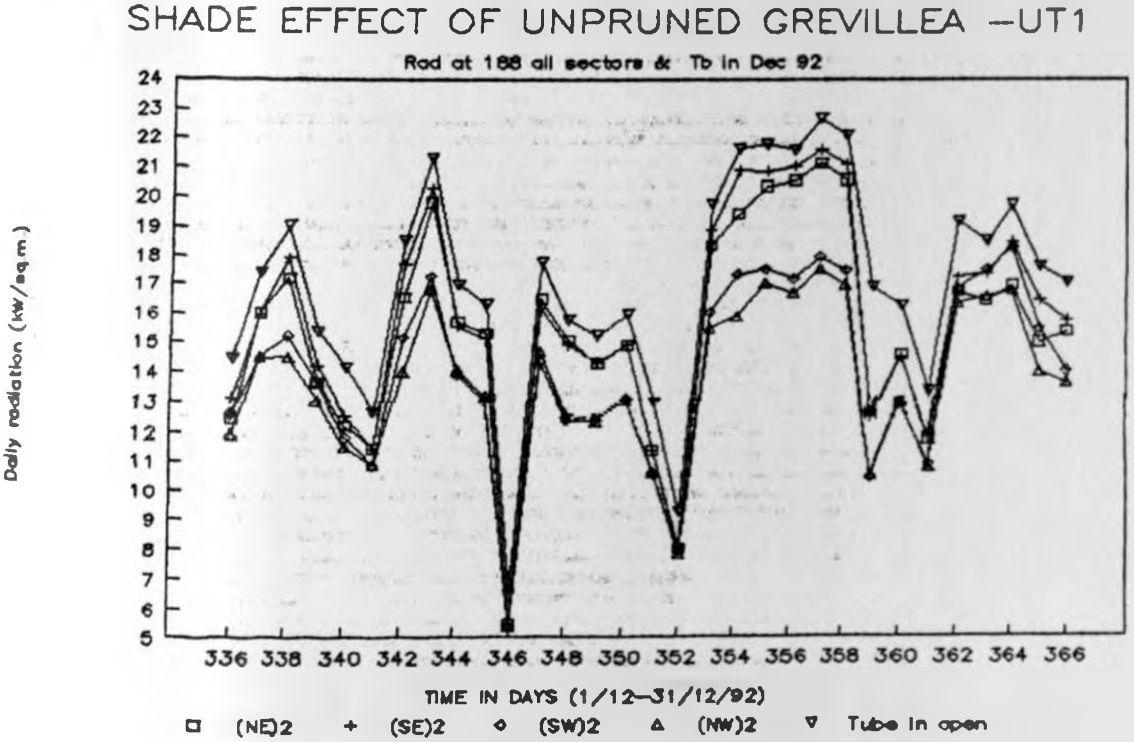

Fig. A25

Figs. A24–A26. Comparison of daily radiation in the four (NE, SE, SW, NW) of Grevillea tree (UT1) at 94, 188 and 376 cm from the tree stem and in the open in Decemer, 1992

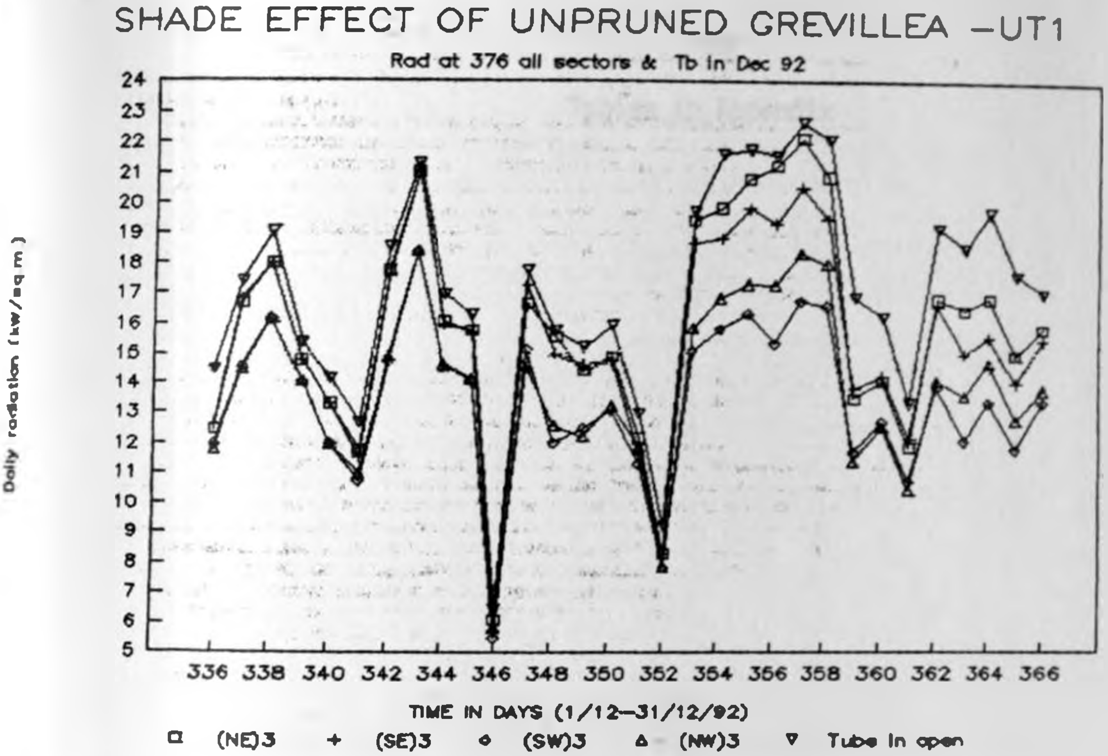
SHADE EFFECT OF UNPRUNED GREVILLEA –UT1
Rad at 376 all sectors & Tb in Dec 92
Daily radiation (kW/sq m)
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
336
338
340
342
344
346
348
350
352
354
356
358
360
362
364
366
TIME IN DAYS (1/12–31/12/92)
□ (NE)3
+ (SE)3
◇ (SW)3
△ (NW)3
▽ Tube in open

Fig. A26

Table A1. Sowing and harvesting dates (in DOY) of beans in on-station at Matanya for the seven experimental periods indicating duration beans crop cycle.

operation	seasons SR91	LR92	SR92	LR93	SR93	LR94	SR94
Sowing	288	83	278	94	289	103	283
Harvesting	33	189	20	208	31	207	26
Duration	110	106	108	104	107	104	108

Table A2.1. **On-station yields** (t/ha) - review table: Maize and beans biomass and bean seed yields (t/ha) at Matanya for seven experimental periods in AF and NAF plots. (a) Maize biomass yields (note that the values in italics are maize grain yields for SR92). (b) beans biomass yields. (c) beans seed yields.

(a) Maize biomass yields (t/ha)

	AF				NAF	
	Pruned		Unpruned		Control plots	
seasons	AFM1	AFL1	AFM2	AFL2	M	L
SR91	1.00±0.23	-	0.91±0.24	-	1.27±0.10	0.93±0.19
LR92	0.54±0.13	0.35±0.06	0.33±0.08	0.42±0.16	0.37±0.08	0.50±0.11
SR92	2.93±0.75	2.64±0.60	2.45±0.52	3.03±0.63	2.42±0.40	2.38±0.46
SR92	*1.54±0.39*	*1.42±0.40*	*1.18±0.26*	*1.30±0.33*	*1.60±0.37*	*1.30±0.34*
LR93	1.52±0.54	0.87±0.58	0.42±0.48	0.62±0.29	2.55±0.85	2.93±0.28
SR93	1.54±0.68	0.83±0.37	0.47±0.33	0.80±0.27	1.97±0.76	2.00±0.74
LR94	2.69±1.10	1.96±1.07	1.28±1.00	2.15±0.80	6.27±1.77	2.81±1.10
SR94	2.75±0.78	2.17±0.77	1.32±0.75	1.83±0.49	4.83±1.83	3.82±1.47

(b) Beans biomass yields (t/ha)

	AF				NAF	
	Pruned		Unpruned		Control plots	
seasons	AFM1	AFL1	AFM2	AFL2	M	L
SR91	0.58±0.17	-	0.54±0.16	-	0.70±0.12	0.52±0.05
LR92	0.24±0.04	0.25±0.03	0.18±0.04	0.23±0.03	0.33±0.07	0.19±0.02
SR92	0.68±0.20	0.46±0.09	0.50±0.26	0.38±0.16	0.98±0.26	0.96±0.30
LR93	0.41±0.12	0.33±0.16	0.19±0.14	0.31±0.11	0.61±0.27	0.67±0.25
SR93	0.29±0.09	0.34±0.11	0.22±0.12	0.24±0.08	0.68±0.46	0.93±0.33
LR94	0.17±0.07	0.18±0.10	0.12±0.08	0.21±0.08	0.38±0.13	0.33±0.12
SR94	0.38±0.12	0.47±0.12	0.27±0.11	0.26±0.07	0.60±0.20	0.60±0.20

(c) Beans seed yields (t/ha)

	AF				NAF	
	Pruned		Unpruned		Control plots	
seasons	AFM1	AFL1	AFM2	AFL2	M	L
SR91	0.37±0.13	-	0.26±0.03	-	0.29±0.03	0.44±0.04
LR92	0.16±0.03	0.12±0.02	0.10±0.02	0.11±0.04	0.14±0.04	0.03±0.03
SR92	0.71±0.10	0.63±0.12	0.63±0.18	0.57±0.26	1.18±0.21	1.02±0.24
LR93	0.53±0.16	0.39±0.15	0.20±0.14	0.37±0.12	0.64±0.20	0.60±0.21
SR93	0.15±0.07	0.12±0.05	0.08±0.06	0.10±0.05	0.31±0.16	0.26±0.13
LR94	0.22±0.11	0.20±0.09	0.14±0.08	0.20±0.09	0.43±0.18	0.33±0.11
SR94	0.05±0.03	0.11±0.06	0.05±0.06	0.11±0.05	0.20±0.10	0.20±0.10

Table A2.2. **On-farm yields** (t/ha) -review table: Maize biomass yields (t/ha) at Kihuko-A (a) & maize biomass yields b (i), maize grain yields b (ii) and seed yields b (iii), at Kihuko-B.

(a) **Kiahuko - A**: Maize biomass yields (t/ha)

	Live-fence			GC
	Pruned		Unpruned	Control plots
seasons				
SR93	4.67±1.50	-	4.20±1.20	3.70±0.90
LR94	-	-	-	-
SR94	1.02±0.79	-	0.84±1.12	1.82±0.37

(b) **Kiahuko-B**

(i) Maize biomass yields (t/ha)

	AF				NAF	
	Pruned		Unpruned		Control plots	
seasons	AGM1	AGL1	AFG2	AGL2	M	L
SR93	1.40±0.40	0.70±0.30	1.00±0.20	1.40±1.20	2.80±0.30	3.80±0.60
LR94	0.11±0.08	0.13±0.09	0.03±0.02	0.09±0.03	2.02±0.44	1.19±0.35
SR94	1.80±0.87	2.54±0.82	0.75±0.45	1.97±0.60	5.76±2.32	5.60±1.05

(ii) Maize grain (t/ha)

	AF				NAF	
	Pruned		Unpruned		Control plots	
seasons	AGM1	AGL1	AGM2	AGL2	M	L
SR93	-	-	-	-	-	-
LR94	-	-	-	-	-	-
SR94	0.61±0.39	0.69±0.42	0.07±0.07	0.12±0.11	1.40±0.59	1.60±0.50

(iii) Beans biomass (t/ha)

	AF				NAF	
	Pruned		Unpruned		Control plots	
seasons	AGM1	AGL1	AGM2	AGL2	M	L
LR94	-	-	-	-	0.11±0.02	0.09±0.02
SR94	-	-	-	-	0.09±0.02	0.14±0.18

Table A3. Monthly seasonal rainfall totals (mm) for SR93, LR94 and SR94 for the two on-farm gauges (at Kiahuko-A and Kiahuko-B) and Matanya station.

Season	Month	Kiahuko-A	Kiahuko-B	Matanya station
SR93				
	OCT	104.1	105.0	65.2
	NOV	118.0	109.2	117.2
	DEC	78.3	62.1	48.3
	JAN'94	4.5	5.2	3.1
LR94				
	MAR	26.5	29.3	29.5
	APR	119.1	174.9	190.5
	MAY	37.8	50.0	73.7
	JUN	42.1	42.6	47.5
SR94				
	OCT	99.2	121.2	98.0
	NOV	150.6	184.7	155.2
	DEC	59.3	35.1	60.3
	JAN'95	17.7	44.6	13.9

Table A4. Volumetric soil moisture content (%) obtained from oven dried gravimetric samples taken at various sites in the AF and control plots at 7.5 cm depth. ctrl M & ctrl L are control Mulched and control Local plots respectively. Other terms are already defined in the text. '-' means data missing data.

1993 dates	DOY	ctrl M	ctrl L	AFL1	AFL2	AFM1	AFM2
1/1	1	26.4	27.9	23.6	29.8	30.6	33.4
8/1	8	36.2	40.0	41.0	40.0	41.0	41.0
15/1	15	40.4	40.2	43.0	39.0	33.0	33.0
22/1	22	34.6	37.2	39.0	32.0	43.0	41.0
30/1	30	37.0	43.4	43.0	40.0	41.0	41.0
6/2	37	30.6	27.3	28.0	30.5	28.2	29.1
12/2	43	36.4	41.8	40.9	42.8	42.9	42.3
20/2	51	29.4	31.0	31.9	21.6	24.1	26.5
26/2	57	26.6	28.5	21.1	25.2	22.2	28.8
5/3	64	21.4	20.5	28.9	26.0	28.3	25.3
19/3	78	11.8	13.6	16.1	14.0	15.2	19.3
2/4	92	26.9	28.8	33.1	36.2	30.3	36.8
9/4	99	20.7	17.4	25.9	21.3	21.7	31.6
17/4	107	22.1	24.8	16.9	22.5	29.6	27.0
23/4	113	30.2	32.7	33.6	34.1	30.7	29.1
30/4	120	23.4	29.0	26.6	31.2	25.9	29.6
7/5	127	23.0	24.4	23.4	27.9	-	-
14/5	134	23.7	22.2	26.7	25.4	21.3	22.3
21/5	141	26.6	27.4	26.9	26.5	27.5	29.4
28/5	148	28.1	29.2	-	-	-	-
4/6	155	20.3	20.4	22.6	21.7	30.4	27.8
11/6	162	18.6	18.6	22.5	25.7	20.8	24.1
18/6	169	18.2	16.8	12.6	16.8	27.8	20.1
25/6	176	15.8	17.4	15.6	17.9	19.4	16.5
2/7	183	12.3	11.0	10.2	9.1	13.3	10.7
9/7	190	9.8	9.4	13.4	10.2	10.5	14.2
16/7	197	7.1	7.9	-	-	-	-
23/7	204	9.0	9.7	8.5	8.3	8.5	8.9
30/7	211	6.5	6.0	6.6	8.2	5.1	9.5
6/8	218	9.7	7.9	16.2	10.8	7.5	8.3
13/8	225	7.0	7.0	7.6	5.7	7.2	9.0
20/8	232	8.5	8.1	9.9	10.7	9.8	12.4
27/8	239	10.9	10.7	15.3	11.7	12.7	15.9
10/9	253	10.7	9.3	10.1	12.3	10.3	9.8
24/9	267	12.9	15.7	18.9	15.6	17.9	19.6
1/10	274	23.8	17.3	17.0	18.2	27.4	20.7
22/10	295	21.9	18.5	9.7	13.7	19.5	25.2
29/10	302	18.5	15.7	12.9	17.8	16.8	17.8
5/11	309	29.6	30.1	31.1	37.9	34.0	22.3
12/11	316	28.9	33.6	28.8	34.3	29.7	37.7
19/11	323	26.0	22.7	22.5	24.9	23.0	28.7
26/11	330	28.9	31.0	34.4	33.5	33.1	34.1
3/12	337	27.7	29.5	35.0	34.6	35.1	31.4
10/12	344	27.2	28.8	27.1	28.6	23.5	32.5

Table A5. Heights to which cup anemometers were adjusted in the field at Matanya in the course of strong winds periods (June-September) during the LR growing season (maize still growing). (a) Long rains 1993 (LR93) (b) Long rains 1994 (LR94). Note that Cup anemometers (both Woelfle and WAU were to be at 20 cm above the highest maize element.

(a) LR93		
date	DOY	height (cm)
		initial 100
4/6/93	155	140
17/6/93	168	200
26/6/93	177	240
Due to poor rainfall the crop could not go beyond 220 cm		
(b) LR94		
		initial 100
29/5/94	149	120
10/6/94	161	150
14/6/94	165	170
19/6/94	170	220
Again due to poor rainfall the crop could not go beyond 200 cm		

Table A6 Experimental periods covering strong wind speeds at Matanya during: (a) 1993 and (b) 1994.

(a) in 1993		
Experimental periods	calendar dates	Days of the year (DOY) (Julian days)
93P1	29/4/-06/5/93	119-126
93P2	13/5/-27/5/93	133-147
93P3	28/5/-02/6/93	148-153
93P4	03/6/-14/6/93	154-165
93P5	15/6/-24/6/93	165-175
93P6	24/6/-01/7/93	175-182
93P7	01/7/-28/7/93	182-209
93P8	28/7/-04/8/93	209-216
93P9	06/8/-13/8/93	218-225
93P10	17/8/-24/8/93	229-236
(b) in 1994		
94P1	04/6/-23/6/94	155-174
94P2	04/7/-15/7/94	185-196
94P3	15/7/-03/8/94	196-215
94P4	04/8/-23/8/94	216-235
94P5	23/8/-31/8/94	235-243
94P6	13/9/-15/9/94	256-258
94P7	21/9/-28/9/94	264-271
94P8	28/9/-11/10/94	271-284
94P9	11/10/-18/10/94	284-291
94P10	19/10/-07/11/94	292-311

Table A7. WAU cup anemometer layout in the AF plot at Matanya station (Figs. 8 & 10) and their distances from western and southern hedges (the two windward sides of the live-fence) in metres (m) and in the hedge heights (H). (Note that the heights of the live-fence sides were: western (WH) 2.1 m; southern (SH) 1.9 m; and eastern 1.9 m. AF bordered fruit trees in the northern side).

	(cups 10...44 in positions A1..A12)						distance from southern side	
	row 1		row 2		row 3		(m)	(H)
line 1	A1	10	A5	14	A9	40	12.3	6H
line 2	A2	11	A6	15	A10	41	17.5	9H
line 3	A3	12	A7	38	A11	43	22.7	12H
line 4	A4	13	A8	39*	A12	44**	27.9	15H
from western (m)		4		15		26		
hedge (H)		2		7		12		

cup 55 was 60 m or 30.8H from eastern side EH.

* - replaced by cup 60 during 1994

** - replaced by cup 61 during 1994

Table A8. The geometry of the *Grevillea robusta* trees (included are three *Grevillea* rows B(TR1), C(TR2) & D(TR3)) in pruned and unpruned area in AF (Fig. 9). **UT** is root unpruned trees: **PT** is root pruned trees: '-' is data not taken: **Th** is height of the whole tree: **Bsh** is the height of the lowest branch: **Crh** is the height of the crown or cone: **Cch** is the canopy centre or centre of the circular base of the cone: **Cdl** and **Cda** are canopy widths measured along and across the crop rows respectively: **Tr** is tree: **Cd**= (Cdl+Cda) /2 is mean canopy diameter: **Circ** is the circumference of the tree trunk measured at 0.2 m above the ground. Appendix Fig. A1 illustrates a *Grevillea robusta* tree geometry. All measurements are in **m**.

Tree No.	Th (m)	Bsh (m)	Crh (m)	Cch (m)	Cdl (m)	Cda (m)	Cd (m)	Circ (m)
(i) row A								
Tr1	-	-	-	-	-	-	-	-
Tr2	-	-	-	-	-	-	-	-
Tr3	6.4	2.1	4.2	4.9	2.5	2.3	2.4	0.4
Tr4	7.4	2.8	4.6	6.0	4.0	3.9	3.9	0.5
Tr5	8.0	2.9	5.1	5.4	3.2	3.4	3.3	0.5
Tr6	-	-	-	-	-	-	-	-
Average	7.3	2.6	4.7	5.5	3.2	3.2	3.2	0.4
std dev	0.7	0.3	0.4	0.4	0.6	0.6	0.6	0.0
(ii) row B								
Tr1	-	-	-	-	-	-	-	-
Tr2 UT2	-	-	-	-	-	-	-	-
Tr3 UT1	9.1	3.1	6.0	7.1	3.8	3.6	3.7	0.5
Tr4 PT2	9.0	3.5	5.5	7.0	3.6	3.2	3.4	0.5
Tr5 PT1	10.3	3.8	6.6	7.2	4.9	4.6	4.7	0.6
Tr6	-	-	-	-	-	-	-	-
Average	9.5	3.5	6.0	7.1	4.1	3.8	4.0	0.5
std dev	0.6	0.3	0.4	0.4	0.6	0.6	0.6	0.1
(iii) row C								
Tr1	-	-	-	-	-	-	-	-
Tr2	-	-	-	-	-	-	-	-
Tr3 UT3	8.6	3.6	5.0	6.6	4.1	3.9	4.0	0.5
Tr4	8.4	3.5	5.0	6.5	3.6	4.2	3.9	0.5
Tr5 PT3	8.1	3.1	5.0	6.0	3.8	3.6	3.7	0.5
Tr6	-	-	-	-	-	-	-	-
Average	8.4	3.4	5.0	6.4	3.8	3.9	3.9	0.5
std dev	0.2	0.2	0.0	0.2	0.2	0.2	0.1	0.0

(iv) row D

Tr1	–	–	–	–	–	–	–	–
Tr2 UT5	–	–	–	–	–	–	–	–
Tr3 UT4	9.4	3.4	6.0	5.9	4.0	4.2	4.1	0.5
Tr4 PT5	9.4	3.0	6.4	5.9	3.0	2.9	3.0	0.5
Tr5 PT4	4.3	1.9	2.4	3.0	1.6	1.1	1.3	0.3
Tr6	–	–	–	–	–	–	–	–
Average	7.7	2.8	4.9	4.9	2.9	2.7	2.8	0.4
std dev	2.4	0.6	1.8	1.4	1.0	1.3	1.1	0.1

(v) row E

Tr1	–	–	–	–	–	–	–	–
Tr2	–	–	–	–	–	–	–	–
Tr3	8.1	2.9	5.2	3.9	3.7	3.4	3.6	0.4
Tr4	7.7	2.7	5.0	3.0	2.7	3.1	2.9	0.4
Tr5	8.1	2.9	5.2	3.8	3.9	3.6	3.7	0.4
Tr6	–	–	–	–	–	–	–	–
Average	8.0	2.9	5.1	3.5	3.5	3.3	3.4	0.4
std dev	0.2	0.1	0.1	0.4	0.5	0.2	0.4	0.0

Table A9. Cup 55 as reference: Calculated wind speeds and wind reduction ratios for: (a) all 24 weeks case 3 with point (0, 0) not included (case 3, –0) and with point (0, 0) included (case 3 +0) and odd numbered weeks (b) case 5 with point (0, 0) not included (case 5, –0) and with point (0, 0) included (case 5 +0) and (c) case 7 with point (0, 0) not included (case 7, –0) and with point (0, 0) included (case 7 +0): a and b regression coefficients given in Table 76. Note that (1) is average wind speed of the 24 weeks and (2) is standard deviation and (3) is per cent difference of the average of the calculated from the average of measured wind speeds as given in Table 77 (a).

(a) case 3

(i)
calculated wind speeds
point (0,0) not included
case 3 -0 a=0.57b=0.38

	cup14	cup15	cup38	cup39
	2.06	2.10	2.06	1.89
	1.77	1.87	1.77	1.63
	2.32	2.34	2.47	2.27
	2.84	2.85	2.75	2.74
	2.82	2.76	2.76	2.63
	2.84	2.55	2.55	2.42
	3.16	2.93	2.98	2.88
	2.49	2.47	2.82	2.38
	3.26	3.26	2.99	3.03
	2.73	2.74	2.59	2.51
	2.84	2.66	2.79	2.60
	3.16	3.12	3.09	2.95
	1.39	1.65	1.59	1.54
	1.29	1.40	1.25	1.08
	2.53	2.25	2.12	1.68
	2.94	3.12	2.49	2.46
	2.11	1.97	1.82	1.81
	2.74	2.62	2.53	2.54
	2.34	2.43	2.29	2.15
	2.32	2.09	2.28	2.12
	2.59	2.45	2.51	2.32
	2.16	2.15	2.06	1.96
	2.90	2.90	2.79	2.53
	3.14	2.98	3.00	2.98
(1)	2.	2.49	2.43	2.30
(2)	0.	0.47	0.47	0.49
(3)	1.	1.81	-2.03	-0.52

(ii)
Calculated reduction ratios
point (0,0) not included
case 3a=0.57b=0.38

cup14	cup15	cup38	cup39
0.95	0.97	0.95	0.87
0.89	0.95	0.90	0.83
0.84	0.84	0.89	0.82
0.96	0.96	0.93	0.92
0.89	0.87	0.87	0.83
0.93	0.87	0.87	0.85
0.94	0.88	0.89	0.86
0.82	0.82	0.88	0.80
0.94	0.94	0.86	0.87
0.90	0.90	0.85	0.82
0.87	0.82	0.86	0.80
0.86	0.85	0.84	0.80
0.76	0.90	0.86	0.83
0.89	0.96	0.86	0.74
1.07	0.95	0.90	0.71
1.03	1.09	0.87	0.86
1.04	0.97	0.90	0.89
0.97	0.93	0.90	0.90
0.89	0.93	0.87	0.82
0.87	0.79	0.86	0.80
0.84	0.79	0.81	0.75
0.85	0.85	0.81	0.77
0.85	0.85	0.82	0.74
0.85	0.80	0.81	0.80

(iii)
Calculated reduction ratios
point (0,0) included
case 3a=0.98b=0.01

cup14	cup15	cup38	cup39
0.99	1.02	0.99	0.85
0.90	0.99	0.90	0.78
0.79	0.80	0.88	0.76
1.01	1.01	0.95	0.95
0.88	0.85	0.85	0.78
0.95	0.86	0.86	0.81
0.98	0.86	0.88	0.84
0.77	0.76	0.87	0.73
0.97	0.97	0.84	0.86
0.90	0.91	0.82	0.77
0.85	0.76	0.83	0.73
0.83	0.81	0.80	0.73
0.66	0.90	0.84	0.79
0.89	1.01	0.84	0.63
1.20	1.00	0.90	0.58
1.13	1.24	0.85	0.84
1.14	1.03	0.90	0.89
1.02	0.95	0.90	0.91
0.89	0.95	0.86	0.77
0.86	0.71	0.83	0.73
0.80	0.72	0.76	0.65
0.81	0.81	0.75	0.68
0.81	0.81	0.76	0.63
0.81	0.74	0.75	0.73

(iv)
calculated wind speeds
point (0,0) included
case 3 +0 a=0.9b=0.01

	cup14	cup15	cup38	cup39
	2.15	2.22	2.15	1.85
	1.77	1.95	1.78	1.54
	2.21	2.24	2.45	2.11
	2.98	2.99	2.82	2.81
	2.80	2.70	2.70	2.48
	2.84	2.55	2.55	2.42
	3.28	2.89	2.96	2.80
	2.49	2.47	2.82	2.38
	3.37	3.38	2.91	2.99
	2.73	2.76	2.49	2.35
	2.78	2.48	2.70	2.38
	3.06	3.00	2.94	2.71
	1.21	1.66	1.55	1.46
	1.29	1.47	1.22	0.92
	2.84	2.35	2.13	1.36
	3.22	3.53	2.44	2.39
	2.32	2.08	1.82	1.81
	2.89	2.68	2.54	2.56
	2.34	2.49	2.25	2.01
	2.28	1.88	2.21	1.95
	2.46	2.22	2.33	2.00
	2.07	2.06	1.91	1.74
	2.78	2.78	2.60	2.14
	3.01	2.74	2.77	2.73
(1)	2.55	2.48	2.38	2.16
(2)	0.56	0.49	0.45	0.51
(3)	0.95	1.98	0.27	5.38

Table A9. continued

(b) case 5

	(i)				(ii)				(iii)				(iv)			
	calculated wind speeds point (0,0) not included case 5 a=0.45 b=0.44				Calculated reduction ratios point (0,0) not included case 5a=0.45b=0.44				Calculated reduction ratios point (0,0) included case 5 +0 a=0.98b=0.01				calculated wind speeds point (0,0) included case 5 +0 a=0.9b=0.01			
	cup14	cup15	cup38	cup39	cup14	cup15	cup38	cup39	cup14	cup15	cup38	cup39	cup14	cup15	cup38	cup39
	1.93	1.96	1.93	1.80	0.89	0.91	0.89	0.83	0.99	1.02	0.99	0.85	2.15	2.22	2.15	1.85
	1.67	1.75	1.68	1.57	0.85	0.89	0.85	0.79	0.90	0.99	0.90	0.78	1.77	1.95	1.78	1.54
	2.23	2.24	2.34	2.18	0.80	0.80	0.84	0.78	0.79	0.80	0.88	0.76	2.21	2.24	2.45	2.11
	2.66	2.66	2.58	2.58	0.90	0.90	0.87	0.87	1.01	1.01	0.95	0.95	2.98	2.99	2.82	2.81
	2.67	2.62	2.63	2.52	0.84	0.82	0.83	0.79	0.88	0.85	0.85	0.78	2.80	2.70	2.70	2.48
	2.84	2.55	2.55	2.42	0.87	0.83	0.83	0.81	0.95	0.86	0.86	0.81	2.84	2.55	2.55	2.42
	2.96	2.79	2.82	2.74	0.88	0.83	0.84	0.82	0.98	0.86	0.88	0.84	3.28	2.89	2.96	2.80
	2.49	2.47	2.82	2.38	0.79	0.78	0.83	0.77	0.77	0.76	0.87	0.73	2.49	2.47	2.82	2.38
	3.06	3.06	2.85	2.88	0.88	0.88	0.82	0.83	0.97	0.97	0.84	0.86	3.37	3.38	2.91	2.99
	2.58	2.59	2.47	2.40	0.85	0.85	0.81	0.79	0.90	0.91	0.82	0.77	2.73	2.76	2.49	2.35
	2.70	2.56	2.66	2.51	0.83	0.78	0.82	0.77	0.85	0.76	0.83	0.73	2.78	2.48	2.70	2.38
	3.01	2.98	2.96	2.85	0.82	0.81	0.80	0.77	0.83	0.81	0.80	0.73	3.06	3.00	2.94	2.71
	1.36	1.56	1.51	1.47	0.74	0.85	0.82	0.80	0.66	0.90	0.84	0.79	1.21	1.66	1.55	1.46
	1.23	1.31	1.19	1.05	0.84	0.90	0.82	0.73	0.89	1.01	0.84	0.63	1.29	1.47	1.22	0.92
	2.33	2.11	2.00	1.65	0.99	0.89	0.85	0.70	1.20	1.00	0.90	0.58	2.84	2.35	2.13	1.36
	2.72	2.86	2.36	2.34	0.95	1.00	0.83	0.82	1.13	1.24	0.85	0.84	3.22	3.53	2.44	2.39
	1.95	1.84	1.72	1.71	0.96	0.91	0.85	0.84	1.14	1.03	0.90	0.89	2.32	2.08	1.82	1.81
	2.56	2.46	2.40	2.40	0.91	0.87	0.85	0.85	1.02	0.95	0.90	0.91	2.89	2.68	2.54	2.56
	2.22	2.29	2.17	2.06	0.85	0.87	0.83	0.79	0.89	0.95	0.86	0.77	2.34	2.49	2.25	2.01
	2.20	2.02	2.17	2.05	0.83	0.76	0.82	0.77	0.86	0.71	0.83	0.73	2.28	1.88	2.21	1.95
	2.48	2.37	2.41	2.26	0.80	0.77	0.78	0.73	0.80	0.72	0.76	0.65	2.46	2.22	2.33	2.00
	2.06	2.05	1.98	1.91	0.81	0.81	0.78	0.75	0.81	0.81	0.75	0.68	2.07	2.06	1.91	1.74
	2.77	2.77	2.68	2.47	0.81	0.81	0.78	0.72	0.81	0.81	0.76	0.63	2.78	2.78	2.60	2.14
	3.00	2.87	2.89	2.87	0.81	0.77	0.78	0.77	0.81	0.74	0.75	0.73	3.01	2.74	2.77	2.73
(1)	2.	2.36	2.32	2.21									2.55	2.48	2.38	2.16
(2)	0.	0.45	0.46	0.47									0.56	0.49	0.45	0.51
(3)	6.	6.62	2.47	3.16									0.95	1.98	0.27	5.38

Table A9. continued

(c) case 7

(i)
calculated wind speeds
point (0,0) not included
case 7 a=0.7   b=0.22

	cup14	cup15	cup38	cup39
	2.04	2.09	2.04	1.82
	1.72	1.85	1.72	1.55
	2.21	2.24	2.39	2.14
	2.82	2.83	2.70	2.69
	2.73	2.66	2.66	2.50
	2.84	2.54	2.54	2.41
	3.12	2.84	2.89	2.77
	2.49	2.46	2.82	2.37
	3.21	3.22	2.87	2.93
	2.65	2.67	2.48	2.38
	2.74	2.51	2.68	2.44
	3.03	2.99	2.95	2.77
	1.28	1.61	1.53	1.46
	1.26	1.39	1.20	0.98
	2.59	2.23	2.06	1.50
	2.98	3.20	2.40	2.36
	2.13	1.96	1.77	1.76
	2.72	2.57	2.47	2.48
	2.28	2.39	2.21	2.03
	2.24	1.95	2.19	1.99
	2.47	2.29	2.37	2.12
	2.06	2.06	1.94	1.82
	2.77	2.77	2.64	2.30
	3.00	2.80	2.82	2.79
(1)	2.	2.42	2.35	2.18
(2)	0.	0.46	0.45	0.48
(3)	3.	4.37	1.46	4.42

(ii)
Calculated reduction ratios
point (0,0) not included
case 7a=0.72b=0.22

cup14	cup15	cup38	cup39
0.94	0.96	0.94	0.84
0.87	0.94	0.87	0.78
0.80	0.80	0.86	0.77
0.95	0.95	0.91	0.91
0.86	0.84	0.84	0.79
0.91	0.84	0.84	0.81
0.93	0.85	0.86	0.83
0.78	0.77	0.85	0.75
0.93	0.93	0.83	0.84
0.87	0.88	0.82	0.78
0.84	0.77	0.82	0.75
0.82	0.81	0.80	0.75
0.70	0.87	0.83	0.79
0.87	0.96	0.83	0.68
1.10	0.94	0.87	0.64
1.04	1.12	0.84	0.83
1.05	0.97	0.87	0.87
0.96	0.91	0.87	0.88
0.87	0.91	0.84	0.78
0.85	0.73	0.83	0.75
0.80	0.74	0.77	0.69
0.81	0.81	0.76	0.72
0.81	0.81	0.77	0.67
0.81	0.75	0.76	0.75

(iii)
Calculated reduction ratios
point (0,0) included
case 7 +0   a=0.99b=0.00

cup14	cup15	cup38	cup39
0.99	1.02	0.99	0.85
0.89	0.99	0.90	0.78
0.79	0.80	0.88	0.76
1.01	1.01	0.95	0.95
0.88	0.85	0.85	0.78
0.95	0.85	0.85	0.81
0.98	0.86	0.88	0.83
0.77	0.76	0.87	0.73
0.97	0.97	0.84	0.86
0.90	0.91	0.82	0.77
0.85	0.76	0.83	0.73
0.83	0.81	0.80	0.73
0.66	0.90	0.84	0.79
0.89	1.01	0.84	0.63
1.20	1.00	0.90	0.57
1.13	1.24	0.85	0.84
1.14	1.03	0.89	0.89
1.02	0.95	0.90	0.91
0.89	0.95	0.85	0.76
0.86	0.71	0.83	0.73
0.80	0.72	0.75	0.64
0.81	0.81	0.75	0.68
0.81	0.81	0.76	0.62
0.81	0.74	0.74	0.73

(iv)
calculated wind speeds
point (0,0) included
case 7 +0 a=0.9b=0.00

	cup14	cup15	cup38	cup39
	2.15	2.22	2.15	1.85
	1.77	1.95	1.77	1.53
	2.20	2.23	2.45	2.11
	2.98	2.99	2.82	2.80
	2.79	2.69	2.70	2.47
	2.84	2.54	2.54	2.41
	3.28	2.89	2.96	2.79
	2.49	2.46	2.82	2.37
	3.37	3.38	2.90	2.98
	2.73	2.76	2.49	2.35
	2.78	2.47	2.69	2.37
	3.05	2.99	2.94	2.70
	1.21	1.65	1.55	1.45
	1.29	1.47	1.22	0.92
	2.84	2.35	2.12	1.35
	3.23	3.53	2.44	2.39
	2.32	2.08	1.82	1.80
	2.89	2.68	2.54	2.56
	2.34	2.49	2.24	2.00
	2.28	1.87	2.20	1.94
	2.46	2.22	2.32	1.99
	2.06	2.06	1.90	1.73
	2.77	2.77	2.59	2.13
	3.00	2.73	2.76	2.72
(1)	2.55	2.48	2.37	2.15
(2)	0.56	0.49	0.45	0.51
(3)	1.04	2.10	0.44	5.66

Table A10. Cup 38 as reference: Calculated wind speeds and wind reduction ratios for: (a) all 24 weeks: case 4 with point (0, 0) not included (case 4, -0) and with point (0, 0) included (case 4 +0) and even numbered weeks: (b) case 6 with point (0, 0) not included (case 6, -0) and with point (0, 0) included (case 6 +0) and (c) case 8 with point (0, 0) not included (case 8, -0) and with point (0, 0) included (case 8 +0): a and b regression coefficients given in Table 76. Note that (1) is average wind speed of the 24 weeks and (2) is standard deviation and (3) is per cent difference of the average of the calculated from the average of measured wind speeds as given in Table 78 (a).

(a) case 4

	(i) calculated reduction ratios point (0,0) not included case 4 -0 a=0.87 b=0.10 cup 38 as refence				(ii) calculated wind speeds point (0,0) not included case 4 -0 a=0.87 b=0.10 cup 38 as refence				(iii) calculated reduction ratios point (0,0) included case 4 +0 a=0.99 b=0.00 cup 38 as refence				(iv) calculated wind speeds point (0,0) included case 4 +0 a=0.99b=0.00 cup 38 as refence			
	cup14	cup15	cup38	cup39	cup14	cup15	cup38	cup39	cup14	cup15	cup38	cup39	cup14	cup15	cup38	cup39
	0.97	1.00	0.97	0.85	2.05	2.11	2.05	1.79	0.99	1.02	0.99	0.85	2.09	2.16	2.09	1.80
	0.97	1.06	0.97	0.85	1.72	1.88	1.73	1.52	0.98	1.09	0.99	0.86	1.76	1.94	1.77	1.53
	0.88	0.89	0.97	0.85	2.20	2.23	2.43	2.12	0.89	0.90	0.99	0.85	2.22	2.26	2.48	2.13
	1.02	1.02	0.97	0.97	2.90	2.91	2.76	2.75	1.05	1.05	0.99	0.99	2.98	2.99	2.82	2.81
	1.00	0.97	0.97	0.90	2.75	2.66	2.67	2.47	1.02	0.99	0.99	0.91	2.82	2.72	2.72	2.50
	1.07	0.97	0.97	0.92	2.80	2.53	2.53	2.42	1.11	0.99	0.99	0.94	2.89	2.59	2.59	2.45
	1.06	0.95	0.97	0.92	3.07	2.74	2.80	2.66	1.10	0.97	0.99	0.93	3.16	2.79	2.86	2.70
	0.87	0.86	0.97	0.83	2.40	2.38	2.68	2.30	0.87	0.86	0.99	0.83	2.41	2.39	2.74	2.30
	1.11	1.11	0.97	0.99	3.31	3.31	2.89	2.96	1.15	1.15	0.99	1.02	3.42	3.43	2.95	3.03
	1.05	1.06	0.97	0.92	2.69	2.71	2.47	2.35	1.09	1.10	0.99	0.93	2.77	2.79	2.52	2.38
	1.00	0.90	0.97	0.87	2.66	2.39	2.58	2.31	1.02	0.91	0.99	0.87	2.72	2.42	2.64	2.32
	1.00	0.99	0.97	0.90	2.99	2.94	2.89	2.67	1.03	1.01	0.99	0.91	3.06	3.00	2.95	2.70
	0.78	1.03	0.97	0.92	1.22	1.61	1.52	1.44	0.77	1.06	0.99	0.93	1.21	1.66	1.55	1.46
	1.02	1.15	0.97	0.76	1.28	1.44	1.21	0.95	1.05	1.20	0.99	0.75	1.32	1.50	1.24	0.93
	1.26	1.06	0.97	0.65	2.65	2.23	2.04	1.37	1.32	1.10	0.99	0.63	2.78	2.30	2.08	1.33
	1.25	1.36	0.97	0.95	3.06	3.32	2.37	2.32	1.31	1.44	0.99	0.97	3.20	3.50	2.42	2.37
	1.21	1.10	0.97	0.96	2.10	1.91	1.69	1.67	1.26	1.13	0.99	0.98	2.19	1.97	1.72	1.71
	1.09	1.02	0.97	0.98	2.64	2.46	2.34	2.36	1.13	1.05	0.99	1.00	2.73	2.53	2.39	2.41
	1.01	1.07	0.97	0.88	2.23	2.37	2.15	1.94	1.03	1.10	0.99	0.88	2.29	2.44	2.19	1.96
	1.00	0.84	0.97	0.87	2.18	1.83	2.11	1.89	1.02	0.84	0.99	0.87	2.23	1.83	2.16	1.90
	1.02	0.93	0.97	0.84	2.45	2.23	2.33	2.03	1.05	0.94	0.99	0.85	2.51	2.27	2.38	2.03
	1.04	1.04	0.97	0.89	2.04	2.03	1.89	1.74	1.07	1.07	0.99	0.90	2.10	2.09	1.93	1.76
	1.03	1.03	0.97	0.81	2.75	2.75	2.59	2.17	1.06	1.06	0.99	0.81	2.83	2.83	2.64	2.17
	1.05	0.96	0.97	0.96	2.95	2.71	2.74	2.70	1.08	0.98	0.99	0.97	3.04	2.76	2.80	2.75
(1)					2.46	2.40	2.31	2.12					2.53	2.47	2.36	2.14
(2)					0.53	0.48	0.44	0.49					0.56	0.50	0.45	0.51
(3)					4.30	5.02	3.00	7.14					1.64	2.63	1.00	6.20

Table A10. continued

(b) case 6

(i)					(ii)				(iii)					(iv)			
calculated reduction ratios					calculated wind speeds				calculated reduction ratios					calculated wind speeds			
point (0,0) not included					point (0,0) not included				point (0,0) included					point (0,0) included			
case 6 -0 a=0.66 b=0.27					case 6 -0 a=0.66 b=0.27				case 6 +0 a=0.99 b=0.01					case 6 +0 a=0.99b=0.01			
cup 38 as refence					cup 38 as refence				cup 38 as refence					cup 38 as refence			
cup14	cup15	cup38	cup39		cup14	cup15	cup38	cup39	cup14	cup15	cup38	cup39		cup14	cup15	cup38	cup39
0.93	0.95	0.93	0.84		1.96	2.01	1.96	1.77	1.00	1.03	1.00	0.86		2.11	2.18	2.11	1.82
0.93	1.00	0.93	0.84		1.65	1.78	1.66	1.50	0.99	1.10	1.00	0.87		1.78	1.96	1.78	1.54
0.86	0.87	0.93	0.84		2.16	2.18	2.33	2.09	0.90	0.91	1.00	0.86		2.25	2.28	2.50	2.15
0.97	0.97	0.93	0.93		2.76	2.76	2.65	2.64	1.06	1.06	1.00	1.00		3.01	3.02	2.84	2.83
0.95	0.93	0.93	0.88		2.62	2.55	2.56	2.41	1.03	1.00	1.00	0.92		2.85	2.74	2.75	2.53
1.01	0.93	0.93	0.90		2.63	2.43	2.43	2.34	1.12	1.00	1.00	0.95		2.92	2.61	2.61	2.48
1.00	0.91	0.93	0.89		2.89	2.64	2.68	2.58	1.11	0.98	1.00	0.94		3.19	2.82	2.88	2.72
0.85	0.85	0.93	0.83		2.36	2.34	2.57	2.28	0.88	0.87	1.00	0.84		2.44	2.42	2.76	2.33
1.04	1.04	0.93	0.95		3.09	3.09	2.77	2.83	1.16	1.16	1.00	1.03		3.45	3.46	2.98	3.06
0.99	1.00	0.93	0.89		2.53	2.55	2.37	2.27	1.10	1.11	1.00	0.94		2.79	2.82	2.55	2.40
0.95	0.88	0.93	0.85		2.53	2.33	2.48	2.27	1.03	0.92	1.00	0.88		2.75	2.45	2.66	2.35
0.96	0.94	0.93	0.88		2.84	2.80	2.77	2.61	1.04	1.02	1.00	0.92		3.09	3.03	2.98	2.73
0.78	0.98	0.93	0.89		1.23	1.53	1.46	1.40	0.78	1.07	1.00	0.94		1.23	1.67	1.57	1.47
0.97	1.07	0.93	0.77		1.22	1.34	1.16	0.96	1.06	1.21	1.00	0.76		1.33	1.51	1.25	0.95
1.15	1.00	0.93	0.69		2.42	2.10	1.95	1.45	1.33	1.11	1.00	0.64		2.80	2.32	2.10	1.35
1.14	1.23	0.93	0.92		2.79	2.99	2.27	2.24	1.32	1.45	1.00	0.98		3.23	3.53	2.44	2.39
1.11	1.03	0.93	0.92		1.93	1.78	1.62	1.61	1.27	1.14	1.00	0.99		2.21	1.99	1.74	1.72
1.02	0.97	0.93	0.94		2.47	2.34	2.25	2.26	1.14	1.06	1.00	1.01		2.75	2.55	2.42	2.44
0.96	1.00	0.93	0.86		2.13	2.22	2.06	1.91	1.04	1.11	1.00	0.89		2.31	2.46	2.22	1.98
0.95	0.83	0.93	0.85		2.07	1.81	2.03	1.85	1.03	0.85	1.00	0.88		2.25	1.85	2.18	1.92
0.97	0.90	0.93	0.83		2.33	2.16	2.23	2.01	1.06	0.95	1.00	0.86		2.54	2.29	2.40	2.06
0.99	0.98	0.93	0.87		1.93	1.92	1.82	1.70	1.08	1.08	1.00	0.91		2.12	2.11	1.95	1.78
0.98	0.98	0.93	0.81		2.61	2.61	2.48	2.17	1.07	1.07	1.00	0.82		2.86	2.86	2.67	2.20
0.99	0.92	0.93	0.92		2.79	2.60	2.63	2.60	1.09	0.99	1.00	0.98		3.07	2.79	2.82	2.78
				(1)	2.33	2.29	2.22	2.07					(1)	2.55	2.49	2.38	2.17
				(2)	0.48	0.44	0.43	0.46					(2)	0.56	0.50	0.46	0.51
				(3)	9.42	9.68	7.00	9.30					(3)	0.71	1.69	0.00	5.16

Table A10. continued

(c) case 8

Table A10. continued.

(i)
calculated reduction ratios
point (0,0) not included
case 8 -0 a=1.04 b=-0.03
cup 38 as refence

cup14	cup15	cup38	cup39
1.01	1.05	1.01	0.87
1.00	1.11	1.01	0.87
0.90	0.92	1.01	0.86
1.07	1.07	1.01	1.01
1.05	1.01	1.01	0.92
1.13	1.01	1.01	0.96
1.12	0.98	1.01	0.95
0.89	0.88	1.01	0.84
1.18	1.18	1.01	1.04
1.11	1.12	1.01	0.95
1.04	0.92	1.01	0.89
1.05	1.03	1.01	0.92
0.78	1.08	1.01	0.95
1.08	1.23	1.01	0.75
1.36	1.12	1.01	0.63
1.35	1.48	1.01	0.99
1.29	1.16	1.01	1.00
1.16	1.07	1.01	1.02
1.06	1.13	1.01	0.90
1.04	0.85	1.01	0.88
1.07	0.96	1.01	0.86
1.10	1.09	1.01	0.92
1.08	1.08	1.01	0.82
1.10	1.00	1.01	0.99

(ii)
calculated wind speeds
point (0,0) not included
case 8 -0 a=1.04 b=-0.03
cup 38 as refence

	cup14	cup15	cup38	cup39
	2.13	2.21	2.13	1.83
	1.79	1.99	1.80	1.55
	2.26	2.30	2.53	2.16
	3.05	3.06	2.87	2.86
	2.88	2.77	2.78	2.54
	2.96	2.64	2.64	2.50
	3.24	2.84	2.91	2.75
	2.45	2.43	2.79	2.34
	3.51	3.52	3.01	3.09
	2.83	2.86	2.57	2.42
	2.78	2.46	2.69	2.36
	3.12	3.06	3.01	2.75
	1.22	1.69	1.58	1.48
	1.35	1.54	1.26	0.94
	2.86	2.35	2.12	1.33
	3.29	3.61	2.46	2.41
	2.25	2.02	1.75	1.74
	2.79	2.58	2.44	2.46
	2.34	2.50	2.24	1.99
	2.28	1.86	2.20	1.93
	2.57	2.31	2.43	2.07
	2.15	2.14	1.97	1.79
	2.89	2.89	2.70	2.20
	3.11	2.82	2.85	2.81
(1)	2.59	2.52	2.41	2.18
(2)	0.57	0.51	0.46	0.52
(3)	-0.55	0.54	-1.00	4.59

(iii)
calculated reduction ratios
point (0,0) included
case 8 +0 a=1.00 b=-0.00
cup 38 as refence

cup14	cup15	cup38	cup39
1.00	1.03	1.00	0.86
0.99	1.10	1.00	0.86
0.90	0.91	1.00	0.86
1.06	1.06	1.00	1.00
1.04	1.00	1.00	0.92
1.12	1.00	1.00	0.95
1.11	0.98	1.00	0.94
0.88	0.87	1.00	0.84
1.16	1.16	1.00	1.03
1.10	1.11	1.00	0.94
1.03	0.92	1.00	0.88
1.04	1.02	1.00	0.92
0.78	1.07	1.00	0.94
1.06	1.21	1.00	0.75
1.34	1.11	1.00	0.64
1.33	1.45	1.00	0.98
1.27	1.15	1.00	0.99
1.14	1.06	1.00	1.01
1.04	1.11	1.00	0.89
1.03	0.85	1.00	0.88
1.06	0.95	1.00	0.86
1.09	1.08	1.00	0.91
1.07	1.07	1.00	0.82
1.09	0.99	1.00	0.98

(iv)
calculated wind speeds
point (0,0) included
case 8 +0 a=1.00b=-0.00
cup 38 as refence

	cup14	cup15	cup38	cup39
	2.11	2.18	2.11	1.82
	1.78	1.96	1.78	1.54
	2.25	2.28	2.50	2.15
	3.01	3.02	2.84	2.83
	2.85	2.74	2.75	2.52
	2.92	2.61	2.61	2.48
	3.20	2.81	2.88	2.72
	2.44	2.41	2.76	2.33
	3.46	3.47	2.98	3.06
	[illegible]	[illegible]	[illegible]	2.40
	2.75	2.44	2.66	2.35
	3.09	3.03	2.98	2.73
	1.22	1.67	1.57	1.47
	1.33	1.51	1.25	0.94
	2.81	2.32	2.10	1.34
	3.23	3.54	2.44	2.39
	2.21	1.99	1.74	1.72
	2.76	2.55	2.42	2.44
	2.31	2.46	2.22	1.98
	2.25	1.85	2.18	1.92
	2.54	2.29	2.40	2.06
	2.12	2.11	1.95	1.78
	2.86	2.86	2.67	2.19
	3.07	2.79	2.82	2.78
(1)	2.56	2.49	2.38	2.16
(2)	0.56	0.50	0.46	0.51
(3)	0.65	1.65	0.00	5.25

Table A11. Soil temperature measuring positions in agroforestry plot (see Fig. 11). (i) pruned and (ii) unpruned. Note that we use (1, 2), (3, 4),..., (15, 16) to represent (ATM1, ATM2), (BTM3, BTM4),..., (BTM15, BTM16) for clarity in Fig. 11.

Distance from the *Grevillea robusta* trees					
		94 cm		376 cm	
Tree No	depth (cm)	7.5	15	7.5	15
(i) Pruned					
PT1	position	AM1		BM1	
		ATM2	ATM1	BTM4	BTM3
PT2	position	AL1		BL1	
		ATM6	ATM5	BTM8	BTM7
(ii) Unpruned					
UT4	position	AM2		BM2	
		ATM10	ATM9	BTM12	BTM11
UT5	position	AL2		BL2	
		ATM14	ATM13	BTM16	BTM15

Table A12. Weeks of soil temperature data in Matanya plots for (i) SR91, (ii) LR92, (iii) LR93, (iv) SR93.

(a) Agroforestry (AF) plot

i. SR91	ii. LR92
wk1: 18/10-21/10/91	wk1: 21/03-28/03/92
wk2: 23/10-29/10/91	wk2: 29/03-04/04/92
wk3: 30/10-05/11/91	wk3: 05/04-11/04/92
wk4: 06/11-11/11/91	wk4: 13/05-19/05/92
wk5: 12/11-18/11/91	wk5: 20/05-26/05/92
wk6: 19/11-25/11/91	wk6: 27/05-03/06/92
wk7: 26/11-03/12/91	wk7: 04/06-10/06/92
wk8: 04/12-09/12/91	wk8: 11/06-15/06/92
wk9: 10/12-16/12/91	wk9: 18/06-25/06/92
wk10: 17/12-19/12/91	wk10: 26/06-02/07/92
wk11: 20/12-26/12/91	wk11: 03/07-09/07/92
wk12: 27/12-02/01/92	wk12: 30/07-05/08/92
wk13: 03/12-09/01/92	wk13: 06/08-12/08/92
	wk14: 13/08-19/08/92
	wk15: 20/08-26/08/92

iii. LR93	iv. SR93
wk1: 22/03-28/03/93	wk1: 11/10-17/10/93
wk2: 29/03-04/04/93	wk2: 18/10-24/10/93
wk3: 05/04-11/04/93	wk3: 25/10-31/10/93
wk4: 12/04-18/04/93	wk4: 01/11-07/11/93
wk5: 19/04-25/04/93	wk5: 08/11-14/11/93
wk6: 17/06-23/06/93	wk6: 15/11-21/11/93
wk7: 24/06-30/06/93	wk7: 22/11-28/11/93
wk8: 01/07-06/07/93	wk8: 29/11-06/12/93
wk9: 07/07-13/07/93	

(b) Non agroforestry (NAF) plots

i. SR91	ii. LR92 June & July 1992
wk1: 02/11-07/11/91	wk1: 03/06-09/06/92
wk2: 08/11-14/11/91	wk2: 10/06-16/06/92
wk3: 15/11-21/11/91	wk3: 17/06-23/06/92
wk4: 22/11-28/11/91	wk4: 24/06-30/06/92
	wk5: 01/07-07/07/92
	wk6: 08/07-14/07/92
	wk7: 15/07-21/07/92
	wk8: 22/07-28/07/92

iii. LR93	iv. SR93
wk1: 20/03-26/03/93	wk1: 05/10-11/10/93
wk2: 27/03-02/04/93	wk2: 12/10-18/10/93
wk3: 03/04-09/04/93	wk3: 19/10-25/10/93
wk4: 10/04-16/04/93	wk4: 26/10-01/11/93
wk5: 17/04-23/04/93	wk5: 02/11-08/11/93
wk6: 24/04-30/04/93	wk6: 09/11-15/11/93
wk7: 18/06-24/06/93	wk7: 16/11-22/11/93
wk8: 25/06-01/07/93	wk8: 23/11-29/11/93
wk9: 02/07-07/07/93	wk9: 03/12-09/12/93
wk10: 08/07-13/07/93	wk10: 10/12-16/12/93
	wk11: 17/12-23/12/93
	wk12: 24/12-30/12/93
	wk13: 31/12-06/01/94
	wk14: 07/01-12/01/94

Table A13. Soil temperature characteristics in Matanya agroforestry plot for (a) SR91, (b) LR92 (c) LR93, (d) SR93 (see also Table A11 & Fig. 12)

Soil tempera parame- ters	plot: AFM1 Pruned Grevillea tree PT1				plot: AFL1 Pruned Grevillea tree PT2				plot: AFM2 Unpruned Grevillea tree UT4				plot: AFL2 Unpruned Grevillea tree UT5			
	AM1 94 cm		BM1 376 cm		AL1 94 cm		BL1 376 cm		AM2 94 cm		BM2 376 cm		AL2 94 cm		BL2 376 cm	
	ATM1 dep15	ATM2 dep7.5	ATM3 dep15	ATM4 dep7.5	ATM5 dep15	ATM6 dep7.5	ATM7 dep15	ATM8 dep7.5	ATM9 dep15	ATM10 dep7.5	ATM11 dep15	ATM12 dep7.5	ATM13 dep15	ATM14 dep7.5	ATM15 dep15	ATM16 dep7.5
(a) Short Rains growing season of 1991: SR91																
1. SR91: October																
	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	19.16	18.80	19.06	18.80	18.76	18.31	18.33	17.99	18.68	18.21	18.78	18.71	19.07	18.82	18.70	15.88
Std dev	0.35	0.88	0.42	1.12	1.01	2.77	0.60	1.35	0.59	1.42	0.57	1.22	0.61	1.54	0.60	3.55
Max	19.65	20.11	19.64	20.43	20.23	23.02	19.15	20.11	19.50	20.40	19.60	20.52	19.93	21.14	19.50	22.32
Time	15.15	11.15	14.15	10.15	10.15	6.15	12.15	8.15	12.15	9.15	11.15	10.15	10.15	10.15	11.15	8.15
Min	18.64	17.52	18.48	17.28	17.38	14.97	17.45	16.30	17.83	16.34	17.93	17.12	18.20	16.84	17.58	11.49
Time	3.15	2.15	4.15	1.15	1.15	21.15	2.15	22.15	3.15	23.15	3.15	0.15	3.15	0.15	1.15	0.15
Amplitu	0.51	1.29	0.58	1.57	1.43	4.02	0.85	1.91	0.83	2.03	0.83	1.70	0.86	2.15	0.96	5.41
2. SR91: November																
	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	19.46	19.37	19.03	18.80	18.82	18.57	18.55	18.35	19.58	19.31	19.27	19.37	19.90	20.10	18.90	16.39
Std dev	0.40	0.94	0.39	1.10	0.97	2.66	0.39	0.94	0.67	1.49	0.53	1.32	0.74	1.96	0.51	3.92
Max	20.00	20.72	19.59	20.48	20.28	23.27	19.07	19.81	20.53	21.67	20.02	21.35	20.94	23.17	19.63	23.32
Time	23.25	19.25	21.25	17.25	18.25	14.25	20.25	17.25	19.25	17.25	20.25	17.25	20.25	16.25	20.25	12.25
Min	18.84	17.97	18.41	17.17	17.39	15.06	17.93	16.92	18.56	17.16	18.44	17.48	18.76	17.35	18.13	11.35
Time	12.25	10.25	11.25	8.25	9.25	7.25	10.25	8.25	11.25	8.25	11.25	8.25	11.25	8.25	11.25	6.25
Amplitu	0.58	1.38	0.59	1.65	1.44	4.11	0.57	1.44	0.99	2.26	0.79	1.94	1.09	2.91	0.75	5.99
3. SR91: December																
	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	20.81	20.97	19.94	19.94	20.48	21.19	19.62	19.73	21.68	21.56	21.56	22.41	21.66	22.26	20.45	17.34
Std dev	0.57	1.48	0.60	1.65	1.68	5.60	0.83	1.87	1.02	2.38	0.90	2.86	1.11	3.13	0.78	5.96
Max	21.60	23.17	20.72	22.35	23.00	23.09	20.78	22.76	23.11	25.33	22.78	27.03	23.24	27.46	21.47	26.43
Time	22.02	18.02	22.02	17.02	18.02	14.02	20.02	17.02	20.02	17.02	20.02	16.02	20.02	17.02	20.02	14.02
Min	19.94	18.71	18.99	17.45	18.04	14.16	18.42	17.04	20.16	18.03	20.16	18.53	19.98	17.90	19.27	10.15
Time	13.02	10.02	11.02	9.02	9.02	7.02	11.02	9.02	10.02	8.02	11.02	9.02	11.02	9.02	11.02	6.02
Amplitu	0.83	2.23	0.86	2.45	2.48	8.97	1.18	2.86	1.48	3.65	1.31	4.25	1.63	4.78	1.10	8.14

Table A13. continued

(b) Long Rains growing season of 1992: LR92

1. LR92: March

	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	20.88	20.03	20.75	20.31	20.61	20.24	21.29	21.33	21.01	20.74	17.99	20.54	21.07	21.15	21.16	18.35
Std dev	0.97	2.63	0.83	1.96	0.98	2.63	1.22	2.26	0.88	1.72	0.69	2.52	1.56	3.05	0.82	4.30
Max	22.21	24.53	21.89	23.41	21.96	24.75	23.08	24.87	22.17	23.16	19.32	24.45	23.32	25.81	22.29	25.71
Time	19.45	14.45	18.45	15.45	19.45	15.45	18.45	16.45	18.45	16.45	18.45	15.45	17.45	14.45	19.45	11.45
Min	19.37	16.31	19.48	17.57	19.10	16.59	19.48	18.15	19.59	18.18	16.81	17.03	18.70	16.86	19.88	13.06
Time	10.45	7.45	9.45	7.45	10.45	7.45	9.45	8.45	10.45	8.45	12.45	7.45	8.45	7.45	10.45	4.45
Amplitu	0.92	2.84	1.62	2.97	1.03	2.36	0.85	1.74	0.64	1.34	5.30	3.71	2.31	4.48	1.20	6.32

2. LR92: May

	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	22.44	22.34	21.30	21.11	21.89	22.19	22.36	22.43	21.36	21.32	21.60	20.88	21.67	21.61	21.77	17.48
Std dev	1.06	3.15	0.64	1.62	1.25	3.64	1.08	2.29	0.85	1.31	0.64	1.81	1.33	2.38	0.85	3.71
Max	24.05	28.11	22.18	23.58	23.76	28.76	24.01	26.22	22.47	23.31	22.52	23.89	23.63	25.47	23.07	23.40
Time	19.18	15.18	19.18	16.18	18.18	15.18	18.18	16.18	19.18	17.18	19.18	17.18	17.18	16.18	18.18	12.18
Min	20.95	18.37	19.93	18.83	20.08	17.71	20.81	19.26	19.94	19.37	20.64	18.42	19.65	18.36	20.54	12.78
Time	10.18	7.18	11.18	8.18	10.18	7.18	9.18	8.18	10.18	9.18	11.18	7.18	8.18	8.18	11.18	6.18
Amplitu	1.55	4.87	1.13	2.38	1.84	5.52	1.60	3.48	1.26	1.97	0.94	2.74	1.99	3.56	1.27	5.31

3. LR92: June

	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	21.41	21.12	19.47	19.39	20.41	20.30	20.45	17.39	20.13	20.13	19.57	19.78	20.05	20.41	19.01	20.16
Std dev	0.70	2.24	1.01	2.02	1.04	1.87	1.56	1.92	1.29	2.11	0.99	4.27	1.27	0.96	1.87	3.37
Max	22.36	25.04	20.79	22.84	21.62	23.33	22.79	22.22	21.93	23.77	20.82	28.30	21.79	21.50	21.98	26.61
Time	19.25	17.25	18.25	15.25	20.25	16.25	17.25	14.25	18.25	17.25	19.25	14.25	18.25	20.25	15.25	14.25
Min	20.34	18.27	17.50	16.57	18.22	17.70	17.74	13.78	17.68	17.16	17.61	15.40	17.86	18.30	16.16	16.27
Time	11.25	10.25	10.25	10.25	11.25	10.25	10.25	23.25	10.25	10.25	11.25	6.25	11.25	11.25	14.25	7.25
Amplitu	1.01	3.39	1.65	3.14	1.70	2.82	2.52	4.22	2.12	3.30	1.60	6.45	1.96	1.60	2.91	5.17

4. LR92: July

	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	23.15	23.13	22.47	22.85	22.60	23.42	22.98	23.41	22.28	22.28	22.58	22.41	22.97	23.50	22.43	17.27
Std dev	1.25	3.49	0.82	2.47	1.44	4.37	1.18	2.32	0.76	1.58	0.81	2.49	1.77	3.47	0.89	3.77
Max	25.07	29.44	23.78	27.06	24.84	31.48	24.83	27.21	23.45	24.84	23.77	26.69	25.76	29.61	23.81	23.89
Time	18.17	15.17	19.17	15.17	18.17	15.17	18.17	17.17	19.17	17.17	19.17	17.17	17.17	16.17	18.17	14.17
Min	21.38	18.90	21.33	19.75	20.61	18.20	21.34	20.31	21.19	20.13	21.41	19.12	20.48	19.08	21.20	12.60
Time	10.17	8.17	10.17	8.17	10.17	7.17	10.17	8.17	10.17	9.17	11.17	8.17	9.17	8.17	11.17	6.17
Amplitu	1.84	5.27	1.22	3.66	2.12	6.64	1.74	3.45	1.13	2.36	1.18	3.78	2.64	5.27	1.31	5.64

5. LR92: August

	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	20.82	20.52	20.76	20.55	20.48	20.74	21.16	21.26	20.69	20.77	20.97	20.47	21.47	21.31	21.08	21.00
Std dev	1.01	2.78	0.92	2.42	1.21	3.40	0.97	1.85	0.94	2.04	0.77	2.29	2.13	4.10	1.00	5.87
Max	22.30	25.42	22.11	24.86	22.29	26.89	22.58	24.25	22.03	24.05	22.06	24.35	24.86	28.97	22.63	31.80
Time	19.42	16.42	18.42	16.42	19.42	15.42	18.42	17.42	19.42	16.42	19.42	17.42	17.42	16.42	18.42	14.42
Min	19.30	16.91	19.41	17.57	18.76	16.50	19.71	18.66	19.24	18.01	19.79	17.43	18.53	15.62	19.48	14.25
Time	10.42	7.42	9.42	7.42	9.42	7.42	10.42	8.42	7.42	8.42	10.42	8.42	8.42	8.42	8.42	6.42
Amplitu	1.50	4.26	1.35	3.65	1.76	5.20	1.44	2.80	1.40	3.02	1.13	3.46	3.17	6.67	1.57	8.78

Table A13. continued

(c) Long Rains growing season of 1993: LR93

1. LR93: April

	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	18.71	17.98	18.20	17.65	18.47	18.00	18.71	18.50	19.21	18.65	18.79	17.97	18.59	19.14	18.50	19.23
Std dev	0.61	1.87	0.57	1.13	0.73	1.84	1.06	1.82	0.66	1.44	0.58	2.30	1.30	1.65	1.64	3.48
Max	19.61	20.92	18.98	19.29	19.47	20.89	20.27	21.38	20.19	20.64	19.61	21.42	20.47	21.40	20.97	24.80
Time	20.54	16.54	19.54	16.54	20.54	16.54	18.54	16.54	18.54	16.54	19.54	14.54	17.54	14.54	16.54	13.54
Min	17.79	15.46	17.30	16.10	17.42	15.59	17.20	16.10	18.26	16.60	17.92	15.30	16.66	16.90	16.06	14.94
Time	10.54	9.54	10.54	9.54	10.54	9.54	9.54	8.54	8.54	10.54	11.54	6.54	8.54	7.54	7.54	6.54
Amplitu	0.91	2.73	0.84	1.59	1.02	2.65	1.53	2.64	0.97	2.02	0.85	3.06	1.90	2.25	2.45	4.93

2. LR93: June

	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	21.38	21.21	19.60	19.52	20.55	20.43	20.58	17.49	20.26	20.26	19.70	19.96	20.18	20.55	19.12	20.31
Std dev	0.76	2.19	0.79	1.92	0.80	1.77	1.38	2.06	1.10	2.03	0.77	4.33	1.10	0.70	1.73	3.39
Max	22.46	25.04	20.79	22.84	21.62	23.33	22.79	22.95	21.93	23.77	20.82	28.32	21.79	21.48	21.98	26.61
Time	21.25	17.25	18.25	15.25	20.25	16.25	17.25	14.25	18.25	17.25	19.25	15.25	18.25	19.25	15.25	14.25
Min	20.06	18.27	18.54	17.15	19.28	17.95	18.76	13.78	18.73	17.51	18.66	15.40	18.61	19.40	16.77	16.27
Time	11.25	9.25	10.25	8.25	11.25	8.25	9.25	23.25	10.25	8.25	11.25	6.25	9.25	11.25	8.25	7.25
Amplitu	1.20	3.39	1.13	2.85	1.17	2.69	2.01	4.59	1.60	3.13	1.08	6.46	1.59	1.04	2.60	5.17

3. LR93: July

	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	21.01	20.52	19.72	19.88	19.68	19.28	20.77	21.61	20.14	20.14	19.96	19.86	20.42	20.89	20.02	21.02
Std dev	0.57	1.64	1.32	1.97	0.54	1.36	1.23	3.46	0.83	1.59	0.64	4.43	1.20	0.66	1.51	4.63
Max	21.85	23.49	21.15	23.58	20.55	21.48	22.83	29.39	21.43	22.97	20.97	30.39	22.37	21.85	22.46	30.77
Time	21.05	17.05	18.05	15.05	20.05	17.05	18.05	20.05	19.05	17.05	20.05	14.05	18.05	21.05	17.05	15.05
Min	20.22	18.49	16.00	17.61	18.82	17.47	19.10	18.07	18.96	18.07	19.05	15.46	18.77	19.80	18.07	16.35
Time	12.05	9.05	10.05	8.05	12.05	9.05	9,05	8.05	9.05	8.05	12.05	7.05	9.05	12.05	9.05	7.05
Amplitu	0.82	2.50	2.58	2.99	0.86	2.01	1.87	5.66	1.24	2.45	0.96	7.47	1.80	1.03	2.19	7.21

4. LR93: August

	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	20.09	19.59	19.52	19.49	19.04	18.74	20.62	20.08	19.32	19.38	19.57	19.11	20.23	20.54	20.53	
Std dev	0.80	2.18	1.04	2.44	0.55	1.29	1.46	2.67	0.87	1.76	0.72	5.16	1.47	0.91	2.12	
Max	21.28	23.46	21.15	24.03	19.85	20.77	22.99	25.72	20.65	22.16	20.60	30.75	22.45	21.86	23.95	
Time	19.58	16.58	17.58	15.58	20.58	16.58	17.58	16.58	18.58	16.58	19.58	12.58	17.58	19.58	15.58	1
Min	18.95	16.66	18.12	16.50	18.20	16.91	18.68	17.09	18.07	16.95	18.57	13.62	18.04	19.14	17.77	1
Time	10.58	7.58	9.58	7.58	10.58	8.58	9.58	7.58	9.58	7.58	10.58	5.58	9.58	10.58	9.58	6
Amplitu	1.17	3.40	1.51	3.76	0.82	1.93	2.15	4.32	1.29	2.60	1.02	8.57	2.19	1.36	3.09	9.1

Table A13. continued

(d) Short Rains growing season of 1993: SR93

1. SR93: October

	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	18.25	17.53	19.40	18.79	19.12	18.76	20.64	20.07	20.29	20.28	19.32	18.67	19.56	19.91	20.10	20.27
Std dev	0.52	1.03	0.53	1.42	0.62	1.47	0.81	2.41	0.92	2.10	0.42	1.33	0.72	1.63	0.56	1.01
Max	19.00	19.07	20.20	21.05	20.03	20.97	21.85	24.29	21.59	23.55	19.95	20.73	20.60	22.59	20.83	21.69
Time	18.29	16.29	18.29	15.29	19.29	16.29	18.29	15.29	17.29	16.29	19.29	15.29	19.29	16.29	21.29	19.29
Min	17.40	16.03	18.61	16.88	18.17	16.73	19.39	17.05	19.01	17.49	18.68	16.86	18.49	17.72	19.21	18.71
Time	9.29	7.29	9.29	7.29	10.29	8.29	9.29	7.29	10.29	6.29	10.29	7.29	10.29	8.29	11.29	10.29
Amplitu	0.80	1.52	0.79	2.09	0.93	2.12	1.23	3.62	1.29	3.03	0.63	1.94	1.05	2.43	0.81	1.49

2. SR93: November

	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5	dep15	dep7.5
Average	18.18	17.60	18.46	17.94	19.14	18.86	19.24	17.20	19.32	19.59	18.84	18.11	19.16	20.46	18.99	18.87
Std dev	0.42	0.93	0.49	1.19	0.65	1.60	0.86	1.93	0.91	1.67	0.38	1.34	0.70	1.45	0.51	1.24
Max	18.76	19.03	19.15	19.99	20.06	21.37	20.51	21.61	20.63	22.15	19.39	20.26	20.18	22.63	19.72	21.06
Time	18.29	16.29	19.29	17.29	19.29	16.29	17.29	18.29	17.29	17.29	20.29	15.29	18.29	16.29	21.29	18.29
Min	17.49	16.20	17.69	16.26	18.14	16.52	17.99	15.11	17.93	17.26	18.22	16.26	18.14	18.56	18.23	17.61
Time	9.29	7.29	10.29	8.29	10.29	8.29	9.29	10.29	10.29	8.29	10.29	7.29	10.29	9.29	11.29	10.29
Amplitu	0.63	1.42	0.73	1.86	0.96	2.42	1.26	3.25	1.35	2.44	0.59	2.00	1.02	2.04	0.74	1.72

Table A14. Soil temperature characteristics in Matanya nonagroforestry plot for (a) SR91, (b) LR92 (c) LR93, (d) SR93 (for LR92-SR93 see also Fig. 13)

Note that LR92-SR93 temperature measurements were carried on newly opened site ~~(Fig. 14[illegible]~~

Soil temperat-ure parame-ters	Local control (L)		Mulched control (M)		Bare soil (BS)		Local control (L)		Mulched control (M)		Bare soil (BS)	
	(a) SR91 1. SR91: October						(c) LR93 1. LR93:April					
	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5
Average	18.93	18.16	18.60	17.88	19.60	19.23	19.36	19.36	19.01	18.94	21.38	21.49
Std dev	0.83	2.07	0.66	1.50	0.33	0.77	1.53	2.40	0.62	1.63	0.74	1.86
Max	20.05	21.10	19.48	20.05	20.00	20.20	21.64	23.12	19.87	21.40	22.38	24.24
Time	19.50	23.50	17.00	20.50	18.5	21.5	17.25	16.00	20.25	16.58	21.25	17.25
Min	17.65	15.13	17.58	15.60	19.07	17.95	17.17	16.04	18.08	16.62	20.26	18.75
Time	11.00	13.00	9.50	11.50	9.5	11.5	8.75	8.00	10.25	8.58	11.25	9.25
Amplitude	1.20	2.99	0.95	2.22	0.47	1.12	2.24	3.54	1.16	2.13	1.06	2.74
	2. SR91: November				Bare soil		2. LR93: June					
	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5
Average	18.89	18.73	18.47	18.27	19.62	19.55	20.06	19.79	19.16	18.77	21.62	21.74
Std dev	0.88	1.97	0.65	1.39	0.43	0.90	1.78	2.06	0.69	1.37	0.75	1.81
Max	20.16	21.83	19.39	20.44	20.18	20.86	23.23	23.40	20.16	21.05	22.65	24.50
Time	18.88	16.38	18.88	15.88	21.38	18.38	17.90	16.90	19.07	17.07	21.4	17.4
Min	17.61	16.02	17.51	16.34	18.91	18.18	17.83	17.26	18.14	17.05	20.36	19.24
Time	9.88	7.38	9.88	7.88	11.38	9.38	9.15	8.40	10.07	9.07	11.4	9.4
Amplitude	1.27	2.90	0.94	2.05	0.64	1.34	2.70	3.07	1.01	2.00	1.15	2.63
	(b) LR92 1. LR92: June						3. LR93: July				BS	
	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5
Average	21.75	21.95	21.48	21.42	22.17	21.83	20.65	20.68	19.58	19.25	21.00	21.18
Std dev	1.43	2.64	0.99	1.32	1.16	2.48	1.71	2.06	0.65	1.41	0.65	1.56
Max	23.99	26.22	23.00	23.52	23.93	25.92	23.59	24.33	20.60	21.58	21.90	23.67
Time	18.75	16.75	20.33	18.00	20.00	17.00	17.58	17.08	19.00	17.66	21.33	17.33
Min	19.79	18.59	20.14	19.64	20.49	18.54	18.55	18.14	18.67	17.52	20.12	19.00
Time	10.25	8.75	11.67	10.00	11.00	9.00	9.08	8.33	10.33	9.00	11.33	9.33
Amplitude	2.10	3.81	1.43	1.94	1.72	3.69	2.52	3.10	0.97	2.03	0.89	2.33
	2. LR92: July						4. LR93: August					
	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5
Average	21.32	21.52	21.34	20.91	21.78	21.63	20.32	20.67	19.81	20.16	20.08	20.65
Std dev	1.44	2.82	1.14	1.30	1.27	2.89	4.50	4.68	4.06	4.67	4.09	4.56
Max	23.63	26.30	23.13	22.97	23.75	26.44	23.30	24.28	21.10	23.52	21.18	23.65
Time	19.00	17.00	20.33	18.33	20	17	18.38	17.38	19.80	17.80	22.13	19.13
Min	19.35	17.95	19.75	19.15	19.97	17.85	17.89	17.70	18.46	17.31	18.80	17.78
Time	10.25	8.75	11.33	10.00	11	9	9.38	9.13	10.46	9.80	11.13	9.13
Amplitude	2.14	4.17	1.69	1.91	1.89	4.30	2.70	3.29	1.32	3.10	1.19	2.94

Table A14. continued

	3. LR92: August					
	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5
Average	20.55	20.63	20.23	20.38	21.30	21.01
Std dev	1.38	2.93	0.83	1.67	1.35	3.00
Max	22.77	25.67	21.51	23.09	23.39	26.10
Time	17.79	16.04	18.96	17.29	18.29	16.29
Min	18.66	16.96	18.93	18.14	19.37	17.17
Time	9.29	7.79	9.62	8.29	9.29	7.29
Amplitude	2.05	4.36	1.29	2.47	2.01	4.46

Soil temperat-ure parame-ters	Local control (L)		Mulched control (M)		Bare soil (BS)	
	(c) SR93 1. SR93: October					
	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5
Average	20.73	20.68	19.36	19.39	21.50	21.58
Std dev	0.94	2.25	0.47	1.54	1.00	3.06
Max	22.12	24.28	20.02	21.92	22.95	26.63
Time	18.75	16.25	19.92	16.25	18.25	15.25
Min	19.38	17.69	18.65	17.32	20.04	17.59
Time	9.75	8.25	10.92	7.58	10.25	7.25
Amplitude	1.37	3.30	0.69	2.30	1.45	4.52
	2. SR93: November					
	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5
Average	19.31	19.12	18.63	18.38	20.19	20.19
Std dev	0.82	1.80	0.49	1.24	1.06	5.20
Max	20.45	21.82	19.29	20.20	21.68	28.86
Time	19.25	16.50	18.58	17.25	19.25	12.25
Min	18.06	16.50	17.87	16.52	18.53	13.62
Time	9.75	8.25	8.92	8.58	9.25	6.25
Amplitude	1.20	2.66	0.71	1.84	1.57	7.62
	3. SR93: December					
	Dep15	Dep7.5	Dep15	Dep7.5	Dep15	Dep7.5
Average	19.30	19.30	19.05	18.83	21.32	21.77
Std dev	0.69	1.54	0.44	1.00	1.21	6.30
Max	20.26	21.63	19.64	20.30	23.04	32.20
Time	20.43	17.43	21.18	18.18	19.18	13.18
Min	18.25	17.06	18.37	17.22	19.46	13.97
Time	10.43	8.93	8.18	9.18	10.18	7.18
Amplitude	1.00	2.29	0.64	1.54	1.79	9.11

Abbreviations and acronyms

$a = \lambda/C$ - thermal diffusivity
A - Area of a horizontal leaf assumed to be perpendicular to the sun's rays (or amplitude of the temperature wave)
A1. A2. ...., A12 - positions of WAU electrical cup anemometers in AF plot
ALF - a pruned portion of on-farm live-fence (lf) marked A
A_h - Area of shadow of leaf
A_o - diurnal amplitude of the temperature wave at the soil surface
AF - Agroforestry plot
AFL1 & AFL2 - Agroforestry unmulched deep tilled sub-plots
AFM1 & AFM2 - Agroforestry mulched minimum tilled sub-plots
AGL1 - unmulched deep tilled pruned G. robusta trees on-farm plot
AGL2 - unmulched deep tilled unpruned G. robusta trees on-farm plot
AGM1 - mulched minimum tilled pruned G. robusta trees on-farm plot
AGM2 - mulched minimum tilled unpruned G. robusta trees on-farm plot
Ap - horizon of the plough surface soil
ASALs - Arid and semi-arid lands
AWT(s) - Average weekly soil temperature(s)
BOD - Biomass oven dry
Bd - soil bulk density
BLF - a pruned portion of on-farm live-fence (lf) marked B
C - wind agressivity (or erosivity also thermal capacity)
°C - degrees centigrade
Ca - calcium
Cb1. Cb2 & Cb3 - wind system calibration periods 1. 2 & 3 at Embori
CCTA - commission for Technical Cooperation in Africa
CD - cool dry season (July - September)
CEC - carbon exchange capacity
CER - carbon dioxide exchange rates
CGP - Cob plus grain weights per plant
CIAT - Centro Internacional de Agricultura Tropical (International Centre for Tropical Agriculture)
CLF - a pruned portion of on-farm live-fence (lf) marked C
Cr - Calibration ratio
Cv - coefficient of variation of wind speed
d - density of live-fence or barrier or windbreak
D - soil temperature damping depth
DAP - Days after planting
D_{be} & D_{ml} - differences between the daily temperatures at time and depths and actual averages at the same time and depths of the bare and mulched soils
dL - a small increment in leaf area
DLF - unpruned portion of on-farm live-fence (lf) marked D
DOY - Days of the year (or julian days)
DM - plant dry matter (t/ha)
e - radiative conversion efficiency (or the amount of dry matter formed per unit of radiation)

E	direct evaporation from the exposed soil surface
ELF	unpruned portion of on-farm live-fence (lf) marked E
ET	canopy evapotranspiration
ETP	actual evapotranspiration
f	fraction of mean daily insolation intercepted by the canopy
F	the fraction of light intercepted by the tree canopy alone
FAO	Food and Agriculture Organization
F.C.	Field Capacity
FLF	unpruned portion of on-farm live-fence (lf) marked F
GC	a general control treatment for live-fence experiment
GOD	Grain oven dry weight
H	height of shelterbelt or live-fence or barrier or windbreak
HD	hot dry season (January - early March)
I	total irradiance at a depth of the canopy
I_o	the radiation arriving at the top of the canopy
ICRAF	International Centre for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
ITK	Indigenous technical knowledge
k	extinction coefficient of radiation
K	potassium
kg/ha	kilograms per hectare
L	Local or unmulched control plot (or accumulated leaf area index)
LAI	Leaf area index
Local	used here for 'unmulched deep tilled plot(s)
LR(s)	Long Rains Season(s) (mid March - late May)
LR90, LR91, LR92, LR93, LR94	Long rains seasons for 1990 till 1994
LRP	Laikipia Research Programme
M	Mulched control plot
m.a.s.l.	metres above mean sea level
mCi (or Ci)	millicurie (or curie): unit of radio-activity
$Mgha_{-1}$	megagram per hectare
MPTS	multipurpose trees
mrem	a unit of ionizing radiation such as gamma radiation
Mt.	mount
Mts	mountain ranges
NAF	non-agroforestry plot(s)
N	nitrogen
NCP	Number of cob per plant
NPH	Number of plants per hole
θ (cm^3 cm^{-3})	volumetric water content of free water (water released on drying at 105°C for 12 hours)
θ_e	Constitutional hydrogen or equivalent water.
θ_t (cm^3 cm^{-3})	total hydrogen content
P	phosphorus (P also used for precipitation or experimental period)
P1, P2, ...	experimental period 1, 2, ...
PAR	Photosynthetically active radiation
PE	potential evapotranspiration
PPFD	Photosynthetic photon flux density

PT1, PT2, PT3, PT4, PT5	- Root pruned Grevillea robusta trees 1 till 5 for on-station agroforestry plot marked thus.
(P.) W.P.	- (Permanent) Wilting point
q	- water (g/kg) extracted in producing dry matter
ϕ	- phase shift of soil temperature wave
$\phi_0 = \omega t_0$	- a phase constant determined by the time scale
Q_j	- the radius of sphere of importance
r	- correlation coefficient
R	- wind speed reduction ratio (or wind speed ratio or horizontal wind speed ratio or wind deficit radio or wind ratio)
Rcv	- normalized coefficients of variation of wind speed
Rsd	- normalized standard deviations of wind speed
R_{sti}	- Stigter's ratio
S	- Sulphur (or sunfleck parameter or solid component of the soil or total radiation (MJm^{-2}.)
SAT	- semi-arid tropics
Sd	- saturation deficit (in kPa) (also standard deviation or saturation deficit)
SR(s)	- Short Rains Season(s) (early October - late December)
SR90, SR91, SR92, SR93, SR94	- Short rains seasons for 1990 till 1994
τ	- leaf transpiration to radiation
Σdt	- the duration of crop growth in days
$\bar{T}$	- the 24-hr average soil temperature for the day in question.
TBY	- Total biomass yields
t/ha	- metric tonnes per hectare
TR	- tree row
TR1, TR2, TR3	- tree row 1, 2, 3
TSL(s)	- tube solarimeter(s)
TTMI	- Traditional Technique of Microclimatic Improvement
U (or u)	- monthly average wind speed (m/s)
UT1, UT2, UT3, UT4, UT5	- Root unpruned Grevillea robusta trees 1 till 5 for on-station agroforestry plot marked thus.
VSMC	- Volumetric soil moisture content
ω	- radial frequency
WA, WB	- woelfle anemographs marked thus
WAU	- Wageningen Agricultural University
wk(s)	- week(s)
wk1, wk2, ...	- week 1, 2, ... of experimental period
WMO	- World Meteorological Organization
WUE	- water use efficiency of crop
Ψ	- total penetration of light to the undercrop
Ψ_c	- light which passes through the tree canopy
Ψ_f	- light which misses the trees completely to reach the undercrop
γ	- gamma particles in the rays
λ	- thermal conductivity
YLD	- biomass yields
Zn	- Zinc