MICROCLIMATE IMPROVEMENT AND SOIL PROTECTION ASPECTS OF INTERCROPPING SORGHUM AND PEARL MILLET WITH COWPEA.

A DISSERTATION

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Doctor of Philosophy
in
Soil Science

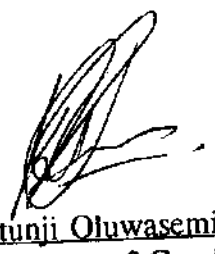
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1997

DECLARATION

I hereby declare that this dissertation has been written by me and that it is a record of my own research work. It has not been presented before in any previous application for a higher degree.



Kolapo Olatunji Oluwasemire
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Prof. J.J. Owonubi
Name and Signature of Chairman
Supervisory committee

CERTIFICATION

This dissertation titled **'MICROCLIMATE IMPROVEMENT AND SOIL PROTECTION ASPECTS OF INTERCROPPING PEARL MILLET AND SORGHUM WITH COWPEA'** meets the regulations governing the award of the degree of Doctor of Philosopy (Agroclimatology) of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

"To all those who have genuinely chosen to remain in the field of scientific research in Nigeria from the past ten years to date."

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Abstract

A better understanding, scientifically of the optimization and sustainability of resource use in small scale agricultural production under low rainfall, poor and deteriorating nutrient supply situations of the semi-arid zone of Nigeria necessitated this research. It had the objective of investigating the effects of millet, sorghum and cowpea planted sole, at recommended optimum densities and intercropped, under cultural practices similar to the farmers' condition. The research set out to assess the effects of two-three crop mixtures on the microclimate, soil conditions and their productivities in a semi-arid environment. A survey of the cereal based cropping systems of the Sudan savanna zone of Nigeria revealed the prominence of millet/cowpea and millet/sorghum/cowpea intercropping systems. The component crops in these systems are relay sown at relatively wide row spacings.

Field trials were conducted at Minjibir near Kano (12° 08 N, 8° 32 E) during the 1993, 1994 and 1995 rainy seasons to compare growth, light use, water use and root development in relation to the yield of millet, sorghum and cowpea planted sole at the recommended optimum densities and intercropped at farmers' planting densities under two levels of soil fertility. Another microclimatic parameter measured was near soil surface temperature, while the consequences of these cropping systems on seasonal nutrient balance were assessed.

The varying amounts and distribution of rainfall during the three years of experimentation did influence millet productivity and in the intercropping systems this was also true for growth. Sorghum grain yield was reduced by about 50% when rainfall did not extend beyond the first decade in September. An excessively wet season in 1994 reduced the yields of cowpea in the various cropping systems by 20

to 70%. The soil fertility status at the start of a cropping season plus the added pre-planting organic manure ensured adequate soil fertility in all the three years of field experimentation for millet production. Top dressing of millet components with inorganic fertilizer before panicle initiation (6 WAS) did not significantly ($P < 0.05$) increase millet grain yield. Total dry matter accumulation was also not affected by application of fertilizer at reproductive stage in the different cropping systems. However, sorghum dry matter production and grain yield was improved significantly ($P < 0.05$) by additional fertilizer applied at the initiation of reproductive stage (8 WAS). Dry matter production per stand of cowpea in the intercrops was significantly ($P < 0.05$) reduced by the associated cereal(s) planted 2 or 3 weeks earlier, and particularly by the high tillering and faster growing millet component, compared with the sole cowpea. There was poor vegetative growth of the cowpea components at relatively low total plant densities in the intercrops (26667 plants ha^{-1}) compared to the sole cereal systems (53333 plants ha^{-1}). This was worsened by the wetness of 1994, partly as a direct effect of weather conditions towards the end of growing season, and partly by pest and diseases caused by these conditions. Growth and development of the cowpea component in the widely spaced intercrops influenced radiation interception. At peak periods of canopy development, midday radiation interception by the intercrops varied from 60 to 80% in the direction of cereal/cereal association while the least interception (< 30% in 1994) occurred between sorghum and the grain cowpea (1T89KD-374) in plots with pre-planting organic manure application alone. The higher density of the sole cereal crops caused higher overall peak radiation interception (about 70%) than in the intercrops. The higher amount of cowpea vegetative growth in 1995 under adequate radiation availability increased

radiation interception within the intercrops by 5 to 20% over the sole millet at peak canopy development (45 DAS millet). The intercrop dry matter production was increased even at lower millet density (< 25% of sole millet) by 10 to 65% at millet and cowpea physiological maturity.

Diurnal near surface soil temperature fluctuation on cloudless days was reduced in all the cropped treatments compared to the bare soil. However, in 1994 with more pronounced differences early in the season, the reduction began earlier and was more effective until millet LAI exceeded 2.5 (55 DAS millet) in the intercrops (fluctuation < 6.5°C) than in the sole cereals (fluctuation of 10.0- 13.0°C). About the same period in 1995, amplitudes were much smaller and diurnal differences less pronounced.

All the crops sown sole and intercroppped rooted beyond 1 m depth in the loose sandy soil of our experimental site. Sorghum root production was greater than that of millet, while both cereals produced greater root densities than cowpea. The overlap of the roots of component crops in intercropping suggests competition for below ground resources. Cowpea produced greater root densities and achieved deeper rooting depths when intercropped with millet and/or sorghum than when sown sole, suggesting a better adaptation and competitive ability under intercropping. Rooting depths of crops were shallower in a relatively wet season than when water was limiting. The root densities and proliferation front of cereals below the surface layer were much higher in relatively low fertility status soils than when nutrients are readily available.

Dry matter production and system productivity of the intercrops were higher or equal to the sole millet when cowpea productivity was better in 1993 (LER< 1.7)

and 1995 (LER< 1.2). High soil water availability favoured the growth and development of cereals more than the cowpea, resulting in reduced intercrop systems productivity in the relatively wetter 1994 season. Sole millet used water more efficiently than its intercrops with cowpea, in 1994, when annual rainfall was above the long term average. When the rainfall amount was below normal in 1995 (typical of the recent climate situation in semi-arid Nigeria as also found in 1993), the intercropping systems showed better WUE of about 20% in grain production and 15% in total dry matter production in the millet/cowpea intercrop over the sole millet. The situation in the millet/sorghum/cowpea intercrop gave for OM + IF about 35% better WUE in both grain and total dry matter production compared to sole sorghum (Gaya Early). In the OM sorghum based intercrop, the grain WUE figure was about 30% and for total dry matter, 45% better than sole Gaya Early. Millet with heavy tillering, even at low densities in the intercrops, was the dominant crop in the intercropped systems. Deep percolation loss accounted for 15 to 20% of the seasonal available water in 1995 (with least annual rainfall amount) at low planting density. The farmer's cowpea cultivar (Dan-ilia) sown sole produced higher dry matter and was a more efficient water user than the introduced improved cowpea cultivars.

This study supports the need for the manipulation of the millet/cowpea and millet/sorghum/cowpea intercropping systems for better resource use and increased productivities. Appropriate suggestions for achieving these improvements are proffered.

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CHAPTER 1

INTRODUCTION

1.1 General

The arid and semi arid zone of Nigeria is vast and has a potential for increasing food production through judicious management of crops. The major crops adapted to this low rainfall region are pearl millet, sorghum, cowpea and groundnut. However, they are grown on soils low in water holding capacity and subjected to inadequate precipitation to meet evaporative demands of the atmosphere. The unevenness of seasonal distribution and high year-to-year variability of rainfall and deep percolation losses are additional stresses. They also suffer from high soil and air temperatures. The zone is defined in terms of rainfall limits, which range from 400 to 1000mm, and the average growing season length, varying from 60 to 150days (Figure 1.1a and b). The efficient use of the limited rainfall in this zone is therefore a crucial factor for future increases in crop production, which should come primarily from increased yield per unit area of land (Sivakumar and Wallace, 1991).

The crop water use problems in this region are not limited to rainfall, but also pertain to the use and abuse of the soil moisture reservoir. That water supply to the crop is a key to increasing production is not contestable, but the conservation of moisture by manipulating the environment on a micro and meso scale, the crop, or both, needs to be quantified in relation to improved system productivity. A major problem of the fragile land and environmental resources of the region is the limited knowledge of the technologies that would be appropriate to lead to such improved conditions under low or no external input situations.

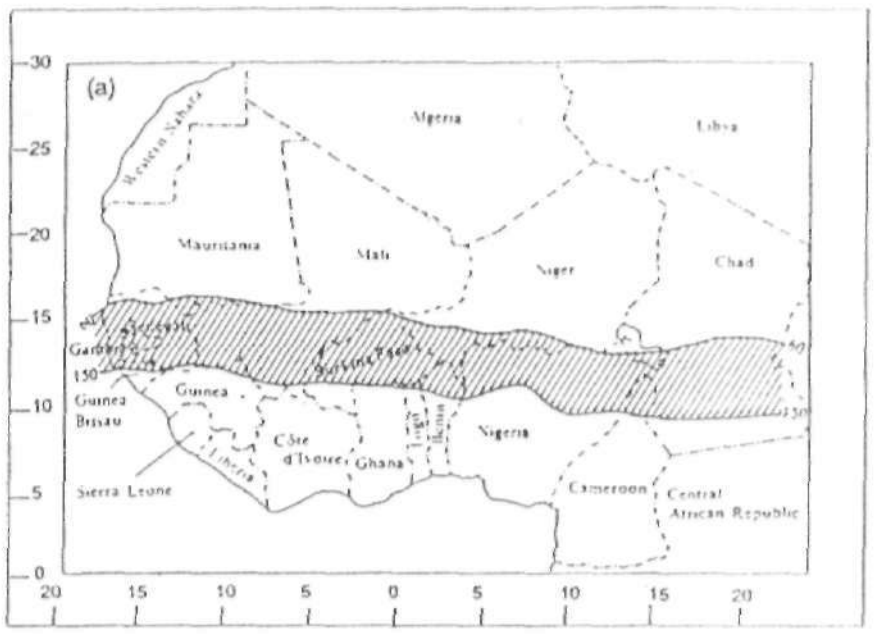


Figure 1.1(a) Geographical extent of the West African Arid and Semi Arid zone. Growing isolines of 60 and 150 days are shown (___). Reprinted from Sivakumar and Wallace (1991), (b) Map of Nigeria showing the Arid and Semi Arid zone. Reprinted from Ojanuga (1987).

Research on climatic data, water balance and microclimatic attributes of the complex cropping systems of this region has been grossly inadequate. Although some efforts have been made to quantify the soil hydrological characteristics (Kowal and Knabe, 1972; ICRISAT, 1984; 1989 and IAHS, 1991), the need for actual quantification of evaporation in this zone, with its implication for other ways in which water are lost, cannot be over-emphasised. While attempts have been documented on agronomic manipulations of intercropping systems for better productivity e.g. Fussell and Serafini, (1985); Ntare *et al.*, (1989); Nouri and Reddy, (1991); their actual water use and microclimatic quantification have received little or no attention. Studies have also questioned the claim of nitrogen transfer from the living roots of the legume component to the associated cereals as a basis for increased system productivity (Giller and Wilson, 1991). The interactions between plants below ground rather than above ground are suggested as important in causing the yield advantages recorded in intercropping (Snayon and Harris, 1981). Knowledge of the roles crop roots play in underground resource sharing and of their contribution to system performance are also lacking.

Research institutes such as the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria; The Institute for Agricultural Research (IAR), Samaru, Nigeria and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Niamey, Niger, have been looking into cropping system improvement in this zone for some years. IITA's main focus is now on the improvement of the cowpea component of the existing crop mixtures. Nigeria accounts for nearly 80-90% of the world cowpea production. Emphasis is given to the improvement of traditional cowpea varieties and for this purpose the IITA Kano sub-station was established in

1990, to represent the agroecological zone and cropping systems of several central and west African countries in the arid and semi arid region of Africa (Singh, 1992). ICRISAT with a sub-station in Nigeria at Bagauda, south east of Kano, has the mandate for sorghum, millet and groundnut improvement (ICRISAT, 1987), while IAR, Samaru, is part of the Nigerian National Agricultural Research System (NARS), with the mandate for genetic improvement of sorghum, groundnut and grain legumes and also the improvement of cropping systems in the North West of Nigeria.

A rapid assessment of different cropping systems in the sudano-sahelian zone of Nigeria was carried out by IITA from 1992 to 1994 with the aim of determining the crop varieties, the importance of these crops and the crop mixtures within the systems (Henriët *et al.*, 1994).

The cropping systems of the zone are cereal-based, and have evolved from shifting cultivation to intercropping (Beets, 1990). The systems are based on pearl millet (Pennisetum glaucum (L.) R.Br) and sorghum (Sorghum bicolor (L.) Moench). These cereals are predominantly intercropped with cowpea (Vigna unguiculata (L.) Walp) and/or groundnut (Arachis hypogaea (L.)) and occur in the fields in various mixtures. The cereals are mainly grown for consumption and cash. Cowpea is a dual purpose crop: the grain is used for human consumption and the remaining biomass serves as fodder for animals (Ntare, 1990). Some cowpea varieties are planted specially within the intercrops for fodder production, producing little or no grain, to take care of animal feeds during the dry season (Henriët *et al.*, 1994).

Due to increasing population pressure in several parts of northern Nigeria, the extent of fallow land for the traditional cropping system diminished to negligible

proportions and land holdings per individual reduced (Baker and Norman, 1975). Because of the intensification of land use over the years, there have already been long lasting changes in surface microclimate. Much of the drier lands has been stripped of woody vegetation, to provide fuel and fodder with regrowth coming up at a slow pace. Shallow ground water also suffered severe depletion in many areas (Hare, 1985). In densely populated regions, the fields near the residential areas are permanently cultivated with the level of fertility maintained in part through the application of organic manure from livestock and household refuse.

The use of high inputs such as chemical fertilizers and insecticides is being promoted by the government and its agencies, but the structural adjustment programmes presently diminish subventions. The seasonal increases in the prices of these inputs that rose earlier because of the decreasing value of the local currency, have caused a decline in the use of such inputs. Moreover, the generally unfavourable economic factors related to prices of agricultural produce are not encouraging the use of increased inputs either, while land use intensification continues.

In situations of such rapid changes, leading to new environmental hazards such as decreasing soil fertility, desert encroachment, increased climate variability, large scale migration into semi-arid environment, non-availability of labour in times of peak demands and introduction of new insect pests and parasitic weeds, there is need for better understanding of the traditional intercropping system (Stigter and Baldy, 1995). This would improve the possibility of mitigating these limiting factors, as well as make optimum use of the limited resources.

This work is done with the aim of contributing to the understanding of resource use, mainly water and its interaction with crop productivity, and to answer questions on the microclimatic aspects of the intercrop environment management. The farmer should be better informed on the current availability of environmental resources, and how to manage them more efficiently under the prevailing conditions of diminishing external inputs.

1.2 The TTMI-Project

The main objective of the Traditional Technique of Microclimate Improvement (TTMI) project is the building of national research capacity by post-graduate training. The approach involves Ph.D-degree research training at African universities using the 'PICNIC' model (Stigter *et al.*, 1995). This approach is aimed at increasing the basic understanding and subsequent use of indigenous technical knowledge (or concepts) of microclimate management and manipulation for solving local problems. It uses the mobilization of local expertise for developing local human resources and modest local capacity building in equipment in combination with available Wageningen Agricultural University (WAU) expertise when appropriate. The TTMI project is also aimed at contributing to the design and development of appropriate methodologies and equipment for environmental quantification under tropical conditions (Coulson and Stigter, 1988; Stigter and Darnhofer, 1988). There was a need for a more quantitative approach in studying the manipulation and management of microclimate applied as indigenous techniques, to use the results for improvement, transfer and dissemination, as applicable to local African constraints and conditions. The weather advisories resulting from this approach would be in suitable forms for adoption and

dissemination by extension agents to farmers (Stigter and Weiss, 1986).

The results of some African TTMI sub-programmes in dealing with rapid changes by the use of indigenous traditional technical knowledge and concepts have been discussed in numerous papers (e.g Stigter, 1990; 1994a, b and c; Mungai and Stigter, 1993; Mohamed *et al.*, 1995; Kainkwa and Stigter, 1993 and Onyewotu *et al.*, 1994) with appropriate weather advisories proffered .

In line with the above, this research work is done because of the identified major need for a better understanding of the traditional intercropping practices of the local farmers of northern Nigeria. Field work was done by quantifying the processes within the major cropping systems, with a view of validating the scientific content of local farmers' practice. The synthesis of such and other knowledge should be used to effect improvement on identified constraints within such systems.

The identification of the need for the work was carried out within the mandate of the IAR (ABU) at the Department of Soil Science, with the local TTMI-unit under the same umbrella of the Ahmadu Bello University (ABU), Zaria. One of IAR's main priority area of mandate is specifically in the area of integrating some legumes into farming systems for sustainable crop and livestock production in the savanna. This work was done in collaboration, through a memorandum of understanding, in what operated as an ABU/TTMI/IITA affiliation. In line with the TTMI-project approach, the affiliation at the national level also identified the need and started research on areas specifically, such as microclimate quantification of weed suppression aspects of cereals/cowpea intercropping systems and more generally on the development of a synthesis on the appearance of cropping systems in the northern part of Nigeria as a

result of changing land use. These choices are also in line with the Nigerian National food and environmental policies.

1.3 Nigerian food and agricultural research policy priorities

The Nigerian economy is heavily dependent on agriculture which employs more than two-third of its labour force. Owonubi (1994), in the synthesis of a consultant's report on the Nigerian Agricultural Research Strategy Plan highlighted the followings:

Agriculture as the backbone of the Nigerian economy contributed about 60% of the Gross Domestic Product (GDP) at independence in 1960, and up till 1970. Between 1971 and 1982, this sector experienced a steady decline in its contribution to national growth, with an all time low of 20% recorded in 1979, as a result of the wealth derived from the crude petroleum sales (oil boom). This decline was the result of price effects of the oil boom, as public expenditures were financed by oil revenues which were concentrated outside the agricultural sector. The Nigerian currency ('Naira') got appreciated, while wages were increased, reducing the ability of the agricultural sector to retain its labour force.

The government's introduction of the Structural Adjustment Programme (SAP) in 1986 brought new incentives to the agricultural sector as a result of the now depreciated value of the Naira. The resultant appreciable increases in producer prices of several crops, especially those with export potentials, brought positive growth in the agricultural sector of the economy. Agricultural production as a percentage of

GDP got a boost and was increased to 37% by 1992 (UNDP, 1995).

The Nigerian population, based on the 1991 population census is put at about 90 million people, with the age group 15-49 representing 35% of the total population. At the national level, only 17% of the people live in settlements with population over 10,000. In essence, the rural, mainly farming communities constitute the bulk of the country's population i.e 75-93%. The status of the rural population, and the projection of national population into the year 2000, given an annual growth rate of 2.9%, put the national population at about 129 million (UNDP, 1995).

The Federal Office of Statistics report covering 1970 to 1981 showed the progressive decline recorded in agricultural food crops production. Production of sorghum, millet, maize, rice, cassava, yam and cocoyam declined at an average annual rate of 1%, with a total aggregate decline of 50%. Crop production generally declined by over 60%, while agricultural exports of some commodities disappeared altogether.

The current and projected food demand outstrip supply, while national growth rate in the agricultural sector stands at about 3% as against the 5% target rate projected until year 2005. The price of crude oil, Nigeria's main source of foreign exchange, has also been on the decline in the international market. The fact that the country's oil resource is also being rapidly depleted makes agriculture the main sustainable lifeline for national development. Increased productivity per unit land area of the cropping systems through recommended improved management practices from

research findings would help alleviate hunger and sustain a steady economic growth.

Nigerian national policy on agriculture published by the Federal Ministry of Agriculture, Water and Rural Development, 1987, has as its objectives: the attainment of self-sufficiency in basic food commodities; increased production of agricultural raw materials for an expanding industrial sector; increased production and processing of export crops; modernization of agricultural production, processing, storage and distribution.

The strategies for attaining these objectives are addressed by the National Research Strategy Plan (NRSP). The current NRSP, covering 1995 through 1999, with a projection for the next 10 years thereafter, is aimed at ensuring the required agricultural research efficiency through:

i. provision of a long-term perspective for factors which influence the demand for agricultural products;
ii. giving a strategic research outline which harmonizes the long-term perspective and short-term government priorities;
iii. providing an authoritative and agreed framework for future investments to enhance the Nigerian agricultural research systems; and
iv. the identification of immediate and long-term needs for skills to support productive research.

There exist a total of 18 National Agricultural Research Institutes in Nigeria, amongst which 6 have the mandates for the genetic improvement and research into the

farming systems of the food crops, fruits and vegetables within the ecological zones of their locations.

The TTMI-Project research policy on environmental problem and protection issues fits in well with the NARP (e.g. IAR, Forestry Research Institute of Nigeria and National Agricultural Extension and Research Liason Services). The study on the microclimatic quantification of some traditional cropping systems of semi-arid Nigeria, with unpredictable weather conditions, was formulated as an urgent area of need, taking into consideration the above national agricultural policy. While meteorological data spanning over 50 years are available for more than 25 stations in the country, current data generation is largely confined to the airports. Detailed agro-climatological analyses are few and only limited to regional level. The intensification of efforts at improving and building of the national research capacity of the NARS is demonstrated by the IAR/TTMI/IITA affiliation to provide facilities for the development of manpower in the field of agroclimatology.

1.4 Objectives of the study and output

The broad objective of the study is to design (a) sustainable intercrop system(s) involving the major crops (cereals and legumes) of the arid and semi arid zone. Specifically, the study:

1. quantifies the changes in microclimate of sole cowpea, pearl millet and sorghum and their intercrop combinations and resulting contributions to their development, growth and yields;

2. assesses the relationship between the rooting patterns of the component crops in the intercrops, and their consequences on within season water extraction and seasonal nutrient balance;

3. quantifies above ground environmental resource sharing under sole and intercropping systems;

4. evaluates cowpea as a leguminous cover crop for its suitability to protect the soil; and

5. generates data that could be used as weather advisory for the zone.

CHAPTER 2

LITERATURE REVIEW

2.1 General

The arid and semi-arid zone of Nigeria lies approximately between 12^0 and 14^0 N latitude. It includes the Sokoto river and its tributaries to the west; and Hadejia river, its tributaries and the great plateau to the east. The Hausa plateau is fairly level, at elevation of 500-700 m above sea level. The zone has a high potential for the production of grain and livestock. Agriculture is essentially rainfed, and productivity is dependent on rainfall, adequate soil and crop management. The rainy season varies from 5 months in areas south of Kano to 3 months in the most northerly part towards the Niger republic. A study of the rainfall pattern in Nigeria over a 30-year period, from 1961 to 1990 (IITA, 1992), has suggested the following:

i. a steady shift southwards of isohyets at an annual level, emphasizing the need to re-examine the suitability of the crops being planted;
ii. shortening of the periods available for crop growth by nearly one month because of delayed onset of rains;
iii. higher rainfall intensities, but fewer wet days, emphasizing the need for impoved soil and water conservation methods, and
iv. trends enumerated above would create more drier areas and desert on the long run.

A proposal for strategic technology developments was suggested for dealing with the various aspects of possible adverse climatic impacts for the ecoregion.

The soils are generally deep and range from well drained to somewhat poorly drained. Soil clay and organic matter contents are low (Swindale, 1982; Spencer and Sivakumar, 1987).

While the favourable conditions for the production of legume (protein) crops and livestock, combined with a cereal diet, have contributed to the high population densities and relatively healthier population found in this zone when compared with other areas within the West African semi-arid region, periods of drought and other environmental disasters have also subjected this zone to severe pressures of basic survival.

The population in this zone is predominantly of the Hausa traditional cultivator and pastoral and settled Fulanis. The cultivation system was the rotational bush fallow in low population density areas, with millet occupying the greatest area. Groundnut, cowpea and sorghum were also combined in rotation (Morgan and Pugh, 1969). The exception are the densely populated areas around Kano, where land has been more intensely cultivated under intercropping and manuring practised over most important croplands (McCown *et al.*, 1979; Hill, 1972). Farmer practices re-cycle nutrients through the farming system as much as possible. The farming system is based on crop-livestock integration, involving the use of crop residues, especially those of the legume crops as animal fodder.

High premium is placed on livestock in this zone. Van Raaij (1974) reported that at least 85% of all rural households own livestock. Leguminous residues are

transferred to the compound at harvest, where they are fed to livestock which are tethered in the compound during the rainy season. The manure produced, together with compound waste, is returned to the field during the following dry season. During the dry season, livestock roam the field grazing cereal residues.

The Harmattan dust during the dry season is also reported to bring in some cations and micronutrients that enrich the fields for the next cropping season (Owonubi and Esu, 1991; Harris, 1995). Mϕberg *et al.*, (1991), observed from their work that the Harmattan dust is more basic in reaction when compared with the savanna soils in general. The dust has higher CEC, higher amounts of extractable phosphate and organic matter, but less extractable aluminium and exchangeable acidity than the soils on which it is deposited. Higher content of 2:1 layer silicate mineral and a lower amount of 1:1 layer silicate minerals and oxy-hydroxides of iron than the savanna soils are also attributes of the Harmattan dust.

Although earlier major population centers have existed in this zone, there has been a progressive growth stimulation through increase of commercial industries, easier accessibility by road and rail, and the 1970s oil boom in Nigeria. The increased growth in commercial cropping, with more intensification of land use, resulted in degraded soils with poor fertility status. Fallow periods were shortened, while manure and fodder became short in supply. These environmental degrading practices and the farmer potentials for risk lowering gave rise to the practice of inter-cropping. The term mixed cropping and intercropping have been used inter-changeably by various researchers to mean the same thing (Okigbo and Greenland, 1976; Willey, 1979; Ranganathan, 1993). Intercropping is described as one aspect of multiple cropping

which involves growing several species in the same plot during one year (Sinoquet and Cruz, 1995). Crop intensification is in both time and space dimensions, and involves intercrop competition during all or part of crop growth (Krantz *et al.*, 1975). Abalu and D'Silva (1980) reported 174 different crop mixtures, while sole crops accounted for only 17% of total cultivated average, despite all the efforts by researchers and extension workers to promote sole cropping. Farmers have limited natural resources, so they have limited capacity to stand failure in their production systems. Some level of risk is attached to their assessment of innovations, preferring incremental changes rather than radical departures from existing practices (Edwards, 1993). This confirms the belief that the existing cropping practices and rural community structure may be subject to manipulation but rarely, if ever, to replacement (Perrin, 1977).

2.2 Features of the traditional cropping systems- The traditional knowledge basis.

In the northern Nigerian savanna, cereal based intercropping systems are predominant. Pearl millet and sorghum are the major cereals, intercropped with each other and with cowpea and/or groundnut in various mixtures and arrangements (Buntjer,1971; Abalu, 1976; Norman *et al.*, 1981; Ntare, 1990; Henriët *et al.*, 1994). The dominant crop mixtures are millet/cowpea, Millet/sorghum/cowpea, millet/cowpea/groundnut, sorghum/cowpea and sorghum/cowpea/groundnut (Norman, *et al.*, 1981; Spencer and Sivakumar,1987; Henriët *et al.*, 1994). The cowpea component of the mixtures often consists of two types, i.e fodder and grain types that differ in growth habit and maturation period (Henriët *et al.*, 1994).

The general objective of the farmer is to achieve a sustained productivity of reasonable levels, with minimal risk, to satisfy subsistence and commercial needs (Beets, 1990).

From the studies on the traditional cropping systems in the sahelian part of Niger Republic (ICRISAT, 1987), and the sudan savanna of northern Nigeria (Henriët *et al.*, 1994), a clear understanding of the cropping systems and their features have emerged as follows:

i. The cropping season starts with land preparation, followed by the application of manure, and subsequent ridge making. Henriët *et al.* (1994) reported an average of 61% of farms sampled received manure application. The average rate of manure application is 4tons/ha. Land preparation is done manually with the aid of hoe or with implements drawn by bullocks. Land ridging starts early June, at the onset of rains, when the soil is moist.

ii. Pearl millet is planted immediately after ridges are made. The number of days available prior to the optimum date of sowing is very crucial. Based on Hargreaves (1975) definition of dependable rainfall as the amount received at 70% probability level, from the week such that, at that or higher probability, 10mm was received and this was followed by another week of that amount at that probability, the safe sowing date was estimated to be between 11 and 17 June for Kano area (Owonubi *et al.*, 1992). Ati's determinations of the onset dates for Kano using Kowal's and a modified Kowal's methods gave in 10 respectively 11 years of the periods 1961-1991 later dates (Ati, 1995).

In the sandy soil of the drier savanna, evaporation rate is generally high immediately following a rain (Wallace *et al.*, 1988). The efficiency with which sowing can be completed before water evaporates is a critical factor. In the sahel, Hoogmoed and Kliaj (1990) observed that the average number of days for successful sowing does not exceed 10 days after a sufficiently rainy day. The planting operation that follows land preparation is therefore a rapid one, and the use of animal traction is one of the ways to achieve this.

The ridging and planting of millet on the ridges has been shown to improve seedling survival compared to flat planting (Kliaj and Hoogmeod, 1987). In addition, ridging concentrates top soil fertility and organic matter on the ridge, increasing its availability to the seedling (Kowal and Stockinger, 1973). Rooting is improved in time and space, and interrow cultivation for weed control during the rainy season is easier. Interrow cultivation between ridges using animal traction is also facilitated.

iii. The pearl millet is traditionally sown manually in wide rows, with the aid of a long-handled hoe, in holes. The number of seeds sown in each hole is large and varies enormously. Henriët *et al.* (1994) observed 90-140 seeds per hole in the sudan savanna, while in studies conducted in the sahelian zone by ICRISAT, up to 400 seeds were found in a single hole/hill (Spencer and Sivakumar, 1987). Low seed germination (< 40%) is a major reason for high seed rate at planting (Henriët *et al.*, 1994), while the selection of the best stands at thinning is also a consideration. Traditionally, farmers sow at low population (5000-7000 hills/ha). The failure of early rains, and sometimes

wind erosion, may affect crop establishment. Farmers are often forced to repeat sowing, sometimes up to three times (Spencer and Sivakumar, 1987).

The distribution of rainfall determines farmer decision on when and how much of the second and/or third crop should be planted after millet. If there is an early season drought with a likelihood for millet survival, the density of the intercrop is reduced, or the sorghum component is eliminated. If, on the other hand, millet establishes poorly, the density of the second or third crop is increased (Fussell *et al.*, 1987). Millet emerges 3-4 days after sowing. In the millet/sorghum/cowpea intercropping, sorghum is sown between 3-10 days after millet, depending on soil moisture status. The sorghum is mostly sown as a replacement in the mixtures along the rows already planted with millet (Baker, 1979). Other arrangements of the millet/sorghum components also occur. The seed rate per hole varies from 20-50 (Henriët *et al.*, 1994). The cause of the delayed sowing of the sorghum component is the competitiveness of the local sorghum varieties. This is necessary to give millet a growth advantage (Andrew, 1974).

iv. The first weeding is done manually between 2-4 weeks after sowing of millet, with the aid of the hoe. The weeding operation reduces the extent of crust formation which could increase runoff and reduce water infiltration into the soil (Hoogmoed *et al.*, 1991). During weeding, the thinning of millet to 2-4 plants per hole/hill is done. Cowpea is sown immediately after the first weeding operation between rows of cereals (Baker, 1979; Sawadogo and

Kabore, 1985; Spencer and Sivakumar, 1987; Henriët *et al.*, 1994). Two cowpea varieties are usually sown:

(a) grain cowpea, for grain production, with early maturity, but low fodder biomass yield and,

(b) fodder cowpea for high fodder yield, but with low grain production and late maturing.

The grain cowpea is usually planted first, while the fodder cowpea is sown after some days. In some cases the fodder cowpea may be planted at the same time as the grain cowpea (Henriët *et al.*, 1994). Sowing of the cowpea component can be done either along or across the ridge. Sowing in the same row is not uncommon, e.g. millet is planted along the ridge, while cowpea is sown at regular intervals between hills of millet along the same ridge. As a result, cowpea occurs in every row of millet (Spencer and Sivakumar, 1987 and Henriët *et al.*, 1994).

v. The second hoe weeding comes up between mid and late July. Interrow cultivation is also carried out with the aid of animal traction, by richer farmers, to remould ridges and smoother weeds. Sorghum is thinned to 2-4 plants per hole/hill, while cowpea is thinned to 2-3 plants per hole/hill. In situations where the farmer has the financial means, some amount of chemical fertilizers is applied to the cereal component as top dress. In millet/cowpea intercrops, a third hoe weeding is not common, but may be done late August at millet panicle initiation. In the millet/sorghum/cowpea intercrop, a third hoe weeding is a necessity for the sorghum component to reach maturity without

much competition from weeds.

vi. The harvest of the millet component of intercropping is between late September and early October. Grain cowpea harvest also starts by mid September and lasts still mid October (Henriët *et al.*, 1994). The fodder type cowpea harvest starts after rain cessation and extends into early November. Where fodder cowpea produces some grains, picking is done before the biomass is cut at ground level and rolled into bundles. The cowpea biomass bundles are transferred to the compounds, where they are stored and later fed to the livestock (Plate 2.1a and b). Sorghum harvest is between late October and mid November.

In conclusion, the optimum time to sow and intercrop density are related to early soil moisture status. Labour requirement periods for farm operations are also time specific. The manipulation of the cropping system for better use of limiting resources and the use of animal traction are ways to meet these needs.

(a)



(b)

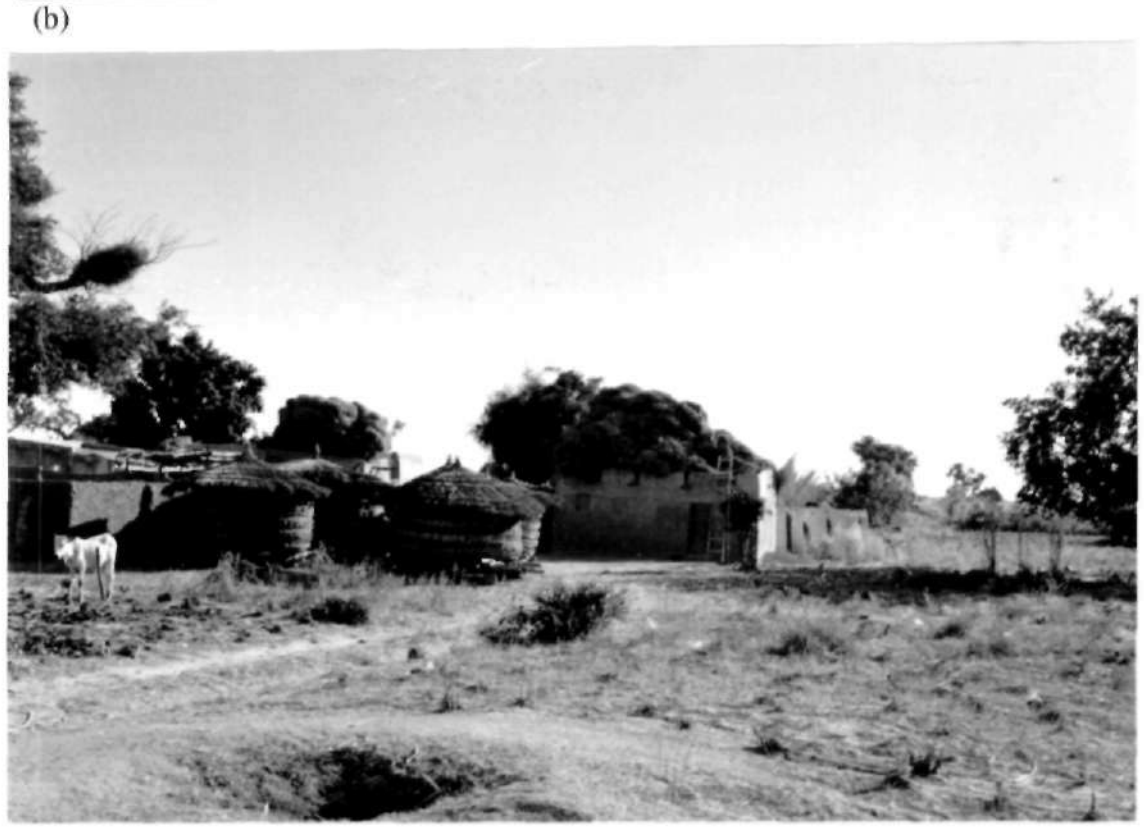


Plate 2.1 (a) A farmer transporting cowpea fodder home for storage to be fed to livestock during the dry season and (b) dry cowpea haulm stored on roof top and periodically fed to tethered livestock during the dry season.

2.3 Intercropping

Intercropping is defined as the growing of two or more crops simultaneously on the same area of ground. The crops are not necessarily sown at exactly the same time and their harvest times may be quite different (Willey, 1979). In terms of microclimate, intercropping can be defined as a traditional method of intensive farming in the tropics which attempts optimal use of available resources and prevailing conditions in the farming systems. These resources and conditions include an association of varieties of food and/or cash crops, land, nutrients, labour, water, solar radiation, other aerial weather conditions and socio-economic factors (Stigter and Baldy, 1995). Intercropping can be in different forms and can be described as mixed, row, strip or relay intercropping.

2.3.1 Basis for intercropping

Intercropping is a major Low External Input (Sustainable) Agriculture (LEI(S)A) cropping system in the developing world. This system of cropping is the consequence of an adaptation process between subsistence and near subsistence as well as the changing limiting factors of their environment (Baldy, 1986; Stigter *et al.*, 1992; Stigter and Baldy, 1995). The main features of the LEI(S)A are the small land holding of farmers and the entirely rain-fed agricultural production system. In Nigeria, some 25 years ago, about 55% of the farms were less than 1 ha, while about 90% were less than 4 ha (FOS, 1972). Increasing population density over the years is expected to have resulted in smaller sizes of farm holdings. The environment of the farmers is characterised by enormous variation, which is caused by the different manifestation of climatic effects and altitude (MacArthur, 1976).

The cropping system adopted in any location depends on tradition, level of technology, resources availability and physical environment. Farmers in the developing world have been growing two or more crops together on the same piece of land for reasons such as better exploitation of the environment, reducing risks, controlling weeds, spreading labour demand, and satisfying medicinal, dietary, fodder and some other requirements. The premise of intercropping is the spatial and temporal sharing of resources by crops in mixture. The crops have different heights and rooting depths or are making their peak demands on resources at different times.

The dominant crop mixtures in the Nigerian drier savanna are millet/cowpea, millet/ sorghum/cowpea, millet/cowpea/groundnut, sorghum/cowpea, and sorghum/cowpea/ groundnut (Norman *et al.*, 1981; Spencer and Sivakumar, 1987; Henriët *et al.*, 1994). In the Nigerian sudan savanna, cereals are dietary staples, complemented with cowpea as a protein source. Groundnut is sold for cash, while cereal stover is used as building material, fodder and for fuel. Cowpea and groundnut haulms are major sources of fodder.

There are several experimental results to show that intercropping leads to higher total yields per unit of land area when compared with sole cropping (de Wit and van den Bergh, 1965; Willey, 1979; Hiebsch and McCollum, 1987; Ntare and Williams, 1992 among others). Such advantages, which may be substantial, can be achieved, not by the use of additional costly inputs, but by simply growing crops together. In the subsistence situation, yield stability over different seasons is also a possibility (Willey, 1979). The concepts of Relative Yield Total-RYT (de Wit and van

den Bergh, 1965), Land Equivalent Ratio- LER (Willey, 1979), Area X Time Equivalent Ratio-ATER (Hiebsch and McCollum, 1987), Area Harvests Equivalency Ratio-AHER (Balasubramanian and Sekayange, 1990), Compensation Ratio-T (Ntare and Williams, 1992) and Production Possibility Frontier-PPF (Ranganathan, 1993) have been used to describe competition and yield advantages in intercrops.

2.3.2 Microclimate improvement and soil protection aspects.

Crop microclimate refers to climatic conditions within and just above a vegetation canopy. Microclimate in general is the climate in which plants, animals and pathogens live. It includes the climate in which agricultural products are dried, transported or stored, and is otherwise known as the biological climate (Rosenberg *et al.*, 1983). Crop response to its environment can be predicted based on the nature of the microclimate in terms of the regime of precipitation, solar radiation, air and soil temperatures, soil moisture, leaf wetness, air humidity, carbon dioxide and wind between the top of plant canopy and the soil near the surface (Monteith, 1975). The interaction between these environmental factors and crops constitute the crop environment (e.g Stigter, 1994a). The microclimatic consequences of intercropping in terms of agrometeorological explanations are becoming areas of interest in recent times. Over the last decades, interest has grown on the potentials of the management and manipulation of microclimate to protect the crop and its environment and improve yields (Stigter, 1988; Ong *et al.*, 1991; Stigter, 1994b; Stigter and Baldy, 1995). Increased attention to the microclimate of intercropping is mainly due to the awareness that progress in the field of agronomic research would be enhanced by a better

understanding of the microclimate of intercrops. It also contributes to explain why performances of sole crops situations are not sufficient to fully understand their performance in intercrops.

Yield advantage is obtained when particular cultivars are grown in such a way that they utilize limiting resources thoroughly and/or giving "services" that lead to yield improvements, and where annuals mature before the resources or other environmental factors become stressful. Yield advantage has for example been reported in an intercrop of millet and groundnut over their sole crops in a replacement (= constant densities) intercrop experiment, as a result of higher Photosynthetic Active Radiation (PAR) use efficiency (dry matter or economic yield/unit of light intercepted) of the intercrop (Reddy and Willey, 1981). Improved productivity per unit incident radiation can be achieved by the adoption of an intercropping system that either increases the interception of solar radiation and/or has greater Radiation Use Efficieny (RUE). Minimizing the proportion of radiant energy reaching the ground is a simple means of promoting efficient use of PAR (Keating and Carberry, 1993). Intercropping has also been reported to give a better Water Use Efficiency (WUE) than sole crop as a result of less evaporation losses from the ground (Reddy and Willey, 1981; Owonubi and Kanemasu, 1982). The higher WUE in intercropping can be a result of plant water status advantages caused by the above ground microclimate. However, this remains a speculation as long as such factors are not quantified (Monteith and Unsworth, 1990; Stigter and Baldy, 1995). Variation in plant density is known to have major effects on water-utilization and its efficiency. Natarajan and Willey (1980) observed that a variation of either sorghum or pigeon pea plant

densities affected intercrop WUE through effects on pigeon pea yield. Severe terminal water stress brought on by early water extraction from a limited supply under high plant population density was suggested as the reason for the negative WUE changes observed.

In terms of resource protection, the growth environment of component crops in an intercrop is often strikingly different from their sole crops. The nature and degree of the difference depend on the phenology of crops in association. Microclimate of an intercrop is modified when there is a large overlap in the active growth of component crops. For example, in a pearl millet/groundnut intercrop, Ong *et al.* (1991), observed that within the total intercrop duration of 80-105 days, the onset of linear growth rate was between 35-40 days for both crops and the overlap lasted for 40 days. Fukai and Trenbath (1993) suggested that the modification of the environment may have a significant impact on the growth and yield of crops. One of such obvious modifications is in an intercrop where a short statured component is shaded by a taller one with consequent reduction of the former's captured PAR and thus a (sometimes temporal, till the harvest of the taller crop) reduction in growth and yield of the shorter crop. The taller crop may provide a shade which also modifies other environmental conditions, such that the changes may benefit the shorter component crop. A reduction of air temperature under shade may favour the growth of the shorter crop, especially when the ambient temperature in the sole crop situation is supra-optimal (Midmore *et al.*, 1988) or when the sole crop is water stressed (Harris and Natarajan, 1987). High soil temperatures enhance the rate of organic matter decomposition, facilitate crusting and land setting and accelerate laterization,

Crop growth and yield are reduced by high temperature through the curtailing of the growth and development of roots, reduction of nutrient and water availability, uptake and translocation (Cassel and Lal, 1992). Since the soil surface under an intercrop may not be exposed as in the sole crops, evaporative loss from it may be reduced such that moisture of the surface layer is often higher during drying cycles under intercrops than sole crops (Midmore *et al.*, 1988). Ensuring good ground cover by intercropping can reduce run-off and increase infiltration (Olasantan, 1988). Increased earthworm activities as a result of reduced soil temperature also increases infiltration rate in intercrops (Hulugalle and Ezumah, 1991). Singh *et al.* (1986) have reported greater population of active bacteria under maize/legume intercrops as a result of reduced soil temperature and improved moisture condition. An increase in the number of rhizosphere bacteria, which are associated with higher total nitrogen and potassium uptake was reported in an intercrop of maize with 'Egusi' melon (Wahua, 1984). These are all examples of consequences of "services" rendered, causing improvement in soil surface conditions.

In the moist savanna zone of Nigeria, a demonstration of resource and companion crop protection is the relay intercropping of sorghum with yam (Dioscorea spp). The sorghum sown earlier in the season protects the ground from adverse environmental effects, such as erosion and high direct solar radiation, while it provides mulch and suppreses weeds. The yam is planted a few weeks before sorghum harvest. Sorghum leaves are used as mulch for yam, while the stalk of sorghum serves as a support pole for yam, allowing more solar radiation on the leaves of the climbing stem (Okigbo and Greenland, 1976). A similar experience with yam relay cropped in

leucaena was reported (Anon, 1984). The reduction of soil temperature under a sorghum/groundnut intercrop is indicated to have favoured the performance of sorghum because of a reduced density of Striga hermonthica- a parasitic weed with a high optimum temperature requirement for germination (Carson, 1989). In a millet/cowpea intercrop in Mali, the cowpea ground cover was also associated with a marked reduction in soil temperature and consequent reduction of Striga hermonthica shoots in the intercrop when compared with the sole millet (Webb *et al.*, 1993). Intercropping is known to render services such as reduced pest attacks on component crops (Perrin, 1977). This service could be through :

(i) diminishing visual and other attractiveness by the presence of companion crop(s),

(ii) creating unsuitable microclimate for the pest and/or favourable ones for predators and parasites, and

(iii) forming mechanical barriers to dispersal and acting as diversionary or trap crops.

The competitive ability of component crops is also important when considering environmental modification aspects of intercropping. For example, legumes which are commonly suppressed by an associated cereal crop under high N condition may become more competitive under low nitrogen conditions (Ofori and Stern, 1987). When growth is limited by the availability of a particular resource, the ability of a component crop to gain better access to the resource determines its competitiveness. The need to specify the limiting environmental factor(s) under which crops grow for sufficient understanding of yield advantages occasioned by the modification of the

microclimate, therefore needs to be emphasised (Stigter and Baldy, 1995).

2.3.3 Intercropping yields and yield advantage analysis.

The above may be summarized in terms of yields advantage in that the increased system productivity in intercropping is understandable if the nature of interactions between component crops in mixtures is known. Plants compete for environmental resources, which may lead, in general, to a reduction in plant growth and performance of intercropped species. However, studies have shown that greater productivity from intercrops were recorded than when component crops were grown alone (with a total intercrop densities comparable to those of sole crops). The examination of biophysical factors and their relationships have shown that greater and better exploitation of resources may be suggested as basis for the higher yields of intercrops (Willey *et al.*, 1986). Crops differ in their use of growth resources in such a way that they may complement one another. Such studies have shown improvement in the amount of dry matter formed per unit radiation intercepted (Hang *et al.*, 1984), greater nutrient uptake (Wahua, 1984) and improved water use (Grema and Hess, 1994). The population dynamics of intercrops also affect the level of interaction between crops. An understanding of the effects of competition began with a study of those reactions of plants to density which determine crop yield in mixtures depending on experimental design (de Wit, 1960).

Models of competition and the index which expresses the results of mixed cropping in terms of relative yield total by de Wit and van den Bergh (1965), helped in gaining some insight into the nature of niche differentiation in natural systems. The effects of total density were also being separated from proportion (Spitters, 1980).

Total plant density and species proportion are known to influence competitive relationships in crop mixtures and hence, the interpretation from replacement series and the additive arrangements experiments.

Relative yield is described as the mixture yield as a fraction of sole crop yield at the same management level. The relative yield total (RYT) is the sum of the relative yields of the species in the mixture. RYT of a two component intercropping can be represented as follows:

$$RYT = (y_{ab}/y_{aa} + y_{ba}/y_{bb}) \qquad (2.1)$$

Where y_{aa} is the yield of component a as sole crop; y_{bb} is the yield of component b as sole crop; y_{ab} is the yield of component a as intercrop grown in combination with component b and y_{ba} is the yield of component b as intercrop grown in combination with component a. The value assumed by the RYT indicates whether the species are performing better in mixture than in sole crops, but only for that particular total density, e.g. RYT equals unity if in a replacement experiment crops are not influencing each other, or if the gain by one crop causes equivalent loss by the other. RYT greater than one shows some levels of complementarity in resource use between species involved and thus a biological advantage of the intercrop. Negative RYT value, can for instance, be the result of allelopathic effects that may exist to the extent that one species may 'poison' the other.

Another concept is the land equivalent ratio- LER (Willey, 1979). LER serves as a basis for assessing yield advantage in situations where yield advantage in a mixture can occur without exceeding the yield of the higher yielding species. A yield

advantage can occur if the mixture produces more yield from a given area of land than can be obtained by dividing that area of land into pure stands of the two species. LER is defined as the relative land area under sole crops required to produce the yields achieved in intercropping. LER does not assume that the total crop densities are constant as the case may be with RYT and is used more in assessing yield advantage from additive experiments. LER can be represented as follows:

$$LER = \sum_{i=1}^{n} (y_{ij}/y_{ii}) \qquad (2.2)$$

Where y_{ij} is the yield of the i^{th} component from a unit area of the intercrop j, y_{ii} is the yield of that component grown as sole crop over the same area and n is the number of crops in association. The LER is popular because it has few restrictive conditions for its use and puts different crops, irrespective of their level of yield, on a comparable basis. The main limitation of LER as a measure of competition or yield advantage is that of interpretation, because effects of total plant density and a high density of one crop on the other are compounded, i.e the proportional composition and the density of the mixture and their effects are completely confounded, thus effecting the formulation of cropping recommendations (Trenbath, 1976; Spitters, 1980). The use of LER therefore requires the choice of a standard sole crop yield obtained at optimum density (Willey, 1979).

The fact that LER does not include a time factor gives it the tendency to overestimate the advantage of intercropping, especially when component crops differ greatly in their maturity time. LER assumes that the land which an early maturing crop occupied would not be used after its harvest until the harvest of the late maturing

crop. This limitation of LER is eliminated when the yield production per day is used (Hiebsch and McCollum, 1987). This concept is called the Area X Time Equivalent Ratio (ATER). ATER can be expressed as:

$$\text{ATER} = \sum_{i=1}^{n} [(t_i^i/t_i) \text{ X } (y_{ij}/y_{ii})] = \sum_{i=1}^{n} (t_i^i/t_i) \text{ X LER} \qquad (2.3)$$

Where t_i^i is the duration of crop i in monocropping, and t_i is the total duration (days) of an intercrop system. The concept of ATER allows for the adjustment of relative yield of a short duration crop in accordance with that of the late maturing crop. The limitations of this concept are its likelihood of an underestimation of the advantage of intercropping when crops differ in growth duration, e.g like when a crop is not planted immediately after the harvest of a preceding crop and thus result in a loss of time in terms of biological productivity in sole cropping. In the semi-arid zone of West Africa, the possibility of having double crop in sole cropping is not feasible, with the cropping systems in practice, but it may be possible to have a long duration crop intercropped with a short duration crop. Hence, LER would be more appropriate for yield advantage assessment in semi-arid areas.

In areas where a long growing season is interrupted by a short dry period, the concept of Area Harvest Equivalency Ratio (AHER) is proposed (Balasubramanian and Sekayange, 1990). During the growth of the long duration crop, a short duration crop (j) may be grown m_j times. The total yield of that crop in sole cropping is the product of sole crop yield (y_{s_j}) and m_j, and this is used as a basis of assessment.

$$AHER = \sum_{j=1}^{n} [\, y_{i,j} \,/(y_{s,j} \,.\, m_j)]. \qquad (2.4)$$

Ntare *et al.* (1992), used the concept of Compensation Ratio (T) to assess the competitive effect of cowpea cultivars on millet yield in a millet/cowpea intercropping situation in the sahelian region of Niger republic. T in this situation is defined as the ratio of the cowpea yield in a treatment to the loss of millet yield as a result of competition from the cowpea. T is expressed as:

$$T = C_i / (M_s - M_i) \qquad (2.5)$$

Here C_i is the yield of cowpea in the i^{th} treatment, M_s is the yield of sole crop millet and M_i is the yield of millet in the i^{th} treatment. A large value of T indicates that the competitive effects of cowpea on the millet were balanced by substantial gains in cowpea, while a value of unity indicates mere substitution of cowpea for millet.

The concepts enumerated above are applicable only for the comparison of crop productivity at a particular season, while no long term effects of various intercropping practices are considered (Fukai, 1993). The costs of various cropping systems, food values of individual crops and market values of crops, among other factors, are others which may be important, but not considered in the methods mentioned above.

Economic analysis has not contributed much to the evaluation of productivity in intercropping. The inappropriateness of economic parameters as a tool for evaluation is mainly due to seasonal price fluctuations of inputs and lack of a cash economy in most areas where intercropping is practised (Beets, 1982). An attempt at

solving this problem is the use of the concept of Production Possibility Frontiers; PPF (Ranganathan, 1993). PPF are curves from economics which assess yield advantage in intercropping by building on the biological processes underlying intercropping. This concept also lends itself readily to economic interpretation and contributes much to an economic evaluation of yield advantages from intercropping. A production function gives mathematical expression to the relationship between quantities of inputs employed and the output produced. This functional relationship is based on an examination of the many alternative ways in which inputs can be combined to produce any given output, and a selection of the most efficient way of using inputs. The PPF is thus the maximum output obtainable from every possible input combination (Henderson and Quandt, 1971). The difficulty with estimating a production frontier empirically from experimental data is one of ascertaining that the fitted curve corresponds with the frontier. This problem is easily solved by deriving the frontier from a prior knowledge of the biological processes that determine the outcome in intercropping. The hyperbolic relationship between biomass yield and plant density, and the parameters that characterize the degree of intra- and inter-specific competition in intercropping are used to derive a PPF. PPF can be adjusted for economic factors affecting production because of its flexibility. It also imposes few restrictions on the parameters under consideration and its application covers results from different kinds of trials.

2.4 Agrometeorology and soil factors affecting intercropping

Agricultural meteorology/agrometeorology used to be described as that branch of science relating climate to vegetation and farm operations (Smith, 1920). The study and application of relationship between meteorology and agriculture involves the efforts at solving problems related to the timing of crop sowing, pest and diseases incidence and prevalence among others.

Micrometeorology and agrometeorological knowledge can be used advantageously for increasing and stabilizing crop production in different environments (Stigter and Weiss, 1986; Stigter, 1994a). These contributions can take the form of weather forecasting for agriculture, agrometeorological forecasting (WMO, 1981) and weather advisories (Stigter, 1984b). The issue of weather advisory refers to production advisories with reference to the use or modification of meteorological conditions in or close to the space occupied by crops, animals or their products and the effects of such advisories on the quantity, quality and protection of crop and animal productivity (Stigter and Weiss, 1986).

A strategy for stabilizing or maximizing long term yield requires basic information about the climate, soils, crops and farming systems of any area as well as the traditional and potential crop environmental management. The relationship between meteorological data and management must be evaluated with respect to crops being grown and the soil in which they are being sown.

2.4.1. Agroclimatic factors

In northern Nigeria, rainfall distribution and soil fertility are the crucial

limiting factors in agricultural production. Soil is the medium in which the plants express their response to microclimate at a given location. Although climate is one of the active factors and most dominant too in the process of soil formation, its effects are modified by other factors to give rise to a variety of individual soils in any given climatic region (Brengle, 1982). Climate and soil are intimately related to determine the potential for exploiting a given environment.

In semi-arid Nigeria, the weather is regulated by the movement of two pressure belts, i.e. the equatorial low pressure belt and the sub-tropical high-pressure belt, which are narrow bands of strong winds bounded by slower moving air called 'jet streams'. These pressure belts have great influence on the dry tropical air and the humid equatorial air, and the InterTropical Convergence Zone (ITCZ) between them. The ITCZ moves following the earth's position relative to the sun at its zenith. In association with the sun's apparent movement, the ITCZ advances and recedes. The characteristic movement of the ITCZ in the northward direction and the disturbances associated with it, bring summer rainfall to northern Nigeria. On a large scale, the rainfall pattern shows some level of regularity because of the geographic uniformity of the zone. Several modifications are often introduced as a result of regional variation in relief, relative areas under land and water, and other parts of the general circulation. In mountainous areas, windward slopes favour the lifting of air and heavy incidence of rainfall. The rainfall period in this zone is between 3 to 5 months. Rainfall in the Nigerian semi-arid zone is uni-modal and ranges from 400-1000 mm, decreasing in amount northwards. The rainfall pattern is variable and undependable, and often characterised by its irregularity and variability. The coefficient of variation of annual rainfall is between 20 and 30% in a similar environment in Niger, thus

adversely affecting agricultural production in such dry arid region (Sivakumar *et al.*, 1992). After the rains, the dry season arrival is marked by the hot and dry continental wind ("Harmattan") in October/November and last until May. A major characteristic of the Harmattan in the West African region generally is that of erosion and transportation of fine powdery dust.

Seasonal changes are represented by the wind patterns: Harmattan winds blow from the desert areas northeast of the region during the dry season and those from the monsoon regime bring humid winds from the Atlantic Ocean and equatorial Africa to the southwest during the rainy season. The location of this zone ensures abundant sunshine with global radiation input of 400-500 W m^{-2} averaged over 12hrs, with relatively low seasonal variation (Yayock and Owonubi, 1986). Radiation loads are at their peak before and after the rains and have a maximum during this dry season. Quantitatively, overall growth and the various phases of development can be related to the amount of energy represented by temperature (Konate, 1984). In the area, temperatures are high, with high values (> 35^{0}C) at the onset of rains, but moderately warm temperatures (20-25^{0}C) during the period of water availabilty (rainy season) for crop development and growth.

2.4.2 Soil Factors

The Nigerian semi-arid landscape is gently sloping with occasional outcrops of rock. The major soil forming rocks have been identified to include granites, gneiss, sandstones, clays shists, pyroclastic rocks and basalt (Aitchison *et al.*, 1972). Others

include ancient alluvium, lacustrine sands, lagoonal clays, aeolian sands and recent alluvium (Maduakor, 1991). The predominant parent material is made up of aeolian, alluvial and lacustrine sediments deposited over older sediments or on the basement complex rock or sedimentary rocks (Ojanuga, 1987). Aeolian deposits constitute the most extensive parent material in the zone. Ojanuga (1987), using the USDA soil survey legend of 1975, further classified these soils as mainly Entisols and Inceptisols, although Alfisols, Vertisols as well as hydromorphic and halomorphic soils also occur in the zone. The Inceptisols and Entisols are formed on aeolian deposit. Typic Ustipsamments are the commonest Entisols, while among the Inceptisols, Typic Ustropepts are dominant. The soils are generally light and sandy in nature with not well defined profiles, and low fertility status. Soil organic matter, available phosphorus, total nitrogen and the cation exchange capacity are all low (Spencer and Sivakumar, 1987; Fussell *et al.*, 1987). The clay type is mainly kaolinitic and often associated with free iron and aluminium oxides (Maduakor, 1991).

In terms of soil physical properties, the soils have poorly developed structure which deteriorates with cropping and compaction (Ojanuga, 1987; Hoogmoed and Klaij, 1990). The soil aggregates are small and unstable in wet conditions, with a tendency to pack early in the wet season, owing to the impact of rain drops and/or cultivation. Soils are deep, especially those derived from aeolian deposits, but the poor structure of aggregates limits the available water held in the soil. The texture ranges from sandy to very fine sandy loam (Iwuafor *et al.*, 1980). Because of their sandy nature, the consistency of the soils is non-sticky and non-plastic when wet and friable to very friable when dry (Ohu *et al.*, 1989). The bulk density of the soils of

the zone ranges from 1.5 to 1.8 g cm^{-3} and can increase as a result of soil compaction (Maduakor, 1991). The infiltration rate of a soil is one of the major factors influencing runoff and water balance and is greatly influenced by the physical conditions of the soil, which in turn depends on soil texture, soil organic matter, plant cover and the soil biota. Runoff or deep percolation may occur depending on slope, bulk density and total porosity. Kowal and Knabe (1972), reported infiltration rates of 2-25 cm h^{-1} for an Argiustoll of sandy loam texture. In north east Nigeria, steady state infiltration rates varying from 7.2 to 22 cm h^{-1} with a mean of 13.5 cm h^{-1} have been reported (Folorunso, 1986). Infiltration generally decreases as the soil texture gets finer.

Although runoff for the drier savanna zone soils of Nigeria is rare, the soils are prone to wind erosion when dry and bare. Infiltration and redistribution of rainfall on the soil of semi-arid regions of West Africa have been reported to be very rapid, while runoff losses are indeed very low (Hoogmoed and Klaij, 1990).

The moisture retention characteristics of a soil determine the amount of moisture that is available for extraction by plants. The ability of a soil to retain water depends on porosity and pore size distribution and these depend on the degree of soil development, soil structure, soil texture, parent material, organic matter content, biological activity, and soil management. Although there is a dearth of research information on the moisture storage characteristics of soils of drier northern Nigeria, there is a general tendency for soils with finer particles to hold appreciable amounts of moisture between field capacity and wilting point (Maduakor, 1991). The root zone water storage in a millet/cowpea intercrop grown on a Typic Ustipsamment with aeolian sand formation, loosely aggregated and with a sandy loam texture, in north

east Nigeria, reached a maximum of about 200 mm at the peak of the rainy season in August (Grema and Hess, 1994).

2.4.3 Soil Moisture

Soil water storage in the semi-arid tropics is crucial for agricultural production. The maximum proportion of rainfall which enters the soil moisture reservoir determines the possibility of its subseqeunt use by plants. The annual rainfall of the Nigerian arid and semi-arid zone ranges from 400 to 1000 mm. The shortage of water therefore is not always a consequence of poor annual rainfall, but more of that of human settlement, particularly for agriculture i.e in terms of the seasonal distribution of rainfall (Sivakumar and Wallace, 1991) and the rate at which water is lost by evaporation (Monteith, 1991). Plants are able to extract water from soils at water contents above in situ field capacity to the wilting point.

For any defined hydrological unit, conservation of mass requires that the input of water over a given time must precisely be balanced by the loss of water and/or by the change in the amount of water stored within the unit. The balance can be written as:

$$P + I = ET + \blacktriangle S + D + R \qquad (2.6)$$

Where P is precipitation, I is irrigation, ET is evapotranspiration, $\blacktriangle S$ is change in soil water storage, D is deep drainage and R is runoff (-) or runon (+). In practical terms, equation (2.6) is better expressed as:

$$P \pm R \pm E - T_w - T_c \pm \blacktriangle S - D + I = 0 \qquad (2.7)$$

In equation (2.7) the term ET has been separated into three components: E is loss by evaporation from the soil or gain by dew, T_w is transpiration from weeds and T_c is transpiration from crops. From equation (2.7), change in soil water storage ($\blacktriangle S$) can be expressed as:

$$\blacktriangle S = P + I \pm R \pm E - T_w - T_c - D \qquad (2.8)$$

The quantities in the expressions above are presented each as an equivalent depth of water per unit time, e.g mm day^{-1}. The objective of soil and crop management practices is to minimize losses by R, E, D, and T_w while optimizing T_c. Too high T_c may be injurious to plant as well.

2.4.3 (a) Soil water determination

Soil water content is an important aspect of the plant environment. The nature of the soil and its water holding capacity give useful information about the distribution of soil water and its availability to the plant. The main physical factors controlling soil moisture storage are adsorption, osmosis and capillarity; while soil water movement is controlled by the soil infiltration capacity, redistribution of moisture, drainage, evaporation and water uptake by plant roots. The soil layer under consideration for soil water quantification is that which interacts with the atmosphere through evapotranspiration, i.e. the top soil, and occupied by the plant root zone. This soil layer is generally 1-2m deep and depends on the stage and the type of plant cover

(Schmugge *et al.*, 1980). Monitoring soil water content serves as a useful tool for assessing crop performance and productivity.

Several methods and techniques are available for soil water quantification. Some methods make direct water measurements e.g. gravimetric method, while others are indirect and require calibration to show the moisture situation in the soil e.g the neutron probe, time domain reflectometry, and instruments determining soil water potential.

2.4.3 (a) i.Gravimetric soil moisture determination

In this method the water content of the soil is measured by oven drying samples at 100-105°C until there is no further change of weight for about 24 hours. The soil moisture content is taken as the difference in the sample weight before and after drying, expressed as a percentage of the sample dry weight. For agricultural conditions, replicate soil moisture samples are essential to obtain representative data (WMO., 1968). Although labour intensive, the gravimetric method is the simplest and particularly if known volumes are used, it serves as the standard method for calibration of other methods (Rawlins, 1976; Vachaud *et al.*, 1977).

The soil water determined through this method on weight basis is expressed as:

$$G = (W_w/W_s) * 100\ \% \qquad (2.9)$$

Where G is the water content expressed as a percentage, on dry weight basis, W_w is the weight of water removed from soil by drying and W_s is the weight of the dried

soil. To convert G to volumetric water content (Θ), the value of G is multiplied by the soil bulk density (Bd_s).

$$\Theta = G * Bd_s \ \% \qquad (2.10)$$

While this method is cheap, easy to calculate and not affected by changes in chemical and physical properties of the soil, the sampling procedure is destructive, making repetitive point measurements impossible. It is labour intensive and requires a power supply source for accurate weight records and oven drying of samples.

2.4.3 (a) ii. Neutron probe method

The neutron meter is designed to measure *in situ* the volumetric soil water content and its change in time and space. The neutron probe method is an advanced technique in the study of soil water in agriculture, forestry and environmental science and can form a central part of an inter-related set of measurements of such diverse quantities as plant water use, ground water recharge, soil hydraulic properties and changes in the landscape water balance (Williams *et al.*, 1981). Several researchers have used this method in the semi-arid zone of West Africa for soil water balance studies (Klaij and Hoogmoed, 1987; Payne *et al.*, 1991; Garba and Renard, 1991; Ibrahim, 1992 and Grema and Hess, 1994). This method of soil moisture determination is a non-destructive field method based on the slowing-down by water of fast neutrons emitted by a radioactive source. A count of the slow neutrons in the vicinity of a source of fast neutrons provides a means of measuring the hydrogen content of the soil. In most agricultural soils, water is the only significant source of

hydrogen. The actual measurement is made by lowering a probe consisting of the source and a detector to the required depth in a suitable access hole in the ground; the reading is indicated on a scale or a rate meter (Greacen, 1981). The calibration of the probe is done by obtaining the readings of the instrument for a range of accurately determined values of volumetric soil water content. The calibration will result from using the regression of count rate ratio (Cr) on volumetric water content (Θ).

$$\Theta = a + b*Cr \qquad (2.11)$$

Where Θ expressed in $cm^3\ cm^{-3}$ is the volumetric water content of free water, a is the regression constant (intercept), b the slope (regression coefficient) and Cr the count rate ratio (measured counts at known depth in the soil/counts in a stardard medium e.g water).

Count rate depends largely on O, but it is also affected by other soil properties, such as the soil dry bulk density, the volumetric content of constitutional hydrogen, i.e. equivalent water, and various other chemical components of the soil and the soil solution (Greacen *et al.*, 1981). Soils contain hydrogen atoms other than those in free water as constitutionally bound hydrogen, in the clay minerals and in organic matter. This hydrogen has been shown to affect neutron response in essentially the same way as the free water in the soil, and it is commonly expressed as bound or equivalent water Θ_e ($cm^3\ cm^{-3}$) (Greacen *et al.*, 1981). Thus a correction for high clay and organic matter content soil is necessary. In field conditions, where soil profile density varies greatly, the effect of bulk density on neutron response would give rise to a calibration error if not given an attention. Density affects the count rate at

constant total water content through its effect on neutron flux caused by a change in the concentration of soil atoms other than hydrogen. In the soils of the Gezira irrigation scheme of Sudan, an increase of 40% in the slope of the neutron probe calibration curve was obtained for an increase in soil bulk density from 1.0 to 1.7 g cm^{-3} (Ibrahim, 1992). Greacen and Schrale (1976) proposed the use of the empirical relationship that count ratio at constant total volumetric water content is proportional to the square root of bulk density to correct for dry bulk density effect. The correction was found to increase the correlation coefficient of the count ratio on soil volumetric water content. The presence of strong absorbers of thermal neutrons in soils, such as boron, chlorine, iron and gadolinium has been shown to give rise to gross errors in neutron probe calibration (Nicolls *et al.*, 1977) as cited by Greacen *et al.*, 1981). Inaccuracy of neutron probe calibration is avoided when data from different soil layers are treated separately.

For the measurement of water closer to the soil surface, the radius of response of the neutron meter extends above the surface, especially in loose sandy soils, resulting in the escape of neutrons to the atmosphere, under-estimation of Θ and creation of possible health hazards for the users. The use of gravimetric soil sampling methods for the surface 0-30cm is recommended (AWRC, 1974), and more recently Time Domain Reflectometry (Dasberg and Dalton, 1985; Dalton, 1987; Topp, 1987), a method based on the dependence of the dielectric properties of water content, which can be followed by measuring electric capacitance.

2.4.3 (b) Soil infiltration rate

Infiltration is the dynamic process of water crossing the soil-air interface (Hoogmoed *et al.*, 1991). The infiltration rate depends on soil characterics and the rainfall and runoff/runon intensity. As we have seen, the semi-arid zone of Nigeria is characterised by erratic and intense rainfall and soils which are generally light, poorly structured and unstable. The major rainfall parameters that influence infiltration capacity of the sandy textured soil of this zone include the rainfall intensity and storm duration. The soil factors are the soil surface conditions e.g slope, the runoff and runon rates, rainfall intensity threshold for runoff and the soil surface water storage capacity (Lamachère, 1991). The infiltration capacity of undisturbed soils of low activity clay types under natural vegetation cover in the semi-arid region is high, but with cultivation the infiltration rate decreases as a result of surface crusting and reduction of macropores (Cassel and Lal, 1992). The measurement of soil infiltration rate can be done in two ways:

- by ponding/flooding: water is applied to the surface without any kinetic energy,
- using rainfall: water is applied as drops.

The most common method used to measure surface infiltration rates is the cylinder infiltrometer: a metal cylinder, inserted a small distance into the soil (Hoogmoed *et al.*, 1991). For a ponded water situation, the double ring infiltration method, using, two concentrically placed rings, is prefered. Measurements are made on the rate at which the water level within the inner ring falls, while water infiltrating into the soil between the two rings ensures one-dimensional flow (FAO, 1979). Since the inner cylinder can be quite large ($\geq$ 30 cm diameter), the result obtained is

acceptable and accurate. This method is simple and cheap, since the cylindrical ring can be fabricated locally. The deep sandy soils of the ICRISAT Sahelian Center (ISC) in Niger have been reported to maintain very high infiltration rates (30 cm h^{-1}) on cultivated plots and very low runoff of about 1% (Hoogmoed *et al.*, 1991). The infiltration rate of topsoil in the Watari valleys of Kano State shows a range of 4 cm h^{-1} for the clay loam texture to 34 cm h^{-1} for the loamy very fine sand soil (Anon, 1981). In north east Nigeria, steady state infiltration rates varying from 7.2 to 22 cm h^{-1} with a mean of 13.5 cm h^{-1} have been reported (Folorunso, 1986).

2.4.3. (c) Deep drainage

The soils of Nigerian semi-arid zone are deep, especially those derived from aeolian deposits, but the poor structure of aggregates limits the available water held in the soil. Most of the soils are sandy and quite permeable, because of the presence of large and continuous pores (Sopher and Baird, as quoted by Owonubi *et al.*, 1991); and have a textural range of sandy to very fine sandy loam (Iwuafor *et al.*, 1980). The consistency of the soils is non-sticky and non-plastic when wet and friable to very friable when dry (Ohu *et al.*, 1989). The bulk density of the soils of the zone ranges from 1.5 to 1.8 g cm^{-3} and can increase as a result of soil compaction (Maduakor, 1991). The high infiltration rate makes deep drainage a very important component of the water balance studies. Deep drainage can be defined with reference to the depth of maximum root penetration as the soil water that is lost (drained out) beyond the root zone (Payne *et al.*, 1990). Although direct measurement of deep drainage loss is very rare in literature, it is often calculated from all the other terms of the water balance (equation 2.2).

Various soil water balance studies, especially in pearl millet-based cropping systems in the semi-arid areas of West Africa, have assumed that no drainage took place because of the low amount and poor distribution of annual rainfall (Dancette, 1971; Azam-Ali *et al.*, 1984; Garba and Renard, 1991). The neglect of the real drainage term in good rainfall years tends to over-estimate the evapotranspiration component of the water balance equation, thus introducing substantial errors into the calculation of crop water use. Agnew (1982), using a model based on field observations made in Niger, concluded that vast quantities of water were lost to drainage from the root zone. The model assumed that drainage did not take place until field capacity was reached. Drainage can also be estimated using an empirical approach described by McGowan and Williams (1980). The changes of water content observed in each soil layer are inspected and changes in the rate of water loss are interpreted as either drainage or uptake by crops. As drainage proceeds, the soil water content of a given layer decreases as a result of small hydraulic conductivity and smaller rate of drainage. If a sudden increase in the rate of water loss occurs from a layer, it is attributed to extraction by plants. The discontinuity in the rate of water loss thereby provides means of distinguishing drainage from evaporation. This method assumes that roots do not extract from a layer while drainage is occuring and vice versa. It also blurs the distinction between layers and does not take into account the spatial variability in soil hydraulic properties, which can result in substantial errors in short term crop water use estimation.

A direct method for field measurement of deep drainage is the draining lysimeter method. A simple drum lysimeter was used at Aspendale, Australia, fitted

with a solid perforated plate at the bottom to induce natural saturation (Slatyer and Mcllroy, 1961). Care must be taken that the soil contained in the lysimeter is representative of the field soil profile (preferably undisturbed) as much as possible. This method can give accurate drainage estimates if unnatural soil saturation conditions are avoided.

2.4.4 Evapotranspiration.

Transpiration by plants and evaporation from soil and water surfaces require some input of energy for the transformation of water to vapour and its subsequent transportation away from such surfaces. The magnitude of evapotranspiration in a given environment is therefore dependent on solar radiation, temperature, humidity and wind speed (Owonubi *et al.*, 1991). In the drier savanna of northern Nigeria, vegetative ground cover is sparse, while evaporation directly from the soil surface represents a major component of the water balance. In cropped land, soil evaporation loss of not less than 30% of annual rainfall has been recorded in the sahelian zone of Niger (Wallace, 1991). Potential evapotranspiration (PET) is defined as the amount of water transpired from an actively growing, short, green plant cover (usually grass) with a full cover and a continuously adequate moisture supply (Penman, 1948). PET or water demand in the semi-arid zone is usually high due to the consistently high air temperatures and radiation loads (Jackson, 1977). Most times rainfall is erratic, but when rainfall exceeds PET, soil moisture reserves are recharged. In the semi-arid zone of Nigeria, rainfall is often less than PET for most periods of the year resulting in a soil moisture deficit. In essence, the quantity of moisture available does not depend

exclusively on rainfall, as soil moisture is also lost through infiltration and/or drainage. Since moisture is available for a relatively short period during the year, it is essential to match the crop phenology with the soil moisture profile during the rainy season, to meet with the crop water requirements at various stages of plant growth for successful crop harvest.

The measurement of evaporation and evapotranspiration is of great importance in crop water use studies, e.g. as it relates to lakes, canal and drainage systems, irrigation and soil water storage. As already noted in semi-arid regions, evaporation from soil surface contributes a substantial part of the total crop water use (evapotranspiration). Research conducted at the ICRISAT Center in Niger has reported very high evaporation values from sparse crops of rainfed millet (Wallace *et al.*, 1990a; Daamen *et al.*, 1995). A reliable measurement to separate evaporation from transpiration is difficult to make and time consuming, but when obtained provides the added advantage of partitioning crop water use appropriately.

Measurement or estimation of evaporation from soil can be achieved in a number of ways (e.g Ritchie, 1972; Ashktorab *et al.*, 1989; Daamen *et al.*, 1995), but, the microlysimeter method (Boast, 1986), has proved to be the most simple, direct and independent measurement of soil evaporation. Microlysimeters are small isolated volumes of bare soil (typically 1-3kg) mounted flush with or slightly above the soil surface and weighed daily (or more frequently) to determine water loss (Daamen *et al.*, 1993). The isolated volumes of soil can also be extracted from and mounted in the soil beneath a crop canopy, thereby allowing separation of soil

evaporation fluxes from transpiration fluxes. Frequent soil core replacement is required throughout a crop season and this makes this method impractical to measure soil evaporation at a continuous basis during a cropping season (Daamen *et al.*, 1993). Measurements are also invalid if interrupted by rainfall (Allen, 1990). The application of a model to supplement direct measurements and correct for these anomalies has been advocated (Allen, 1990; Yunusa *et al.*,1993).

Evapotranspiration (ET) can be determined from the water balance equation (equation 2.1). In these methods, the parameters of rainfall and/or irrigation, runoff or runon, deep drainage and changes in soil water storage are known.

2.4.4 (a) Effect of crop management on soil moisture

Plants make their demands for soil water in response to atmospheric demands through the process of transpiration. When the soil surface is not covered by plant canopy, soil moisture is lost to the atmosphere through evaporation as a result of direct exposure to solar radiation. In terms of water use by plants, studies have shown that the amount of dry matter produced by crops is directly proportional to the amount of water transpired (Tanner, 1981; Kanemasu *et al.*, 1984). If allowance is made for the saturation deficit of the atmosphere, then dry matter production per unit of transpiration is a constant dependent on the crop (Squire *et al.*, 1987; Monteith, 1991). The objective of good soil and crop management practices is to maximize crop transpiration, while moisture losses from evaporation, runoff and drainage are minimized.

2.4.4 (b) Role of cover crop on soil physical properties and moisture conservation

A cover crop refers to a fast, low growing, creeping and/or spreading plant. The plant canopy serves as a live-mulch, covering the soil and protecting it from the direct impact of raindrops and solar radiation, thus influencing soil properties such as bulk density, crustation, infiltration rate and organic matter content. It also affects the rate at which water is lost from the soil surface and soil moisture storage capacity. Kandiah (1979), compared the effects of a grass cover crop and bare ground on soil properties in the Sri-Lanka humid tropics and reported that grass cover decreased soil bulk density by 13%, while soil porosity, organic matter content and infiltration were increased by 12, 59 and 63% respectively. We have indicated that a most prominent cropping system of the Sudano-sahelian West Africa is the millet/cowpea intercrop (Norman *et al.*, 1981; Spencer and Sivakumar, 1987; Henriët *et al.*, 1994).

A leguminous plant such as cowpea has a potential for contributing significantly to the maintenance of nitrogen levels, organic matter content and better physical properties of soil in an intensified cereal based cropping systems (see COMBS, 1992). Legumes also contribute indirectly to the productivity of other crops by reducing biotic constraints as cover crops for weed control or as trap for parasites (Litsinger and Moody, 1975). In a trial conducted at Ougadougou, Burkina Faso, in the semi-arid zone of West Africa, cowpea planted on the mulch of a previous cover crop (Crotalaria) yielded about 62% more than the cowpea planted on ploughed and unmulched plots because of the better soil moisture conservation, when annual rainfall was 40% less than the long term average. The mulched cowpea plots suffered less water stress, while soil temperatures (at 5cm) were remarkably lower during the hot

hours of the day (IITA, 1984). Although several researchers have reported a better water use efficiency of the millet/cowpea intercropping system when compared with their sole crops (Gregory, 1990; Garba and Renard, 1991; Grema and Hess, 1994), information that shows evidence of the quantification of the role of the low growing, ground covering cowpea component on soil moisture dynamics are rare. Intercropping is believed to improve the moisture environment below the soil surface better than sole crop situations. The soil surface under an intercrop of somewhat higher density is not as exposed as in sole crops thus reducing evaporative losses. In a drying cycle, the moisture content of the surface soil layer is indeed often higher under intercrop than under sole crop (Midmore *et al.*, 1988; Olasantan, 1988). In a recommendation for the use of improved crop strategies in the West African sahel, Sivakumar *et al.* (1992) suggested a complementary system of relay intercropping of millet with fodder cowpea, when the onset of rains is early, for the fodder cowpea to make effective use of the rains in September after millet harvest. A large amount of water would otherwise have been lost through evaporation because of the poor water holding capacity of the soils. This way it provides more income to the farmer.

2.4.5 Solar radiation

Solar radiation is a very important resource for crop production because it is the energy source for photosynthesis and transpiration, hence growth and water consumption. The heat energy provided by solar radiation, is also one of the factors determining the rate at which water evaporates from any wet surface. Furthermore, certain wavebands of the solar spectrum act on plant photoreceptors involved in plant morphogenesis, which determines space occupied by plant foliage.

Photosynthetically active radiation (PAR), the spectral waveband roughly from 0.4-0.7 μm, which is utilised by green leaves in photosynthesis, makes up about 50% or more in more diffuse light of global shortwave radiation (Stigter and Musabilha, 1982). Solar radiation is a flux of electromagnetic energy that must be intercepted and utilised instantaneously to energise the photosynthetic process.

In the tropics, a crop canopy can be defined in terms of photosynthetically active or green leaf area, made up of the lamina area of emerged leaves not senesced. Leaf area index (LAI), the amount of green leaf area (one side) per unit ground area is the parameter commonly used to describe the light reception/interception and absorption relationship of crop canopies.

2.4.5 (a) Effects of solar radiation (PAR) on plant growth and development

The more efficient interception and utilization of solar radiation is advanced as a major reason for the advantage of intercropping over other cropping system. Improved productivity per unit incident radiation could be achieved by the adoption of an intercropping system that either increases the interception of solar radiation and/or has greater radiation use efficiency (Keating and Carberry, 1993). Minimizing the proportion of radiant energy reaching the ground is a simple means of promoting efficient utilization of incident solar radiation. The total amount of radiation intercepted by a plant depends on the period over which an intercepting surface is present. This amount increases with increasing extent and size of the photosynthetic surface, which is represented by the LAI (Squire *et al.*, 1987). Plant canopy expands in the absence of drought and nutrient deficiency when solar radiation and seasonal temperature are in adequate supply.

The rate at which plant foliage produce dry matter during the process of photosynthesis, and the amount produced by the time it is harvested, both depend on many environmental and physiological factors (Squire, 1993). In terms of solar radiation use, this is expressed by a conversion efficiency refered to as radiation use efficiency (RUE, the weight of dry matter produced per unit of solar radiation intercepted). Intercepted radiation is the difference between solar radiation received at the surface of the canopy and that transmitted to the soil, after excluding the fraction of incoming radiation reflected from the canopy. Tropical plant species are separated into two groups that differ in their maximum rate of dry matter production. The C4 photosynthetic pathway plants, mostly cereals and grasses, are more efficient, and have been reported to achieve maximun conversion rates of 4.2 g MJ^{-1} PAR, while the C3 pathway plants, e.g. rice, legumes, root crops and palms, have maximum rates of 2.5 g MJ^{-1} PAR (Squire, 1993). Their maximum annual production depends heavily on the longevity of plant foliage.

2.4.5 (b) Light capture (PAR), shade and weed growth in intercrops

In intercropping systems, the management of the light resource is very important, with its main objective aimed at the maximization of total light intercepted while allowing for adequate sharing of light between crop components. This can be achieved by a better spatial and temporal ground cover of the vegetation to increase light capture and so improve the production system. Since a great diversity exists in intercropping, resulting from the various combinations of crops and trees in space and time, such as the planting dates and spatial distribution, leaf size, shape and orientation, and plant/tree height, resource capture is better viewed in terms of

temporal and spatial dimensions (Willey, 1979; Marshall and Willey, 1983). Planting patterns which do not effectively exploit the available space at any time within the duration of the cropping season will result in incomplete radiation interception and, in cases where other resources are not limiting, corresponding loss in productive capability. The competitive ability of intercropping components in terms of resource use has been extensively studied (Reddy and Willey, 1981; Marshall and Willey, 1983; Kanemasu *et al.*, 1984; Keating and Carberry, 1993; Baldy and Stigter, 1993; amongst many others). In these research works, when reviewed with reference to competition for light, the emphasis has been on the ability of one species to compete with and shade another.

Light interception over time can be assessed with reference to the duration of the crop cycle and the rate of leaf area development between emergence and the attainment of the LAI to intercept all or most light. An intercrop of a short duration, high leaf area crop e.g soybean with a long duration but low leaf area one, e.g. cassava and sugarcane, can provide an opportunity for enhanced temporal capture of radiant energy (Keating *et al.*, 1982; Wallace *et al.*, 1990b). Most of the reports on this system, have shown that the pattern of light interception in such intercrops initially follows that of the faster-growing component under sole cropping and, close to or after harvest, the slower-growing component with a longer growth cycle. Examples include also systems involving sorghum (Natarajan and Willey, 1980), maize (Sivakumar and Virmani, 1984) and millet (Rao and Willey, 1983).

In an intercropping situation where component crops have similar growth duration and rate of leaf area development, they can still differ in light interception

because of differences in their vertical arrangement of foliage, due to the canopy architecture, or horizontal arrangement, due to planting pattern. Discussing light interception with reference to space involves a consideration where the intercropping system is between a fully 'additive' or only a 'replacement' type. In an additive system where one crop component is planted in similar arrangement to its sole crop equivalent or at a somewhat lower density and a second component is added such that the total plant population density is increased with respect to each of the sole crops, canopy structure most often varies with plant height. This reflects the canopy characteristics of the intercropped species and the impact of their interaction. In a replacement intercrop system, a number of rows of one crop component is replaced by a second component with the total plant density not necessarily changing (Keating and Carberry, 1993). The consequence for light interception is the need for the consideration of the canopy structure, which becomes more heterogeneous, and differs, according to horizontal position and also in the attenuation of light in the vertical dimension. In the process of light passing through successive layers of leaves of a plant canopy, its intensity decreases almost exponentially with increasing amount of cover, in accordance with the Lambert-Beer extinction law. In two component intercrops with distinct not overlapping layers with height, the daily amount of light intercepted within a given layer j (I_j) can be expressed as:

$$I_j = I_{0(j)} \left(1 - e^{-(k_{j1} L_{j1} + k_{j2} L_{j2})} \right) \qquad (2.12)$$

Where $I_{0(j)}$ is the amount of solar radiation entering the top of layer j, and k_{j1}, k_{j2} and L_{j1}, L_{j2} are, respectively for the two species, their extinction coefficients and leaf area

indices contained within layer j.

If the extinction coefficients of the component canopies are similar and if the intercrop results in increased total leaf area index (LAI) over the corresponding sole crops, then the amount of light intercepted by the intercrop will increase relative to that of the sole crops (Keating and Carberry, 1993). Likewise, the addition of an understorey intercrop with high value for k to crops with low k, would increase the whole canopy extinction coefficient, thus increasing light interception of the intercrop at a given value of LAI. In field conditions, such spatial advantages may be difficult to achieve where sole crops are planted at high densities, because then they are capable of achieving high LAI and close to complete radiation capture. Changing the spatial arrangement of intercrops, either vertically or horizontally, does modify the balance of interception between component canopies. It has been suggested that for such cases vertical canopies of plants with narrow leaves, with the upper leaves increasingly angled to allow radiation penetration through the canopy and avoid light saturation of the upper canopy leaves complete radiation capture (Willey, 1979; Trenbath, 1986).

The competition for light as a result of weed infestation is a factor used for explaining crop yield loss. Weeds are reputed to be more competitive for environmental resources, especially under low levels of external inputs, than genetically manipulated domesticated crops because of their better adaptation (Reijntjes *et al.*, 1992). Crops planted in all cropping systems are sensitive to weed competition especially if the weeds occur before the crops develop full canopy cover. In order for

intercrops to be effective in controlling weeds, they must be able to show complementarity in space by utilizing space more effectively than a sole crop (Cruz, 1995). Moody (1977), suggested that growing of a number of crops in close proximity to one another so that the plant density is greater than in the sole crop situation should result in greater competition against weeds and thus reduce the frequency of weeding.

An important service rendered in an intercropping situation is that the light resource is conserved by suppressing competitive weeds through shading (Stigter and Baldy, 1995). The effects of shading on plant physiology and morphology has shown that a change in light quality can alter plant form (Caldwell, 1987). Changes in the spectral balance of radiation as a result of absorption of PAR and of reflection and transmission of near infra-red, result in an increase in the far-red: red ratio, which has been shown to effect photomorphogenic processes (Allen *et al.*, 1976). Increased internode elongation, reduced branching and reduced leaf production are such typical responses to the increase in far-red:red radiation at lower levels in a canopy (Holmes and Smith, 1975).

2.4.5 (c) Solar radiation measurement methods

The measurement of solar radiation in plant communities is of primary importance because of the role of solar radiation in energy balance determination and in photosynthesis measurements (Pearcy, 1989). In such studies, the energy incident on a leaf or a layer of plant material and how much of this energy is absorbed are the main areas of interest.

Two types of sensor, thermoelectric and photoelectric, are commonly used for solar and long wave radiation measurements and are designed to respond equally to incident energy over their wavelength range. More details on the characteristics of these sensors are described by Pearcy, (1989).

The solar radiation instruments of most use in physiological ecology are pyranometers which measure both direct and diffuse solar radiation and pyrradiometers which measure both solar and long wave thermal radiation. The pyranometers may be based on thermoelectric sensors (thermopiles that detect the difference in temperature of alternate black and white surfaces or between a black receiver and a reference (kept at air temperature) when exposed to solar radiation) or photocells (usually silicon cells). A typical example of a thermoelectric pyranometer is the tube solarimeter which consists of a copper-constantan thermopile whose junctions are embedded in the black and white sectors of the thermopile detector.

Three types of sensors are used for measuring PAR. These are quantum sensors, gallium arsenide phosphide (GaAsP) cells and Photosynthetic Irradiance (PI) sensors (Pearcy, 1989). The original design of the quantum sensor consisted of a silicon-blue photocell mounted under a 400-700 nm broad-band interference filter, a piece of heat-absorbing glass and a Wratten 85A colored gelatin filter (Pearcy, 1989). Modified versions are now available under different trade names. An example is the one from LI-COR Instruments under the name Quantum Sensor (model LI-190SA). Overall, the sensors give good photon response over the PAR waveband range with units of measurement in μmol m^{-2} s^{-1}. The GaAsP cells can be used in an array

mounted directly at different levels within a canopy to give a record of the photosynthetic photon flux density (Gutschick *et al.*, 1985). The photocells may be interfaced to a portable computer via amplifiers and analog-to-digital converters. Photocells are of great use in row crops with incomplete canopies to give information about the spatial distribution of systematically distributed areas of shade (Matthews and Saffell, 1987). The photocells are relatively cheap and thus an attractive choice when large numbers of sensors are needed to measure light in a canopy or at sites in an understory. The problem with the use of GaAsP cells is the potential spectral error, which can however, be kept within a tolerable range.

PI is the radiant energy flux density of PAR: the radiant energy of PAR incident per unit of time on a unit surface (W m^{-2}). PI sensors are used when there is a need for the estimation of the energy conversion efficiency of a physiological system. PI can be directly estimated from pyranometer readings, since the PAR waveband radiation is a fraction of total shortwave radiation (300-3000 nm) that varies only gradually under increasing cloudy sky conditions (Anderson, 1971; Stigter and Musabilha, 1982). PI can also be measured with pyranometers using a different technique by first measuring total solar radiation and then using colored-glass Ultra-violet (UV) and Infra-red (IR) filters that block wavelengths shorter than 400 and 700 nm respectively (Pearcy, 1989). The difference in the readings between these two filters gives the PI. The main disadvantage of PI sensors is that the filters plus the instruments are quite expensive. Cheap filters cause considerable problems in the tropics (Mungai, 1991)

2.4.6 Soil temperature

Soil temperature is an important factor affecting soil physical processes. These factors include evapotranspiration, soil organic matter accumulation, hard setting and biotic activities. In many instances, soil temperature may have a more drastic effect on crop growth, particularly at early stages, than does air temperature, because of its effects on the energy driven processes in physiological ecology (Cassel and Lal, 1992).

Soil temperature is determined by the soil thermal properties (volumetric heat capacity and thermal conductivity) and soil surface heat flux (determined by the radiant energy absorbed by the soil surface and the partitioning of net radiation). The spatial and temporal distribution of soil temperature depends, primarily, on soil surface characteristics, i.e. whether there is a surface cover that provides a form of cover and how uniform the shading it provides can be as well as by surface geometry. In an incomplete surface cover situation, like in some widely spaced intercropped row crops, two or three dimensional heat transfer do occur (Horton *et al.*, 1984). Soil temperature studies have shown that crop growth is reduced for most tropical species and varieties when soil temperatures exceed 35°C (Lal, 1974a). These studies further showed that soil temperature measurements at 5 cm depth of about 40°C is common, and sometimes can exceed 50°C.

Soil temperature affects, among others, seed germination, crop emergence, early plant growth and development, root growth and crop nutrient uptake (Sivakumar, 1987; Squire *et al.*, 1987; Ong *et al.*, 1991; Cassel and Lal, 1992).

Soil temperature measurements and recordings can be obtained with the aid of several types of soil thermometers. Mercury in glass thermometers apart, the most readily used are the thermocouples and the electrical resistance types. Thermocouples are formed by bringing together, two dissimilar metals, to form a junction. Two junctions of the two dissimilar metals are called a thermocouple. The direction of current flow and the magnitude of the electromotive force gradient (voltage) produced depends upon the absolute temperature difference between these thermocouple junctions. Thermocouples are inexpensive, come in various sizes and can respond relatively fast to a change in temperature. The most common type of thermocouple in use is the copper-constantan type.

The principle behind the use of electrical resistance thermometer types is based on the fact that there is a change in resistance with a change in temperature. Wire types include nichrome, copper, silver or platinum. The resistance changes which can be measured with a resistance bridge or potentiometer, are related to temperature changes (Ehleringer, 1989). Another type of resistance thermometer is a semiconductor (usually a metallic oxide) called thermistor. Apart from the fact that it is more expensive and more fragile than thermocouples, it gives greater sensitivity than platinum resistance thermometers and can be made with either positive or negative temperature coefficients.

Both thermocouples and electrical resistance thermometers can be connected to a data logger device for continuous measurement and recording. Data loggers designed for temperature measurements may accept input signals from many different temperature sensors. The microprocessor within the logger is designed to scan a

thermometer (e.g. thermocouples) successively in the form of a millivolt range. Its scanner card allows scanning of several channels at a time and has in-built non-volatile data memory for several single channel locations to be stored. Examples of such dataloggers include CR10, 21X and CR7 dataloggers from Campbell Scientific Limited.

2.4.6 (a) Effects of soil properties on soil temperature

The energy balance of a soil has been shown to be affected by differences in net radiation caused by the difference in albedo (i.e ratio of the amount of visible light reflected by a body to the amount incident upon it) and/or surface temperature gradient (Wallace *et al.*, 1990c). Where vegetation is sparse, the degree to which the soil warms up depends on its color, water and air contents, and on its structure. The albedo of sandy soil can vary widely, depending on the soil moisture status. Relatively lower albedo and day time soil temperatures are associated with wet soils. Diatabé *et al.* (1989) in their description of the sahelian albedo values from the meteosat visible data of West Africa, showed that the albedo displayed a zonal trend, increasing from south to north as the vegetation density decreased. The removal of vegetation by human activities, leaves the soil exposed to solar radiation causing soil temperature to rise. Soil surface temperature and soil heat transfer produce the vertical profile of temperature in the soil and the thermal conductivity varies with pore size, soil texture, soil moisture level, organic matter and mineralogical content. There exists a strong coupling between the heat transfer and the moisture transfer in the soil. The processes of evaporation and dew formation are therefore influenced by the thermal behaviour

of the soil. The upward movement of water (capillary rise) towards the soil surface may take place because of evaporation from the surface and removal of water by roots of transpiring plants (Kramer and Boyer, 1995). At high soil surface temperature, the upward flow to an evaporating surface from a water table can be about twice as rapid in a fine-textured soil as in a coarse-textured soil (Gardner, 1958). The attributes of the semi-arid Nigerian soils make low radiation heat transfer very important at high temperatures within large pores in dry soils. Loose, well aerated soils warm up superficially, whereas compact, wet soils conduct heat to deeper levels. Sivakumar *et al.* (1992) reported a rapid rise of up to 55°C in soil surface temperature on the sandy soils of the sahel in Niger, after a dry clear weather that followed a period of showers, because of the quick evaporation of soil moisture, reaching fast the third stage of drying. Conditions of high soil temperatures rapidly decrease soil organic matter content through decomposition, causing a decline in soil structure and also limiting soil microfauna and microbial activity (Lal, 1987).

2.4.6 (b) Diurnal variation of soil temperature

Diurnal variation of soil temperature is controlled by several conditions. Monteith (1979) enumerated the following as being responsible for the diurnal range of soil surface temperature:

i. the rate at which radiant energy is absorbed;

ii. the fraction of that energy which is available for heating the soil and the atmosphere (sensible heat), i.e the fraction not used for evaporation; and

iii. the partitioning of sensible heat between the soil and the atmosphere.

In nature there are large diurnal and seasonal variations in soil temperature, while during the day the surface soil is warmer, during the night the soil surface cools down and the heat flow in the soil is reversed (Larcher, 1995). The soil thus buffers the heat balance of the habitat by taking up considerable amount of heat during the day and releasing this at night. When there is a close cover of vegetation the soil is protected from strong irradiation and from radiation loss, which leads to an appreciable reduction of diurnal fluctuation in soil temperature.

2.4.6 (c) Effect of cover crop on soil temperature

For the same reasons as given above for vegetation, soil temperature regimes are influenced and even may be controlled by surface mulches. The effects of cover crops as live-mulch or plant residues on soil temperature vary widely. Cassell and Lal (1992), reported that mulching increases soil temperature during cooler weather, in the mornings, and decreases it during hot spells, in the afternoons, when compared with bare soil. The effects of mulch on soil temperature will also vary among soils, with the kind of mulch, the rate applied, and the rate of decomposition (for biological materials, mainly the antecedent soil moisture content, and the prevalent level of insolation. Mulching is known to reduce the amplitude of the diurnal surface soil temperature wave, at the same time creating a favourable soil moisture regime, larger microbial activity and better root growth that affect crop growth and vigour (Lal, 1974b). A study conducted on the influence of mulch, cover crop and irrigation on the diurnal soil temperature pattern of a sandy loam in semi-arid areas of India showed that straw mulching considerably reduced the maximum surface soil

temperature and thus proved beneficial to crops, especially during the hot and dry months of April to June (Prihar *et al.*, 1979). In the Nigerian semi-arid zone, the acquisition of adequate quantities of straw mulch appears not to be feasible, hence the use of leguminous cover crops seems to be the most viable option. Legumes within the cropping systems have been reported to provide a more lasting protective cover for the soil than dead mulch, while they also may reduce the need for nitrate fertilizers and improve the quality of grazing land by providing high protein forage to complement the low quality natural pasture (Tarawali and Ogungbile, 1995).

2.4.6 (d) Soil temperature and crop establishment

When soil moisture is adequate, temperature is the dominant environmental factor which determines when germination may occur. Thereafter, temperature controls the rate of seedling growth, provided the soil structure and nutrient status allows roots to develop vigorously (Monteith, 1979). Soil temperature can adversely affect emergence and also early root growth (Othieno *et al.*, 1985), and in some cases favour emergence, vigour and yield of crops. The effect of temperature in a millet/groundnut intercrop resulted in the development of groundnut 2.5-2.8 days earlier than the sole crop (Ong *et al.*, 1991).

In the humid tropics of Nigeria, Lal (1974), reported that soil temperature above 36°C adversely affect emergence, vigour and yield of crops such as maize, soybean and yam. Sivakumar *et al.*(1992), observed soil surface temperature of about 55°C on the sandy soil of sahelian Niger, causing seedling death, which is a common occurrence, thus leading to very low plant stand establishment.

2.4.6 (e) Soil temperature and plant root development

Root growth is dependent on the microclimate of the soil. Plant root growth is often limited by extremes of soil temperatures. Soil temperature changes within very small distances, while the changes are dependent on the type of ground cover and the heat capacity of the soil. In the tropics, overheating of the surface soil can occur in the absence of mulch, while a thick mulch in the temperate region during spring would slow the soil rewarming process (Wild, 1988). The consideration of the optimum temperature for root growth of different crop species is of ecological and economic importance in crop production. Soil temperature increase to 35°C caused an increase in the exudates around a detached sorghum root, which decreased by nearly 50% at 40°C (BassiriRad *et al.*, 1991). At low soil temperature, root resistance to water movement through the roots increases as a result of the increased viscosity of water and becomes less available for plant growth and development (Kramer and Boyer, 1995). Mulching has been reported to increase root density and causing a greater lateral spread of roots (Chaudhary and Prihar, 1974), but has also been reported to reduce root growth in young tea (Camellia sinensis (L) O.Ktze) plants at very high altitudes (Othieno *et al.*, 1985).

2.4.7 Effects of intercropping on crop growth, development and yields

The availability of environmental resources to each of the component crops is important in determining combined intercrop productivity, and hence intercrop growth analysis must be based on capture of these resources and the efficiency of conversion of captured resources into growth of harvestable organs of component crops (Fukai

and Trenbath, 1993). The emphasis here is the competitive ability of component crops, which determines their biomass production and often yields. This ability also varies according to the growth environment, and hence cultural manipulation can adjust the balance of their yields. In essence, the best combination of crops under a particular system of management in one environment, with a particular set of climate, soil, pest and disease conditions may not necessarily be suitable in another environment. Cultural practices, such as time of planting, planting pattern of component crops, weeding regimes, fertilizer application and pest control, affect the relative competitive abilities and hence the balance of yields of the component crops. The determination of how yields of component crops and total intercrop productivity are related to resource capture and utilization can be examined in terms of the partitioning of assimilates among various plant parts, and particularly, allocation to the harvested parts as important processes determining final yields (Fukai and Trenbath, 1993). A method for the assessment of the assimilate partitioning to the harvested organs is through the harvest index (HI). HI is the ratio of harvestable yield to total biomass produced at maturity. An unfavourable condition during grain filling, such as severe stress, would lower HI. Intercropping to match phenologically different components with the growing season is a way of increasing productivity in intercropping, especially in water limiting environments (Wein and Smithson, 1981). The modification of the crop environment by intercropping itself is another obvious means of manipulating the processes involved in growth and yields of intercrops. A situation where a short-statured component is shaded by a taller one, reduces the capture of PAR and results in reduced growth and yield of the shorter crop, unless the later is shade tolerant.

In the Nigerian semi-arid zone, one major way of ensuring high intercrop productivity is the adoption of relay intercropping of phenologically different crops (cereals and grain legumes), with different growth habits, crop durations, and possibly differing rooting patterns, for better utilization of resources. Fukai and Trenbath (1993) suggested that an additive type of intercropping with components differing greatly in growth duration would yield the most productive intercropping system.

2.4.8 Effects of intercropping on below ground interactions- Root growth and development

The better use of resource is often mentioned as the basis for intercropping when compared with sole crops. The better use and conversion of intercepted radiation and water is often the explanation, with very little information proffered about below ground interaction (Ong, 1995). Intercropping of two contrasting components in terms of growth habit could particularly complement each other if they also differ in their effective rooting depth, thus affecting the amount of water and nutrients they capture. A knowledge of root distribution is important for an improved understanding of inter- and intra-species crop competition, resultant uptake of water and minerals by the crops, and in aiding decisions on soil ammendments and fertilizer application (Vos and Groenwold, 1986; Mungai *et al.*, 1996). The activity of roots in the soil is directly related to surface area or total length of the actively growing portion. The distribution of a crop rooting system can be defined by Root Length Density (RLD), Root Length (RL) per soil layer per unit of surface, Sum of Root Length (SRL) in the soil profile or per rooting depth.

RLD is the most important parameter used for explaining the systematic variation of roots below ground necessary for a sound understanding of root functioning, and has implications for use of below ground resources and soil amendments. Variations in rooting pattern are produced by factors such as soil type, existence of soil pans, soil aeration, soil temperature, soil moisture, nutrient status, soil pH, climate, cropping practices and plant genotype (Ehlers *et al.*, 1990).

Field root studies of several crops have shown the process of water uptake by an expanding rooting system as a function of depth and time (Drew, 1975; Vos and Groenwold, 1986; among others). They show that the dynamics of water uptake depend on RLD and the availability of water. In essence, the maximum water use by a crop is dependent on its RLD. Quantification of the spatial and temporal distribution of the roots of component crops in intercrops would aid in a better explanation of resource sharing among competing crops, and better understanding of the advantages derivable from intercropping (Mungai *et al.*, 1996).

In crops with spaced plants, sampling holes made to identify the smallest land area containing all possible systematic variation in root distribution caused by the planting pattern may be used for root sample collection. Collected samples can be labelled, washed and stained appropriately for RLD measurement. RLD can be estimated, using the direct method of placing a root over millimetre graph paper, and with the aid of a magnifying lens, estimate the given root segment to the nearest millimetre. The direct method is simple, but highly labour intensive. The other methods are the inch counter and the line intercept methods. An inch counter is an instrument used to determine the length of an irregular line between two points. Root

lengths are determined by running the inch counter over the projected image of the root. Since the scale factor is known (determined from a ruler at the edge of the glass tray), the counter readings are easily converted to the actual root length. This method requires less man-hour when compared with the direct method. The line intercept method was developed by Newman (1965) and can be used to estimate root length by the expression:

$$R = (\pi NA)/(2H) \qquad (2.13)$$

Where R is the total length of roots in a field area, N is the number of intersections between the roots and random straight lines of total length H and A is the area over which the root sample is randomly dispersed. An automation of root quantification based on the above principle is now possible using image analyzers manufactured under various trade names. This method gives a good estimate as does the direct count method and requires less time. The automatic image analyzers are expensive and require some expertise to be operated successfully.

CHAPTER 3

MATERIALS AND METHODS

3.1 General

3.1.1 Experimental site location

Experiments were conducted at the Institute of Agricultural Research (IAR)/International Institute of Tropical Agriculture (IITA) research farm at Minjibir, Minjibir local Government, 40km north west of Kano (12° 08' N, 8° 32' E, 500 meter above sea level). The experimental plots were about 300 meter south of Jankara lake. The site is well drained with about 1% slope.

3.1.2 Background survey of cropping systems

A quantitative study of cropping systems of the sudan savanna of northern Nigeria was initiated in 1991 by the IITA Kano station on fourteen selected farms with intercropped cowpea in Minjibir and Gezawa local government areas of Kano state. The survey area was expanded between 1992 and 1993 to include thirteen other local government areas within Kano, Jigawa, Yobe and Katsina states of Nigeria, for a rapid rural appraisal of the cropping systems. There was an average field sample size of eighty farms per local government area. The locations and major cropping systems are shown on Tables 3.1 and 3.3. Table 3.2 shows the frequencies of occurence of the various crops on fields in the semi-arid zone of Nigeria.

From these studies, the major systems appear to be millet/cowpea intercrops with 22.5% occurrence; millet/sorghum/cowpea intercrops with 18.6% and

Table 3.1: The list and co-ordinates of the sites for the Rapid Rural Appraisal (Henriët *et al.*,1993).

LOCATION	LATITUDE	LONGITUDE
Dawakin Kudu (Dk)	11° 50'14"	08° 36'03"
Gezawa (Gz)	12° 06'36"	08° 44'52"
Gabazawa(Gb)	12° 10'45"	08° 54'46"
Minjibir(Mj)	12° 08'01"	08° 32'30"
Gurjiya (Gu)	12° 12'23"	08° 43'21"
Kunya (Ku)	12° 12'23"	08° 32'45"
Danbatta(Dm)	12° 25'51"	08° 30'58"
Garki (Ga)	12° 25'52"	09° 11'34"
Hadejia(Hj)	12° 26'58"	10° 03'02"
Malam Madori(Mm)	12° 33'51"	09° 53'07"
Gumel (Gm)	12° 45'59"	08° 38'40"
Kazaure(Kz)	12° 38'55"	08° 24'49"
Gashua (Gsh)	12° 52'53"	11° 03'00"
Nguru (Ng)	12° 53'09"	10° 27'00"
Daura (Da)	13° 03'51"	08° 18'26"

Table 3.2: The frequency of occurence of crops on the visited fields across the Nigerian sudano-sahelian savanna (Henriët *et al.*, 1993)

crop	Dk	Gz	Gb	Mj	Gu	Ku	Dm	Ga	Hj	Mm	Gm	Kz	Gsh	Ng	Da
Millet	71.3	61.3	76.3	68.8	67.5	77.5	78.8	78.8	77.5	55.0	91.3	73.8	53.8	52.5	60.0
Sorghum	80.0	48.8	42.5	27.5	40.0	50.0	33.8	65.0	77.5	60.0	61.3	21.3	58.8	55.0	58.8
Cowpea	85.0	83.8	82.5	86.3	88.8	87.5	75.0	75.0	58.8	51.3	65.0	56.3	63.8	60.0	52.5
G/nut	17.5	40.0	22.5	30.0	46.3	9.8	27.5	3.8		1.3	2.5	17.5	1.3	2.5	13.8
Sesame								1.3	38.8	38.8	31.3			10.0	
Cassava	10.0	1.3	8.8	5.0			5.0						1.3		
Bambara			2.5		17.5		3.8				1.3	1.3		2.5	1.3
Okra		1.3	1.3						1.3				10.0	10.0	
Maize	1.3													5.0	1.3

Table 3.3: Major cropping systems across the sudano-sahelian savanna of Nigeria (Henriët *et al.*, 1993).

LOCATION	MAJOR CROPPING SYSTEMS (%)		
Dawakin Kudu	MSC (52.5)	SC (12.5)	MSCG(12.5)
Gezawa	MC (27.5)	SC (16.3) SCG (15.0)	MCG (15.0)
Gabasawa	MC (25.0)	MSC (22.5)	MCG (13.8)
Minjibir	MC (40.0)	MCG (23.8)	SC (16.3)
Gurjiya	MCG (26.3)	MC (17.5)	SCG (11.3)
Kunya	MC (36.3)	MSC (23.8)	SC (18.8)
Danbatta	MC (38.8)	MCG (11.3)	MSC (10.0)
Garki	MSC (43.8)	MC (20.0)	SC (11.3)
Hadejia	MSCs (21.3)	MS (20.0)	MSC (18.8)
Mallam Madori	SC (12.5) MSC (8.8) M (8.8) S (8.8) SCs (8.8) Ms (8.8)	MC (8.8)	
Gumel	MSC (25.0)	MC (21.3)	MS (12.5)
Kazaure	MC (30.0)	M (17.5)	MCG (10.0)
Gashua	MSC (22.5)	MC (18.8)	SC (16.3)
Nguru	MC (23.5)	MSC (13.8)	SC (11.3)
Daura	MSC (20.0)	S (20.0)	MC (17.5)

(M-Pearl millet; S-Sorghum; C-Cowpea; G-Groundnut; s-Sesame)

Major cropping system in the Nigerian sudano-sahelian savanna are:

MC (22.5%)
MSC (18.6%)
SC (10.4%)

sorghum/cowpea intercrops with 10.4%. This baseline survey led to the selection of the two most prominent cropping systems and crop combinations of the farmers for the 1993, 1994 and 1995 cropping seasons experiments. The intercrop combinations adopted were designed to mimic farmers' situations.

Two crop mixtures and six sole crop treatments were planted in 1993 and 1994, while an additional sole cowpea treatment was included in 1995. The intercrop treatments of the millet/cowpea mixture were planted as alternate rows of Pearl millet (cv. Ex-Borno) and cowpea. In alternate rows of millet, two cowpea varieties were used in 1993, an improved erect type (IT86D-719) and the local spreading type (Dan-illa), as illustrated in Figure 3.1a. Based on the performance of cowpea variety IT89KD-374 in intercropping situations in the Nigerian Nationally Co-ordinated Cowpea Variety Trials and its subsequent recommendation for the Nigerian savanna, it was adopted as a replacement for IT86D-719 as grain type cowpea in 1994 and 1995 cropping seasons. Cowpea variety IT89KD-374 is an improved semi-erect medium maturity cowpea type with high potential for grain production and multiple disease and moderate insect resistance. The millet/sorghum/cowpea intercrop comprised millet (cv. Ex-Borno), local sorghum (cv. Gaya Early) and the same two cowpea varieties as in the millet/cowpea intercrop. Compared to the millet/cowpea intercrop, every other plant in the millet rows was replaced by sorghum (or differently expressed, in each alternate ridge, millet was replaced by sorghum). This field arrangement is illustrated in Figure 3.1b.

During the 1994 and 1995, the local variety, Dan-illa was retained as the fodder type in the intercrop treatments. Improved cowpea variety, IT88D-867-11 was also selected and planted sole, based on the recommendation from the Nationally

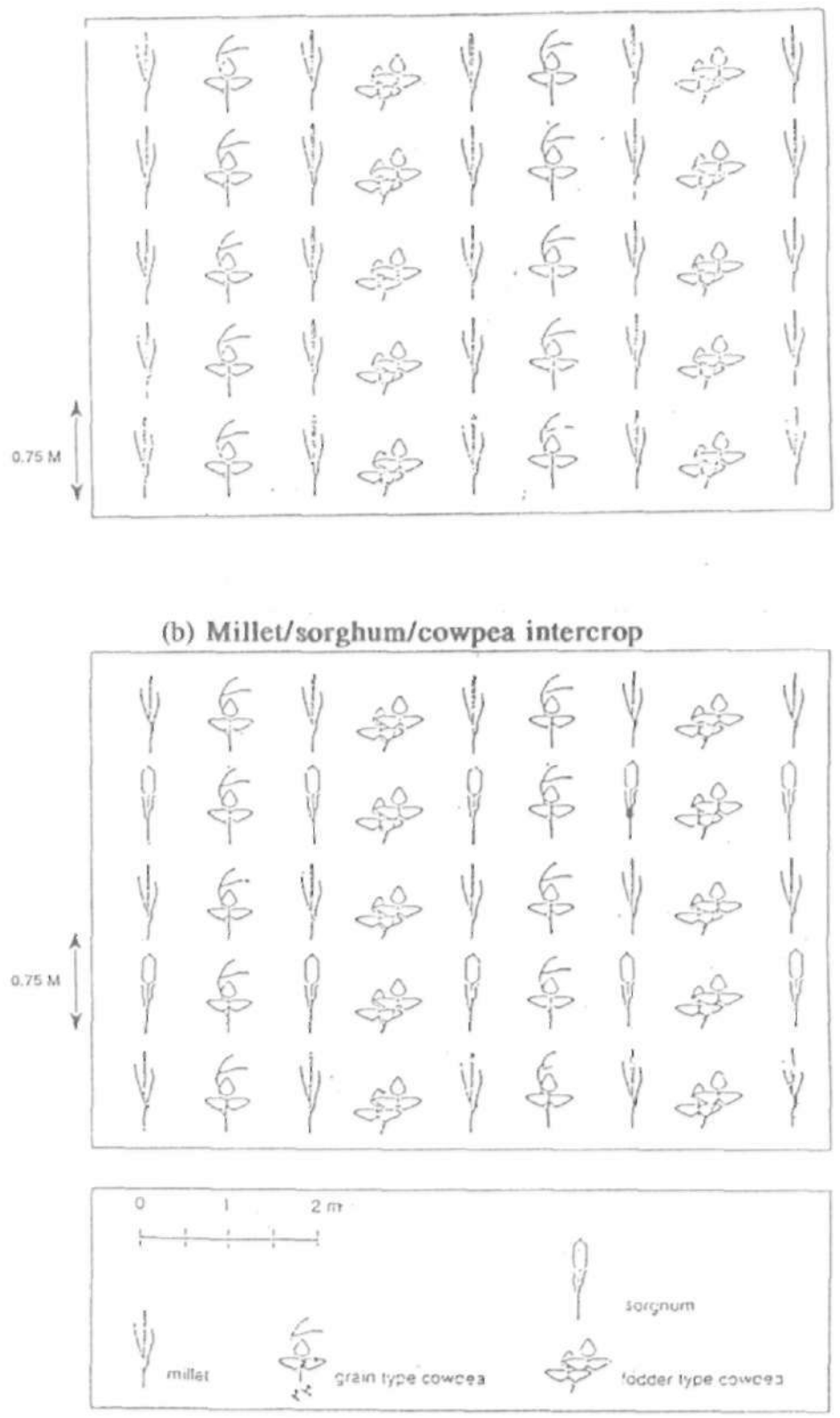


Fig.3.1 (a) Field arrangements of the millet/cowpea and (b) millet/sorghum/cowpea intercropping systems.

Coordinated Cowpea Varietal Trial, and its subsequent release in 1995. IT88D-867-11 is a brown seeded, medium duration, semi erect and determinate cowpea that has some levels of resistance to cowpea *Striga* (Striga gesnerioides) in combination with multiple diseases resistance and moderate insect tolerance.

Sole crop treatments were the sole crops of millet (Ex-Borno), sorghum (Gaya Early and ICVS400) and cowpea (IT86D-719, IT89KD-374, Dan-illa and/or IT88D-867-11). Millet cv. Ex-Borno is a medium maturity, stable and high yielding cultivar, very common with the local farmers. There was no new cultivar that had shown a clear superior performance over Ex.Borno, hence it was the only millet cultivar considered in the experiments.

Sorghum cv. Gaya Early is a late maturity (> 120 days), tall (> 2m) yellow seeded crop common with the local farmers. The tall and relatively strong stem is used for fencing and fuel, while the leaf is used as fodder. A successful crop of Gaya Early in a cropping season is dependent on the duration of the rainy season.
A rainfall period that extends until late September and/or early October favours the reproductive stages and ensures good grain yields, while on the other hand, in years of early cessation of rains in early September, moisture stress problems are created that cause a high reduction in its performance and yield. Gaya Early is also prone to bird attacks being a late maturing cereal which is left on the field after most other cereals have been harvested.

Sorghum cv. ICVS 400 was sown sole for comparison with Gaya Early and as a possible replacement in the cropping systems if its performance was superior in the attributes considered in the experiments. ICVS 400 was bred in ICRISAT, India, and improved at the ICRISAT-WASIP Kano station for the West African semi-arid

region. The ICVS 400 is an improved relatively short duration (< 100 days) variety, short in height and white seeded. It has a high yield potential, and had been tested and released by the national research system to the farmers. The white seeds produced by ICVS 400 enjoy a higher market preference over other sorghum seed colours.

3.1.3 General field conditions

3.1.3 (a) General for all experiments

The experimental site had been under continuous rainfed cultivation for several years with little evidence of fallow. Application of organic manure from household refuse and animal droppings to fields is a common means of maintaining soil fertility in this area.

3.1.3 (b) Experimental design and field layout

Organic manure (cow dung) was evenly applied at the rate of about 6 tons per hectare prior to ridging in 1993. Crops were planted in relay within a 16 days period, after a good land preparation on ridges spaced 75 cm apart. All plant stands were thinned to 2 plants per stand at crop establishment in 1993. Millet was planted on 22 June at 50 cm apart within rows laid across the ridge at the optimum plant population of 53333 plants ha^{-1} for the sole crop, and at 2 m apart for the intercrops (13333 plants ha^{-1}). The millet was maintained at the mentioned plant densities at crop establishment after thinning to 2 plants per/hole(stand) during first hoe weeding 2 weeks after sowing (WAS) millet. The intercrop millet had 25% of the sole millet plant density per hectare.

Planting date for sorghum was 28 June, as a replacement crop on alternate millet ridges i.e. rows are across the ridges that are already spaced at 75 cm apart such that every alternate stand of millet is replaced with a sorghum stand, in the millet/sorghum/cowpea intercrops at 2 m apart i.e. 6667 plants ha^{-1} (Fig. 3.1b) and sole sorghum crops at 0.5 m apart (53333 plants ha^{-1}). The sorghum was intercropped at 12.5% of the sole sorghum crop density (plant population per hectare).

The cowpea components were planted on 8 July, 1993 within the intercrops, as indicated in Figure 3.1, and as sole crops. Spacing for sole cowpea (cv. IT86D-719), was 0.5 m apart on ridges (53333 plants ha^{-1}), while cowpea varieties IT89KD-374 and Dan-illa were sown at 0.75 m apart (35555 plants ha^{-1}). Intercrop spacing for the cowpea components were 2 m apart within the ridge (and for each variety this was 4 m) and 75 cm between the ridges after every row of cereals as illustrated in Figure 3.1b.

Although sole cropping is not a common local farmers' practice, the much higher plant densities in the sole plantings were meant to optimize the performance of these crops and serve as a basis for comparing them with the farmers' intercropping systems (IAR, 1985). The various crops were sown at the same time as the farmers were sowing theirs.

The 1993 experiment was primarily a preliminary field study of the selected cropping systems and only involved limited treatments. The trial was of a randomized complete block design with three replications and there was no additional application of inorganic fertilizers. The plot size for the intercrops were 16 ridges by 15 m, while the sole plots were 8 ridges by 7.5 m. Hoe weedings in the sole and millet/cowpea plots were carried out at 2 WAS millet, 4 WAS millet, 7 WAS millet and additionally

in the millet/sorghum/cowpea intercrops at 10 WAS sorghum. Insecticides Cymbush Super ED and Sharpa plus (active ingredient (a.i) Cypermethrin + Dimethioate) were applied three times from cowpea flower initiation stage to crop maturity at recommended rates to control insect pests of cowpea. The necessity for insecticides application to cowpea was based on past experience in this region that cowpea varieties in existence do not yield properly without this treatment (Jackai *et al.*, 1985). The total annual rainfall for 1993 cropping season was 641.8 mm.

The summary of the experimental conditions and treatments adopted for the 1994 and 1995 trials are given in Table 3.4. Cowpea variety, IT89KD-374 in intercrops is presented as cowpea(g), while Dan-illa is represented as cowpea(l). The experiments were now laid out in a 2^2 factorial randomised block design with 4 replications for the intercrops, while the sole crops remained a randomised block design with 3 replications. The main treatments were soil fertility i.e pre-planting organic manure application to all the experimental fields and the treatment with additional application of inorganic fertilizers as top dress to the cereal components at later stages of growth. The cow dung that was applied to the field thoroughly mixed to ensure even application to guaranttee a reasonable soil fertility function in 1994 and 1995. The different crop combinations and their sole crops constitute the sub-effects. The soil fertility requirements for optimum yield of millet in the Nigerian drier savanna are: 60 kg N ha^{-1}, 30 kg P_2O_5 (13 kg P) ha^{-1} and 30 kg K_2O (25 kg K) ha^{-1} (Singh *et al.*, 1983a), While the requirements for sorghum are 90 kg N ha^{-1}, 40 kg P_2O_5 (17.3 kg P) ha^{-1} and 30 kg K_2O (25kg K) ha^{-1} (Singh *et al.*, 1983b).

Table 3.4

Summary of experimental conditions and treatments (1994 and 1995)

Preplanting application of organic manure (cow dung) to whole experimental field at rate of 4t/ha in 1994 and 6t/ha in 1995.

Sowing Dates: Pearl millet- 23 June 1994 & 13 June 1995

Sorghum - 30 June 1994 & 16 June 1995

Cowpea - 7 July 1994 & 27 June 1995

Design : 2^2 factorial randomised complete block design, 4 replications (Intercrops)

Randomised complete block design, 3 replications (Sole crops)

Plot Size :16 X 15m (Intercrop)

8 X 7.5m (Sole)

Treatments :	Organic manure only	Org. manure+Inorg.fertilizer
i.	Sole millet(Ex-Borno)	Sole millet(Ex-Borno)
ii.	Sole sorghum(Gaya Early)	Sole sorghum(Gaya Early)
	Sole sorghum(ICSV 400)	Sole sorghum(ICVS 400)
iii.	Intercrop 1 : 1 : 1	Intercrop 1 : 1 : 1
	cowpea(g)/millet/cowpea(l)	cowpea(g)/millet/cowpea(l)
iv.	Intercrop 1 : 1 : 1 : 1	Intercrop 1 : 1 : 1 : 1
	cowpea(g)/millet/sorghum/cowpea(l)	cowpea(g)/millet/sorghum/cowpea(l)
v. Sole cowpea	(IT89KD-374)	———
	(IT88D-867-11)	———
	(Dan-illa)	———
Added in 1995	(IT86D-719)	———

Rainfall : 1994 Total= 769.8mm

: 1995 Total= 564.0mm

The soils and organic manure analysis for 1994 supplied about 38 kg N ha-1 to the top soil (0-15 cm), while those of 1995 supplied about 30 kg N ha^{-1}. The deficits were supplied through the application of inorganic fertilizers as top dress at 6 WAS millet and 8 WAS sorghum in the high fertility treatments to achieve the optimum fertility status required by these crops. It should be realised that this comparison was made to investigate the difference with the absence of inorganic fertilizers which has become less and less available as a consequence of the annual subsidy removal by the Nigerian government. Only the sole cereal and cereal components of the intercrops were top dressed with fertilizer. Hoe weedings were carried out in all crops as in the 1993 cropping season while insecticides Cymbush Super ED and Sharpa plus (a.i Cypermethrin + Dimethioate) were applied three times at recommended rates with a knapsack sprayer from flower initiation to control insect pests of cowpea.

3.1.4 Weather data collection

The collection of weather data was carried out with Standard automatic instruments (Campbell Scientific Inc.) installed about 500 meter north east of the experimental plots. The details of parameters recorded, the types of instruments and their accuracies are given in Table 3.5. Measured weather parameters are stored in a datalogger (Campbell 21X) programmed to average and store data on an hourly basis. Stored data in the datalogger are retrieved using appropriate software associated with the datalogger, and data collation and processing are carried out using computer programs developed at the Agroecological unit of IITA, Ibadan. Weather data are summarized on daily, monthly and annual basis .

Table 3.5 AUTOMATIC WEATHER STATION AT IITA KANO STATION

Parameters	Instrument Type	Sensitivity	Accuracy
Rainfall	Tipping bucket rain gauge	± 0.2mm	0.5mm
Pot.Evaporation	Computed from Penman-equation		
Wind speed	MET 014A Cup Anemometer	± 2%	5%
Solar Radiation	LI200S LI-COR Pyranometer	± 1%	5%
Temperature & Relative humidity	Model 207 RH & Temp. Probe Campbell Scientific Inc.	± 0.2°C ± 2%	0.3°C 3%

3.1.5 Soil data collection

Composite surface soil samples (0-15cm depth) were collected from the experimental site, passed through a 2mm sieve and analysed at the Department of Soil Science, IAR, Ahmadu Bello University, Samaru and IITA analytical services laboratory, Ibadan. Pre-planting soil samples were collected for laboratory analysis before organic manure applications to the experimental plots. The pre-planting and post-harvest soil samples from the 1994 and 1995 trials were analysed for their particle size distribution, pH, available phosphorus (Bray P1), organic carbon, exchangeable cations and micronutrients (Cu, Zn, Fe and Mn). The soil samples were further subsampled and passed through a 0.5mm sieve for the determination of their total nitrogen (N) contents.

The pre-planting organic manure applied to the experimental fields was also analysed chemically for total nitrogen, total phosphorus (Bray P1), total cations and micro-nutrients (Cu, Zn and Mn) contents. The results of the soil and the organic

manures analyses gave indications of the soil fertility status which were used for computing the amounts of the inorganic fertilizers required to make up for the recommended soil fertility levels for the component crops in sole and intercrop treatments, where applicable.

Pearl millet is reputed to be very efficient in extracting water and nutrients from the soil and as such a proportion of its nutrient requirement is met from the soil at crop establishment. Soil fertility status at planting is also related to the ultimate grain yield at harvest when seasonal moisture distribution is adequate. Sorghum is also reputed to be a heavy feeder on soil nutrients especially nitrogen.

During land preparation for the 1994 cropping season, well mixed organic manure (cow dung) was applied evenly to the whole experimental field. The chemical analysis of the manure gave the equivalents of 28 Kg N, 2 kg P, 18 kg K, 23 kg Ca, 6 kg Mg and 7 kg Na per hectare. The micronutrients Cu, Zn and Mn were 0.1, 0.2 and 0.5 kg ha^{-1} respectively. Inorganic fetilizer type NPK 20-10-10 (20 kg N; 4.3 kg P; 8.3 kg K) was applied at 6 WAS as topdress to the sole and intercropped millet components within the optimum soil fertilization treatments at the rate of 110 kg NPK 20-10-10. The rate supplied was therefore 22 kg N, 4.7 kg P and 9.1 kg K ha^{-1} to reach the recommended soil fertility status for the optimum yield of millet. The sorghum component received 260 kg NPK 20-10-10 at 10 WAS, therefore supplying 52, 11.2 and 21.6 kg ha^{-1} of N, P and K respectively.

For the 1995 cropping season, the manure provided 24 kg N, 1 kg P, 21 kg K, 11 kg Ca, 3 kg Mg and 10 kg Na ha^{-1}. Inorganic fertilizer NPK 20-10-10 at the rate of 150 kg ha^{-1} was applied 6 WAS to complete fertilizer dosage treatments with millet components to supply 30 kg N, 6.5 kg P and 12.5 kg K ha^{-1}. The sorghum

components received 300 kg NPK 20-10-10 ha^{-1} which supplied the equivalents of 60 kg N, 12.9 kg P and 24.9 kg K at 10 WAS.

The topdress inorganic fertilizer were banded and done on plants per stand basis in 1994 and 1995.

3.1.6 Statistical analysis

Analysis of variance and linear regressions were performed with Genstat 5 Release 3.1 (Lawes Agricultural Trust, Rothamsted Experimental Station, 1993). Tests of slopes were done using the method of Snedecor and Cochran (1978) and Gomez and Gomez (1984). The probability levels from 0.01 to 0.05 were used to distinguish the degree of significance between means. Root mapping was carried out with the aid of Surfer Access System version 4.06 (Golden Software Inc., 1989). Roots of crops were mapped to show their distribution within the various treatments at different stages of crop growth, in relation to the crop combinations.

3.2 Plant canopy development and dry matter production

Plant samples were harvested systematically from designated areas of the plot, leaving a minimum 0.75cm guard area between samples. Whole plant stands per ground area for each of the treatments were cut at ground level and separated into leaf, stem, pod, panicle, head at weekly intervals in 1993. During the 1994 and 1995 cropping seasons, sampling was repeated at 14 days intervals. Three replicate samples were taken on every sampling date. Leaf area measurement was done using a leaf area

meter (LI-3100 Li-Cor,Inc., Lincoln,U.S.A). Direct leaf area measurements were given in cm^2. The equipment was cleaned of dusts and sand particles with the aid of a vacum cleaner and a moist clean cotton material before use and at regular intervals during measurements. A regular calibration of equipment was also done by passing a flat regular 50 cm^2 circular plate through the instrument before and when in use. Total leaf area given in cm^2 is the cummulative value recorded per whole stand measurement done by passing every single leaflet through the leaf area meter.

The sole millet, sorghum and cowpea varieties, IT86D-719 and IT88D-867-11 sown at 0.5m x 0.75m had a ground area availability of 3750cm^2, while in the intercrops each component plant stand had a ground area available of 7500cm^2. The sole crops of the prostrate and vegetative cowpea variety Dan-illa had 5625cm^2 available. IT89KD-374 was also expected to occupy the same ground area as Dan-illa as a comparism. The number of plants per stand for millet and cowpea varieties were 2 plants, while for sorghum it was 2 plants per stand in 1993 and 1994; and 4 plants per stand in 1995. Most of the farmers' fields visited in 1994 had a minimum of 4 sorghum plants per stand in the millet/sorghum/cowpea intercropping systems, hence the increase effected in the sorghum component of intercropping systems in 1995. Leaf Area Index (LAI) is calculated thus:

$$LAI = \frac{\text{Total leaf area measured per hill}(cm^2)}{\text{Area of land available for plant hill}(cm^2)} \qquad (3.1)$$

Measured leaves and stems were oven dried at 80°C for 48h and weighed for dry matter production at various stages of growth. The weights of plant parts i.e leaf, stem and reproductive organs were recorded separately in 1994 and 1995 trials, while

only the shoot dry weight was taken in 1993. At flowering and panicle initiation, the productive organs were separated from the shoot and assessed for their dry matter production.

3.3 Radiation use studies

3.3.1 Light (PAR) measurement methods

3.3.1 (a) *Sunfleck ceptometer*

Intercepted PAR was measured periodically using a Sunfleck ceptometer (Decagon Devices Inc., Pullman, WA). The ceptometer measures light using 80 sensors at 1 cm intervals along a line probe. The probe, when inserted into the canopy, scans the sensors through a microprocessor and the average of the readings is displayed on a panel. Measured incident radiation is recorded in μmol m^{-2} s^{-1}. Measurements were made above and below the canopy to comprise a measurement pair of which the ratio gives the percentage PAR reaching the ground, from which the interception can be calculated.

3.3.1 (b) *Mouse ceptometer*

In intercropping situations, especially in the widely spaced intercrops and where the taller cereal shades the shorter creeping legume, a complete description of the horizontal light profile is crucial in explaining an advantage of a cropping system over another. The need for an instrument to determine the horizontal profile of light of such stands with incomplete canopies from a series of readings of irradiance at short intervals along a specified distance, representative of unit row width, is achieved

with the use of a 'mouse' ceptometer. The terminology "mouse" was used to describe this equipment by Laisk (1969) and Matthew *et al.*, (1987).

The "mouse" developed at ICRISAT, India, is 150 cm long inserted below a crop canopy and levelled horizontally (Plate 3.1). The "mouse" is used to determine irradiance at points 6 cm apart along the whole length of the instrument. The sensor unit, mounted in a tube with holes at a regular distance of 6 cm, was connected by a long cable to the scanning device. The cable was also used to pull the sensor along the length of the tube. A second radiation sensor is mounted on a vertical extension to measure incident radiation above the canopy at the same time as each reading below the crop is taken. These pairs of readings are recorded in millivolts per μmol photons m^{-2} s^{-1} and then stored in a small portable data logger (Polycorder, Omnidata, Logan, Utah, U.S.A). The data pair are thereafter unloaded into a larger computer for analysis.

The polycorder was programmed using specific polycode language (see Appendix 3.1) of the machine to scan the input channels with a 1-ms intergration time. Measurements collected were used to calculate fractional light interception per hole by expressing again the values of recorded irradiance below a crop canopy as a fraction of the value above canopy. The total number of holes scanned per measurement depends on the distance between crops under consideration, when measuring within or between rows.

The 'Sunfleck' ceptometer and the 'Mouse' were compared above crop canopies, simultaneously, for uniformity in terms of PAR measurements, under the same environmental condition, and found to give similar readings. While the sunfleck

ceptometer gives its records in μmol m^{-2} s^{-1}, the mouse recording is in millivolts per μmol photons m^{-2} s^{-1}. The PAR measurement above crop canopy in a clear sky, midday on 17 August, 1994 showed the sunfleck to give a reading of 2064 μmol m^{-2} s^{-1}, while the mouse gave a reading of 20.80 millivolts m^{-2} s^{-1}.



Plate 3.1 The mouse being used for measuring the incident radiation intercepted by crop canopies.

3.3.2 Sampling technique and time

Light measurements were taken, at 2 week intervals from 2 WAS cowpea which corresponded to about 4 WAS millet and 3 WAS sorghum, during the 1994 and 1995 cropping seasons within the sole and intercrop systems. All light measurements were carried out near solar noon between 11:00h and 14:00h, and only measurements made on cloudless days were used for the analysis of results. Measurement pairs were taken perpendicular to the crop rows and both adjacent to and between plants along rows, to give a light use profile between and among component crops in the intercrop. With the sunfleck ceptometer, the above canopy light measurement was the first to be taken, followed immediately after by the measurement below crop canopies. A measurement record using the Sunfleck ceptometer is an average of 10 readings per point. The mouse records and stores the measurement pairs automatically into the programmed Polycorder to which it was attached. In the millet/sorghum/cowpea intercropping system, eight measurement pairs were taken in the direction between and within rows, involving all the component crops in combination. In the millet/cowpea intercrop, three measurement pairs were taken in 1994 while in 1995, five measurement pairs were taken. In the sole crops, two measurement pairs i.e. between and within crop rows were taken. Readings were taken at the same tagged permanently marked positions from designated area of the plots. The measurement pairs were used to determine light interception by the canopy in relation to crop component stands in space. The length of the 'sunfleck' ceptometer is 80 cm, while in the intercropping systems, wide crop spacings (1m) were adopted between rows to simulate farmers' conditions. The 'mouse', being longer and more flexible, was used to measure intercepted radiation at much wider crop spacing in the intercrops than in

sole plantings. The measurements from the 'sunfleck' and 'mouse' were selected for the computation of intercepted radiation based on their appropriateness to crop spacing and also combined for the analysis of the results presented. Intercepted radiation computation in the sole crop treatments with relatively denser plant spacing was done using the sunfleck ceptometer data, while the mouse data were used for intercrops light interception computation.

$$\text{Fractional light interception (PAR)} = 1 - \frac{\text{PAR below canopy}}{\text{PAR above canopy}} \qquad (3.2)$$

The fractional light interception is expressed as percent light interception obtained in crop canopies during a specified growth stage. These measurements were averaged to obtain the daily plot mean for a treatment. Two plots per treatment (cropping system x fertility level) were sampled and plot means were averaged to obtain treatment means.

3.4 Soil temperature measurements

Soil temperatures have been measured with PT-100 platinum resistance thermometers horizontally inserted between 7-10 cm depth below crop canopies in 1994 and below plant stands in 1995. The laboratory accuracy of the PT-100 sensors was 0.05°C, while the resistance elements had a diameter of about 4mm. They were connected to a datalogger (21X micrologger) with installed relay multiplexer (AM416) having multiple channels for soil temperature measurements (Plate 3.2). Soil

temperature measurements were taken with 8 PT-100 sensors installed within locations on 8 different plots in 1994, while 10 sensors were used in 1995. The datalogger was programmed to scan and collect soil temperature data every minute, which are then averaged and stored at 15 minutes interval.



Plate 3.2 Field layout showing the wire cables bearing the platinum resistant (PT-100) thermometers installed on plots connected to the micrologger.

The soil temperature data were retrieved from the datalogger at a regular interval of 3 days with the aid of a portable computer for processing. Soil temperature measurements were however not replicated with the limited number of PT-100 sensors available. From an agronomic point of view, this was also not necessary. The soil temperature is of agronomic importance particularly at germination, when too high temperatures can be lethal with inadequate soil moisture conditions. In addition, when

the soil is bare, a small number of sensors already form replicates wherever they are mounted. One sensor was placed 10 cm below a weed free uncropped bare soil surface as a control during 1995 cropping season.

3.5 Water balance studies

3.5.1 Soil infiltration

3.5.1 (a) *Design description and measurement technique*

During the 1995 cropping season, a Double Ring Infiltrometer method was used to determine the infiltration rates of water into the soil in the different cropping systems. The infiltrometer set comprises of three pairs of metal cylinders (infiltrometers) with inner ring 280 mm, outer ring diameter 530 mm; inner ring 300 mm, outer ring diameter 550 mm; inner ring 320 mm, outer ring diameter 570 mm and a driving plate with handle for the inner and outer rings. Other components are three adjustable measuring bridges and three floats with measuring rods (each for a pair of the cylinders), nylon headed hammer and a stop watch (ELE International Inc., England). The soil surface was cleared of vegetation and dead plant debris before the cylinders were installed and pre-wetted. These cylinders were inserted in pairs, a small distance into the wet soil, and furnished with the associated accessories as shown in Plate 3.3. Water is applied into the pair of cylinders by ponding (condition produced by surface water collecting in shallow pocket in an area). The water was applied to the infiltrating surface, with as little kinetic energy as possible, by slow application of water with the aid of a watering can with a fine meshed (≤ 2 mm) conical outlet. Measurements on the float with measuring rods calibrated in

centimeter are made on the rate of fall of the water level in the inner ring at regular time intervals with the aid of the stop watch i.e. in minutes, at successively longer times of application until a steady state of infiltration rate is reached. The water infiltrating into the soil between the two rings is assumed to ensure one-dimensional flow in the inner ring by limiting the lateral spread of water from the smaller inner ring. The soil in the field is typified by crusting and poor contact between the metal cylinder wall and soil. The basic principle behind this method is the assumption that the pressure head gradient is likely to be equal to 1 mm^{-1}, if soil layers with very different saturated conductivities occur near the surface (Hoogmoed *et al.*, 1991).

The infiltration rate of water into the soil obtained through this method gives an indication of the possibility of the occurrence of runoff at certain periods during the rainy season as a result of insufficient water infiltration downwards, sealing the soil to further infiltration.



Plate 3.3 A field installed double ring infiltrometer used for the measurement of soil infiltration rate at Minjibir research site, Kano.

3.5.2 Soil drainage (deep percolation) losses

3.5.2. (a) *Drum lysimeter (draining) method*

3.5.2.a (i) *Design and installation of lysimeter*

A drum (220 liter) lysimeter was designed as a modification of the type used at Aspendale, Australia and fitted with a solid perforated plate at the bottom to induce natural drainage during 1995 cropping season (Slayter and McIlroy, 1961). The height of the soil column in the lysimeter was 85 cm while the diameter was 55 cm. A slanting PVC plastic pipe was connected to the bottom of the drum at the sloping end of the concrete floor of the collection compartment, that drains the percolates by gravity. The percolates then drain into another container (plastic) placed below the drum level and at a distance away from the drum (Fig. 3.2). Care was taken to ensure that the hydraulic and thermal properties of the soil were kept as similar as possible to the surrounding soil. The soil contained in the lysimeter was carefully loaded with minimum disturbance to represent the field soil profile as much as possible at the beginning of the rainy season. There were two lysimeters, one with vegetation(weeds) on and around the lysimeter and the other without vegetation on it, but with vegetation in its surrounding. Mould dykes of earth were made round the lysimeters to prevent 'run-in' from adjacent plots.

3.5.2.a (ii) *Measurement techniques*

The plastic container for the collection of percolates was checked for drained water one day after every rainfall event and daily thereafter. The amount of water collected is then measured using a graduated cylinder in cubic centimeter of water. The measured percolate is further converted and expressed as a depth equivalent in

millimetre of water and used in the water balance equation for crop water use assessment.

$$\text{Depth equivalent of water (mm)} = \frac{\text{Measured (percolate) water } (cm^3)}{\text{Surface area of drum } (cm^2)} * 10 \qquad (3.3)$$

The drainage through percolation after heavy rainstorms is a continuous process whereas rainfall is relatively discrete, hence drainage loss is observed over a period of time that could extend for days after the storm.

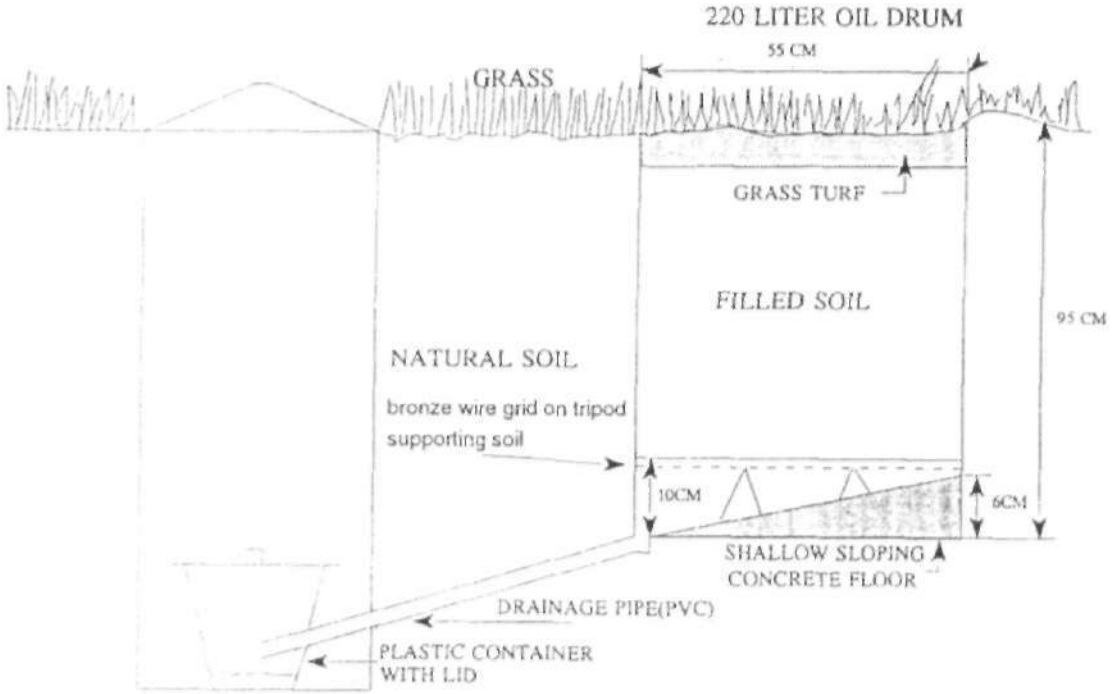


Fig.3.2 The design of the drum lysimeter used for measuring deep percolation losses at the Minjibir experimental site.

3.5.2 (b) *Soil profile water status over time*

Analysis of changes in the status of water in the soil profile is based on an empirical approach as described by McGowan and Williams (1980) and Agnew (1982) and uses the knowledge of field measured soil water characteristics. The approach involves the concept of 'field capacity' i.e. at some time, usually 24 hrs, following thorough wetting of the soil, drainage is assumed to cease throughout the whole profile. The drainage process is based on the assumption that percolation only takes place when field capacity is exceeded, i.e.

$$D = P + SM - FC, \text{ with } D \geq 0.0 \qquad (3.4)$$

Where D= drainage, P= rainfall/ponded water, SM= soil moisture and FC= field capacity.

At the end of the 1995 cropping season, in November, the neutron probe was used to measure potential drainage when no water percolates beyond the bottom of an access tube installed at the centre of the drum lysimeter. The method determines the characteristics of drainage in the field. An access tube was installed to a depth of 85 cm at the centre of soil filled drum, and the whole set-up was covered with a wooden frame to control evaporative water losses. The neutron probe was used to determine the initial moisture content in the soil at various depths between the mid-point and the bottom of the lysimeter.

Ponded water is added to the soil within the drum at some intervals spanning 24 hr while the neutron probe was used to monitor soil water content and the shift in the wetting front. The soil water measurement lasted for a period of 10 days. The

measured soil water content at the stage when drainage commenced gives the soil saturation point. The stage with additional water when there was no gradient in measured soil water with depth corresponded to soil full saturation point.

When full saturation was reached, the addition of water to the lysimeter stopped, while record of drainage was kept until it became zero after some days. The soil moisture when drainage ceased is the field capacity.

The wooden cover was removed thereafter, while soil moisture content measurement continued. The permanent wilting point when soil water content became constant with depth could not be determined because of some logistical problems on the field. The attempt made to determine wilting point by sowing sorghum, millet and cowpea under field conditions and monitoring soil water content when wilting occur did not succeed either.

Deep seepage is related to the total soil water storage (Wilcox, 1960). This assumption seem to suit the conditions on the experimental site because of the sandy nature of the soil, the predominance of macropores, and hence a general high porosity. The soil water storage determined at field capacity, using the method enumerated above, was used for the estimation of deep drainage losses during the 1994 cropping seasons.

During the 1994 cropping season, soil water status determination using the neutron probe, at the peak of the rainy season, was used to estimate field capacity within 24 hrs after a heavy rainfall.

3.5.3 Soil moisture determination

3.5.3 (a) *Neutron probe method*

A neutron probe, model 503 Hydroprobe (CPN corp., Martinez, California, U.S.A) which is a nuclear moisture depth gauge was used to measure soil moisture content at depths 25 to 105 cm with 15 cm increaments. The neutron probe uses a radio-active source and internal electronics.

The neutron probe emits fast neutrons from the Americium 241/Beryllium radio-active source. The emitted neutrons (from ^{241}Am mixed with Be) pass through a detector without causing a response and also get into the soil, bouncing around, and gradually slow down in the process (503 Hydroprobe Operating Manual, Martinez, California, U.S.A). The detector tube, a Boron tri-fluoride (BF_3) detector, is responsive to weak, thermal neutrons but not to high energy, fast neutrons. When the neutrons have bounced around sufficiently enough to slow down to a thermal level, they are then detected by the BF_3 tube.

However, the neutrons are dramatically slowed down if they collide with hydrogen atoms. Since the hydrogen atoms are of the same mass as the neutron i.e. the similarity in the mass of a proton and a neutron, the loss of energy in such collisions is great. In most mineral soils, the only source of hydrogen would be water, hence the major moderation of neutrons is water. When water is present in the soil, the neutron slows down sooner with fewer collisions and a high probability of a detected collision is increased over a dry soil condition. The detected collisions are converted by the internal electronics into counts which are recorded and displayed on an electronic panel on the instrument. The higher the soil moisture content, the higher the counts that are displayed on panel board.

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The neutron probe allows small changes in in-situ soil water storage to be estimated. These subsequent estimates, which are repetitive at the same place, are also not confounded with soil variability, as long as the sphere of importance (or influence) is not changing much.

3.5.3 (b) *Neutron probe calibration*

Calibration of a neutron probe is made by obtaining the reading of the instrument (counts and count rate ratio) for a range of independently determined values (Θ), usually gravimetrically. Field calibration was done for the neutron probe in 1994. The field calibration method (Bell 1976; Gardner 1986) was employed at five sites with a minimum of 50 m distance between these sites at the borders of the experimental field (about 0.5 ha). Two access tubes were installed two metres apart at each site using a soil auger designed specially to ream the access tube installation holes to size. The calibration of 1994 was done over the season to give good points of dry and wet soil conditions and conditions between the two ends.

On the selected days of neutron probe calibration, five standard water count readings were taken at the middle depth of an access tube identical to the field tubes, installed in the middle of a 220 litre drum and filled with clean water, before and after counting the soil. The average of the measured counts is used as the standard water count (w) for that day's calibration. The neutron probe was then lowered into the access tube at marked depths on these sites and the corresponding counts displayed were recorded. The counts (c) recorded at the depths concerned were divided by the average w to give the count rate ratio (n) for every depth measurement.

$$n = c/w \tag{3.5}$$

A soil profile pit was excavated leaving about 30 cm distance from the measured access tube. Gravimetric soil sampling commenced from 25 cm soil depth and subsequently at 15 cm intervals until 105 cm to correspond to the depths of neutron probe measurements. Care was taken to remove overlaying soil with a pick-axe and a sharp knife, used for cutting and removing soil layers to avoid compaction. Four/five standard observation core samples of 100.14 cm^3 (50mm * 51mm) were taken with a driving head close to the access tube at the depth of the neutron probe measurements. Care was taken to ensure that the level of the soil inside the sampler did not move during the driving. Core samples were collected within $\pm$2.5 cm of the depth of neutron probe measurement to centre the selected depth and minimise sampling error. The soil samples within cores were trimmed with a sharp knife to ensure accurate volume sampling. The procedure for soil core sampling was also rapid to preclude significant change in Θ between determining n and taking samples. A portable electronic weighing scale with a sensitivity of 0.01g was used for determining core weight immediately after every sampling in the field. Wetness and dry bulk density were determined gravimetrically. The drying of the soil samples after initial weighing was carried out at 105°C to constant weight while the volume is the volume of the core sampler. The soil gravimetric water content is computed by:

$$W = (M_w - M_d)/M_d \ (g\ g^{-1}) \tag{3.6}$$

where M_w is the wet mass of the soil core (g) and M_d is the dry mass of the soil core

(g).

The soil bulk density (δ) is calculated by dividing the mass of dry soil core with the volume of the core i.e.

$$\delta = M_d/V \text{ g cm}^{-3} \quad (3.7)$$

where V is the bulk volume in cm^3.

Volumetric water content (Θ) is computed by multiplying W by δ, where necessary for every depth.

The calibration of the neutron probe was done regressing n on Θ to establish the required regression calibrations for the different depths.

$$n = a + b\Theta \quad (3.8)$$

where a represents the regression constant (intercept) and b is the regression coefficient (slope).

3.5.3 (c) *Access tube placement in relation to crop rooting pattern*

Crop rooting characteristics in relation to their sensitivity to water extraction in the soil was assessed by installing three access tubes placed 10, 20 and 30 cm from a millet stand (2 plants) sown in the field with a spacing of 1 m by 0.75 m. The neutron probe was used to measure the trend of soil moisture profile from 2 WAS to millet maturity. Soil moisture profile measurements during wetting, i.e. from wilting point to field capacity, and drying periods were used to determine the most sensitive

root extraction point for the optimum placement of the access tubes used for representative crop water use assessment.

3.5.3 (d) *Layout of access tubes in the experimental plots and moisture measurement*

Aluminium access tubes with water-tight seal at the bottom, were installed and placed 10 cm from crop stands within the area marked for final harvest. The installed access tubes were tagged to the stand of every component crop involved in the cropping system on a plot. For example in the millet/sorghum/cowpea intercrop plot, with millet, sorghum, cowpea grain type and cowpea fodder type, four access tubes were installed, each tagged to one crop stand to represent a replicate. There were three replicates for each of the crops within the different cropping system X soil fertility treatment combination. Three access tubes were also installed in areas without vegetation at the border of the experimental field every year, as the control.

The installation of access tubes was done manually with the aid of a drilling auger, which created a hole of the exact outer diameter of the access tube (45 cm). The tight fitting of the tube in the soil along its whole length ensured the elimination of measurement errors in count rates, that could result, if water entered the air gap between a loosely fitted tube and the soil. Access tube installation was to a uniform depth of 110 cm (Maximum length of access tubes available was 120 cm) with a fixed length of 10 cm exposed above the soil for all tubes. The fixed length of access tube above ground level ensured the correct depth placement of the probe at cable marked positions to represent the 'active centre' of detection and reduce systematic count errors.

Each access tube's open side above the soil is covered with a tin, which was also numbered for easy identification, to prevent water from getting into the tubes, after measurements. The preset time for the display of measured counts in the soil was 16 seconds. Data collection and the first neutron probe readings commenced on 17 July 1994 and 5 July 1995. These periods corresponded to 3 WAS millet. The neutron probe was used for soil moisture assessment at 7 and 14 days intervals until the time of harvest of sorghum, which was the last crop on the field in November 1994 and 1995. In 1995, neutron probe measurements were taken at least 2 days after a rainy day. Neutron probe estimations of soil water content were made between 07.00 and 11.00 hr, while the readings given in counts are displayed on a panel of the instrument. The count (c) recorded per depth measurement inside the soil was expressed as a fraction of the standard water count recorded per day of record taking to give n and to minimize the measurement bias that could result from instrument drift.

The standard water count was taken by lowering the probe into the drum of water through an installed access tube, sealed at the bottom to disallow water contact with the probe source, at the beginning and end of daily soil measurements. Five readings were taken at the mid-point within the drum for each of the periods of measurement and the overall mean is used as the standard water count (w). The n was determined as explained by equation 3.5 in 3.5.3 (b). Soil moisture determination using the neutron probe was done at 15cm intervals between 25 cm and 100 cm soil depth.

3.5.3 (e) *Gravimetric soil moisture determination*

Concurrently with the neutron probe measurement, gravimetric soil sampling

of surface soil was carried out to determine moisture content at shallow depths, for which the neutron probe is not suitable. Using an auger of 170.19 cm^3, gravimetric soil samples of surface soil (0-15 cm), taken on the same day as neutron probe readings, were weighed and oven dried at 105^0C for 48 hrs. for water content determination. Since the volume of core taken with the auger is known, the Θ was determined using the methods enumerated in 3.5.3 (b). The gravimetric sampling of surface soil had to be done to avoid the reduction in the n due to an escape of neutrons to the atmosphere in the loose, low water retaining, sandy soil of the trial field. The escape of neutrons would lead to the under-estimation of Θ. There were three replications of gravimetric water determination of surface soil samples per treatment, in accordance with the patterns used with the access tube placements in plots, as explained in section 3.5.3 (d).

3.5.3 (f) *Soil water storage*

The n from a neutron probe measurement at a particular point in the soil, in relation to a crop, is used for computing the corresponding Θ (cm^3 cm^{-3}) from the calibration equation 3.8 as $\Theta = (n - a)b$.

To calculate the equivalent depth of available water stored per unit depth of soil at a specified period during crop growth, soil water storage (Θ_A) is given by

$$\Theta_A = I_S * \Theta \qquad (3.9)$$

where Θ_A is the available soil moisture (cm water/cm soil depth) for a soil depth increment of 15 cm, I_S is the depth of soil (for us 15cm) and Θ is the soil volumetric

water content (cm^3 water cm^{-3} dry soil). For the soil profile depth of 105 cm, the total moisture Θ_t content of the measured soil in each sub-depth for a date of measurement is expressed by the relation:

$$\Theta_t = \Theta_A(15) + \Theta_A(25) + \Theta_A(40) + \ldots + \Theta_A(100)] \qquad (3.10)$$

Θ_t, for the soil profile depth of 0-110 cm, corresponds to an estimate of the total soil water storage on the date of measurement. The difference in the Θ_t values between two separate days of measurements gives an indication of the change in the available soil water content and can be used for the calculation of crop water use.

3.5.4 Crop water use

Crop water use (ET) was calculated for every crop in the different cropping systems, using the water balance equation method. The crop water use based upon a time period (7-14 days) at various stages during crop growth is calculated as:

$$ET = (SAW_a + RF) - D - R - SAW_b \qquad (3.11)$$

where ET is the crop water use over a time period, SAW_a is the measured initial soil profile moisture content at the beginning of a time period, RF is the total cumulative amount of rainfall within the time period, D is the total deep drainage loss, R is the run-off and SAW_b is the final soil water storage measured at the end of the time period. All parameters in this equation are expressed in equivalent depth of water in

millimetre over a time period. The sum of periodical crop water uses for the whole period of crop growth, from establishment to maturity, gives an estimate of the seasonal crop water use and in essence an estimate of the total crop water requirement if no stresses occurred.

3.6 Root studies

3.6.1 Sampling procedure

Root samples were taken by auger from the different cropping systems during 1993, 1994 and 1995 seasons, using the bore hole method. In these cropping systems, the different crops in combination were arranged and spaced at regular intervals. Root samplings were carried out with a view of identifying the smallest land area containing all the possible systematic variation in root distribution caused by the planting patterns. During the 1993 cropping season, root sampling was done for the sole crop treatments alone, while in 1994 and 1995, the sole and intercrop treatments were sampled. The root sample area in the sole cropping systems was a modification of the sampling procedure used by Vos and Groenwold (1986) and shown in Fig. 3.3. The plant hill, which represents the area allocated to a plant stand, was sampled manually with the aid of an auger as shown in Fig. 3.3. In the direction of the ridge, sampling was every 10 cm at four directions, at 3 positions in every direction of a sampled plant.

During the 1993 season, perpendicular to the ridge, only positions (i), (ii) and (iii) were sampled at 4 WAS for each of the component crops, while position (o) was added to these positions at the second sampling, done at the commencement of the

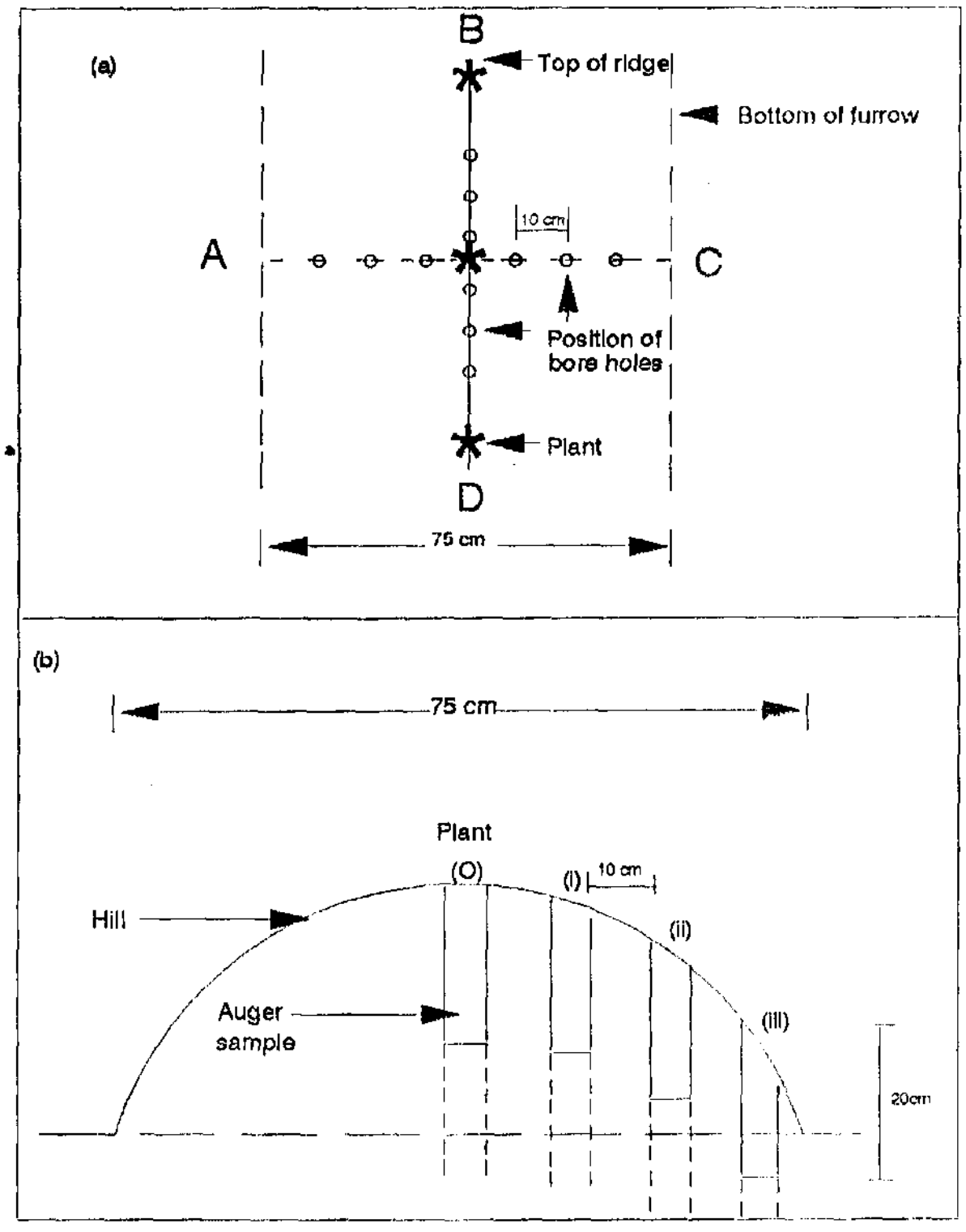


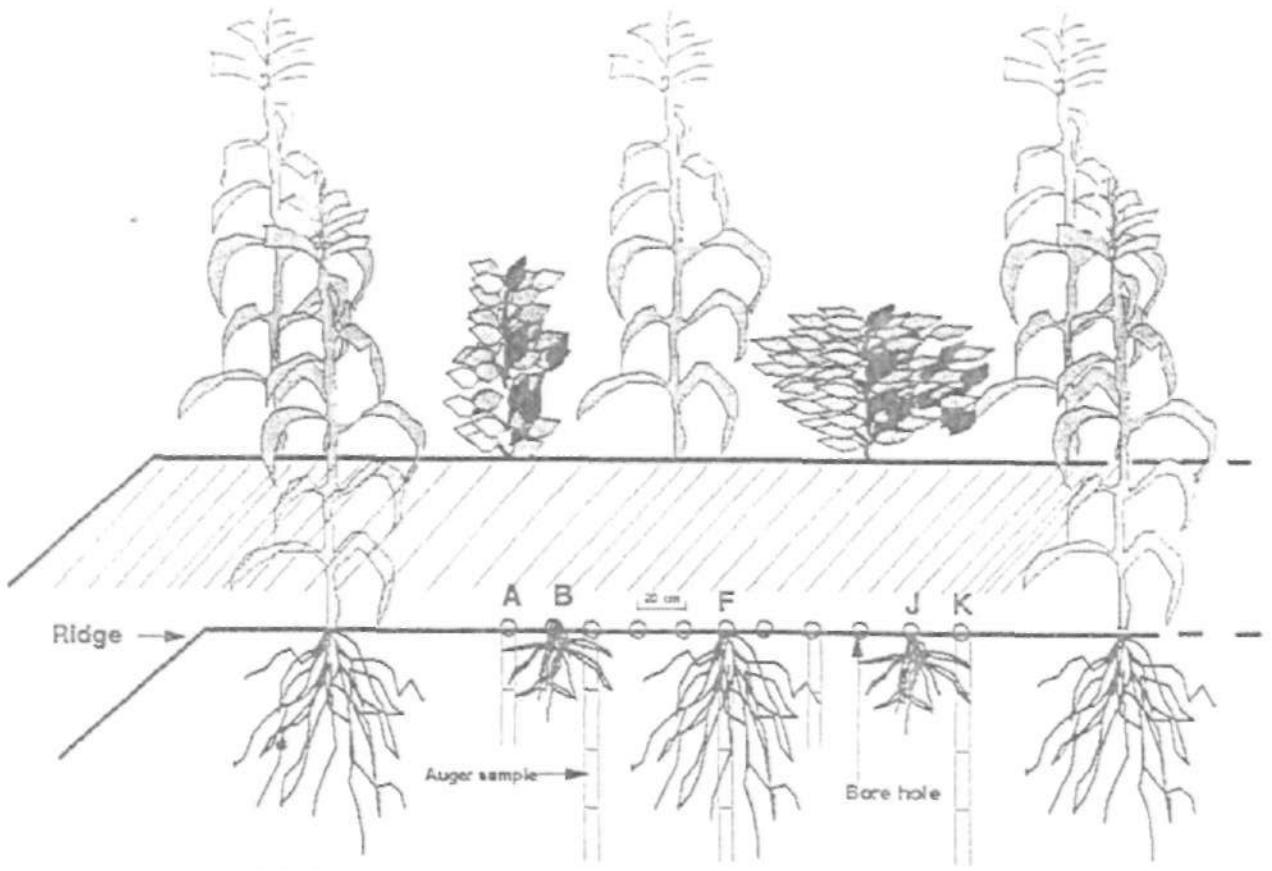
Fig. 3.3 Schematic representation of the pattern of root sampling (a) showing cardinal directions A, B, C and D and (b) showing vertical cross-section of sampling pattern of hills and layers below in sole crops.

reproductive stages of the various crops. In 1994 and 1995, sampling area were positions (o), (i), (ii) and (iii) at the two sampling periods already mentioned above in the sole crops. However, during the 1994 and 1995 seasons, when both sole and intercrop systems were sampled, the bore hole method was used for positions A to M, on a ridge, and involved the different crops in combination. This was to identify land area containing possible systematic variations in root distribution, caused by the planting patterns and the different crops in the intercrops (Fig. 3.4).

During every sampling, the plant shoot was cut and removed at the soil level. The auger sampler with a diameter of 3.8 cm was hammered vertically into the hill to a depth of 20 cm i.e. length of core, and at successively every 20 cm to the maximum depth of rooting. At 4 WAS, the depth of sampling was 1m (5 samples per hole), while at the start of the different reproductive stages (8 WAS millet, 12 WAS sorghum, between 6 and 7 WAS IT86D-719, IT88D-867-11 and IT89KD-374 and 10 WAS Dan-illa cowpea varieties), depth of sampling was to 1.6 m below the plant (8 samples per hole). Two replicates of all the cropping systems were used for the root sampling studies.

Soil auger samples were put into coded plastic bags, and thereafter taken to the nearby Jankara Lake shore, where roots in the cores were washed out manually with water over a 2mm sieve, placed on another 0.5 mm aperture sieve, to aid in the recovery of the finer roots that must have passed through the bigger aperture sieve. Roots were separated from other organic debris, while the discerned 'live' roots were picked using forceps. The roots extracted from each core sample were put in a labelled plastic bag and stored at about -20^{0}C until processing.

A simplified millet-cowpea intercropping System



Millet/grain cowpea type/millet/fodder cowpea type/millet/.....

Fig. 3.4 Schematic representation of the pattern of root sampling in a typical intercropping system, showing positions of bore holes (A, B,...K) and vertical cross-sections of sampling pattern of a position and layers below.

In the intercropping systems, it was difficult to distinguish roots of the component crops, and a mixture of the roots of the component crops, where applicable, had to be accepted. Root sample collections were made during the rainy seasons of the years of field experiments, and at the time of sampling at 4 WAS, in 1994 and 1995, the soil within the depths of rooting was near field capacity. At the start of the reproductive stage, soils were at or more than field capacity, except in the high fertility sole millet system, during the 1995 season, where the soil available water was less than the estimated field capacity.

During the 1995 cropping season, an observatory trial was conducted to show the differences in the characteristics of the rooting systems among the different crop components. A plywood box with a dimension of 80 cm height, 60 cm width and a compartment space of 5 cm, was lined internally with white polythene sheets and filled with top soil (0-30 cm depth) from the experimental field (Plate 3.4). These boxes were watered and buried in a trench dug at the border of the field. Seeds of millet, sorghum and cowpea were sown in the moist soil within the boxes and thinned to two plants, one week after emergence. These boxes with the different crops were left to grow under field conditions during the season until 4 WAS, when the boxes were dug out. The box with the sorghum plant was discarded because of the poor growth observed. One side of each of the boxes was opened leaving the polythene sheet lining to hold the soil and roots intact.

A wooden board with 6 inch iron nails, spaced at 2 cm apart, was forced into the opened side of the box, while the other side of the box was carefully removed without disturbing the plant roots and soil within the plastic lining.



Plate 3.4 Millet in a root box at 4 weeks after planting for observatory root distribution pattern.

The plastic sheet on the open side of the box was removed, and a fine spray of water, under pressure, was used to remove all the soil materials, leaving the intact roots held by the nails in their respective positions. After the soil had been washed out completely, leaving the root systems, they were photographed without removing them from the nail board, to show the rooting patterns of the different crops.

3.6.2 Root sample processing

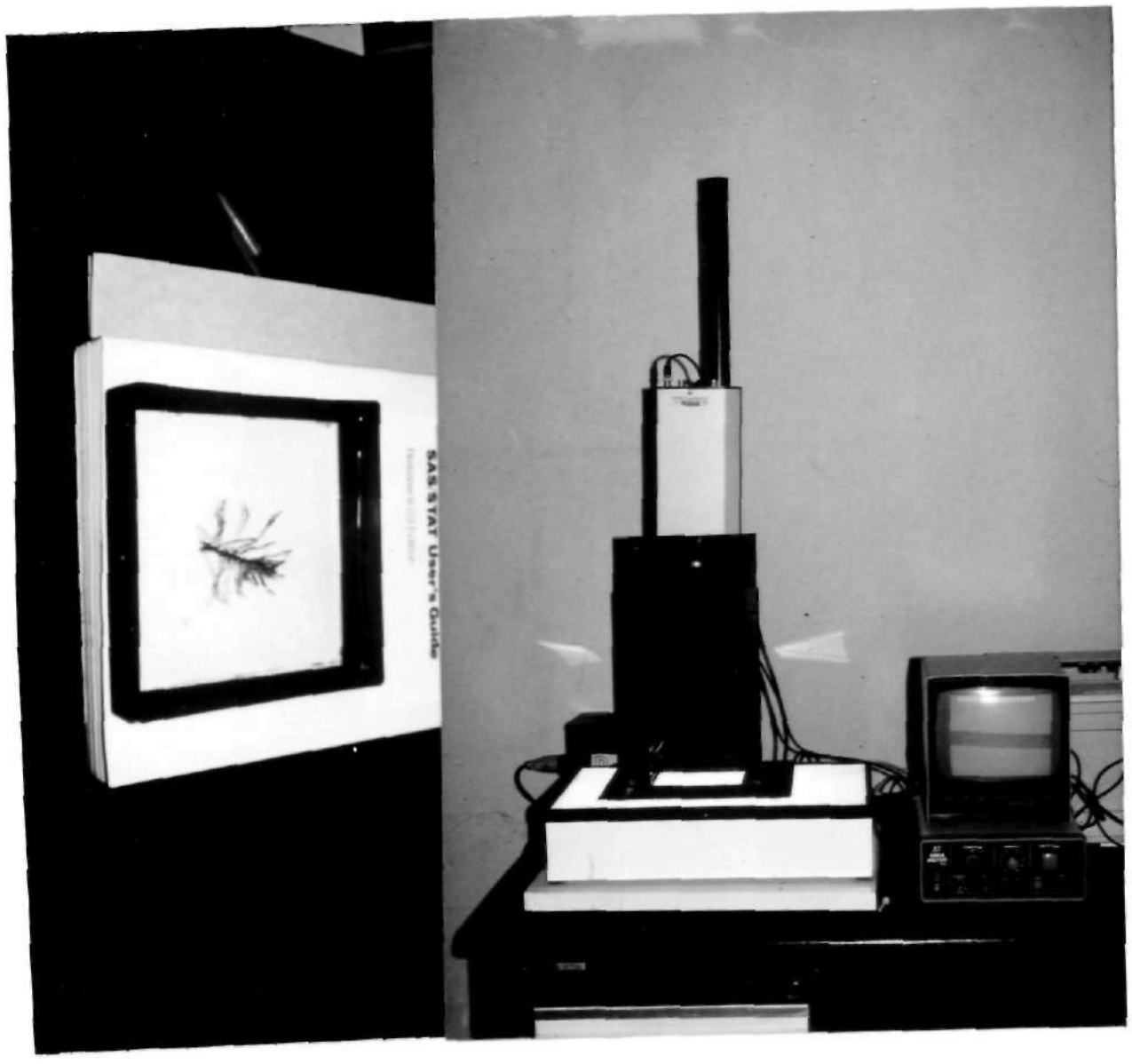
The root samples in coded bags were thawed and separated in a petri dish filled with water. The separation of the roots was to reduce overlap and congestion on a spot, that could cause an error by underestimating root length measurements. The separated root samples were stained using methylene blue dye, to give a strong contrast between roots and the background during measurements and provide better counts with roots. Where high densities of root were obtained from washed cores, they were subdivided into smaller samples, before their dispersal on the trays (Plate 3.5a) with a specified area, used for root measurement, in the Delta-T automatic image analyzer (Plate 3.5b).

3.6.3 Equipment calibration and measurement procedure

Root length measurement was accomplished using a Delta-T Area Meter (Delta-T Devices Ltd, Cambridge, England). The equipment was adapted from an unpublished manuscript by Grant Harris (1986) and Harris and Campbell (1988) and consist mainly of a high-resolution video camera and a comparator, which counts the number of intersections between TV lines and roots in the view area.

The Delta-T image analyzer comprises of a video camera, mounted on a stand and connected to the Area metre, while the Area metre is also connected to a video monitor. A light box is placed on the camera stand base, while the root box is also on the light box. The camera lens is positioned over the hole on the root box by screwing the cross arm of the camera stand into the threaded socket in the base of the camera. A root tray with a black thread is placed in the root box, while the camera lens opening is adjusted to focus the target. All other adjustments were effected with

reference to the Delta-T Root Length Measurement System User Manual.



Plates 3.5 (a) A stained root subsample dispersed on a tray prior to root length measurement on (b) the Delta-T image analyzer system.

The calibration procedure was tested with the camera positioned 26 cm above the root tray, while the window width and height adjustments inside the area meter were at 12 x 12 cm. The measurement period for length measurements and other control adjustments were set on the area metre. Calibration was done using 20 cm lengths of 0.25 mm diameter white cotton thread, stained with methylene blue dye. The threads

were formed into various circular shapes to simulate random orientation with respect to scan lines and placed in the target area of the root box. More 20 cm length threads were successively added to the root tray and data taken at each point. Two readings were taken, the second after the tray was turned 90° and returned into the root box. The average of the two readings (counts) was used for the estimation of length. Readings were accumulated from zero to 120 cm length of thread.

The calibration curve was obtained from a graph of average counts versus actual lengths using the equation:

$$a = bx \tag{3.12}$$

Where a is the average counts, b the slope and x is root length (cm).

3.6.4 Root length (RL) and root length density (RLD) determination

The counts for root length measurements were recorded with the same camera settings as during the calibration of the image analyzing equipment. Root samples and subsamples, where necessary, were measured following the calibration methods, with an average of the two readings per measurement recorded. The length of the root sample can then be calculated from the calibration equation as earlier enumerated. The total root length (RL) for a core sample position relative to a known distance and depth from a plant, is the sum of the subsamples from a core. The volume of the auger sampler used for root sampling is 226.8 cm^3. The root length per unit volume of soil (cm root length per cm^3 of soil) is expressed as:

$$\text{Root length density (cm cm}^{-3}) = \frac{\text{Estimated root length (cm)}}{\text{Volume of core (226.8 cm}^3\text{)}} \qquad (3.13)$$

During the three years of RLD estimation, only two plots were sampled because of the intensive sampling method adopted. This was to reduce the effect of soil variation typical of the Nigerian semi-arid zone, that may be due to fertility and other soil factors. Plot means were averaged to obtain treatment means used for explaining the rooting patterns of crops. The root length density would provide an estimate of the actively absorbing root surface area in sole and intercropping situations, at the stages of crop growth under consideration, and in relation to crop performance under these systems.

3.7 Crop yields and yield components

During the cropping seasons of 1993, 1994 and 1995, designated sample areas, with at least 1 m distance within the plots, away from the border rows, were permanently marked for repeated radiation interception, soil temperature and soil water content measurements. These areas were 84 m^2 and 15 m^2 in the intercrop and sole crop plots respectively. At crop maturity, these areas represented the final harvest areas for the different experimental units. All the experimental plots in the trials were considered for the assessment of crop yields and yield components i.e. four replications in the intercrops and three replications in the sole crop systems. Parameters considered before crop maturity and harvest were the final plant stand per harvest area, days to 50% flowering (cowpea) and head formation of millet and sorghum components. At maturity, the respective final harvest areas per plot were harvested for seeds and dry matter yield. The whole plant stands within harvest areas

were cut at ground level, while the pods from the cowpea plants were hand picked and the millet panicles and sorghum heads were separated from the stover. A subsample of the harvested organs was taken, and along with the remaining bulk net harvest, labelled separately; the total number of pods/panicles or heads and their air dry weights per plot were determined per sample. Harvested organs of the air dried bulk samples were threshed and seed yield determined. The subsamples of harvested organs were oven dried at 60°C for 48 hr, to determine moisture contents. These subsamples were subsequently used to convert final yields to a dry weight basis. The stover and haulms from the final harvest areas per plot were also subsampled and oven dried, before the conversion of their final yields to a dry weight basis. In addition to the panicle/pod weights, stover/haulm weight and grain weights, the total dry matter production per plot was also estimated. All these parameters were converted and expressed in kilogram dry weight on a per hectare basis.

To assess the efficiency of the utilization of resources in the partitioning of assimilates to the harvested organs of crops, within the various cropping systems, the harvest index (HI), i.e. the ratio of the harvestable yields (seeds) to total dry matter produced at maturity was determined.

The number of parasitic *striga* (Striga gesnerioides) plants attached to cowpea components, that had emerged at various stages of reproductive development within the marked final harvest areas in the cropping systems involving cowpea were counted during the 1994 and 1995 cropping seasons. This was with a view of assessing the effects of the intercropping of cereals with cowpea on *striga* behaviour.

CHAPTER 4

RESULTS AND INTERPRETATION

4.1 Weather and its influences

4.1.1 General

The climatic features of the Minjibir research farm site in the trial years are described in comparison with Kano long term and short term data given in Table 4.1 (Jagtap *et al.*, 1994) and shown in Figures 4.1-4.5.

The long term (1960-1995) average value of annual rainfall is 721.6 ± 176.4mm. The monthly total rainfall pattern is unimodal, with August as the wettest month, when rainfall normally exceeds potential evaporation. Within the period of experimentation, from 1993-1995, an exception occurred in 1995, where the monthly rainfall never exceeded the potential evaporation (Fig 4.5). Solar radiation is high throughout the year with only relatively minor variations in the months. Periods of the small radiation depression are associated with the Harmattan dust and cloud covers during the rainy season. This area is also characterised by high average monthly maximum temperatures and low minimum temperatures during the year, the difference ranging from 11-15^{0}C. The Harmattan period of December to February is associated with the lower temperatures, while high air temperatures are recorded between March and May, before the start of the rainy season. Kano has a very high range in terms of average monthly relative humidity (8-83%) when compared with locations at lower latitudes within Nigeria.

A comparison of the rainfall patterns during the 3 years of experiments with the long term average, as shown in Figure 4.1 gives the following:

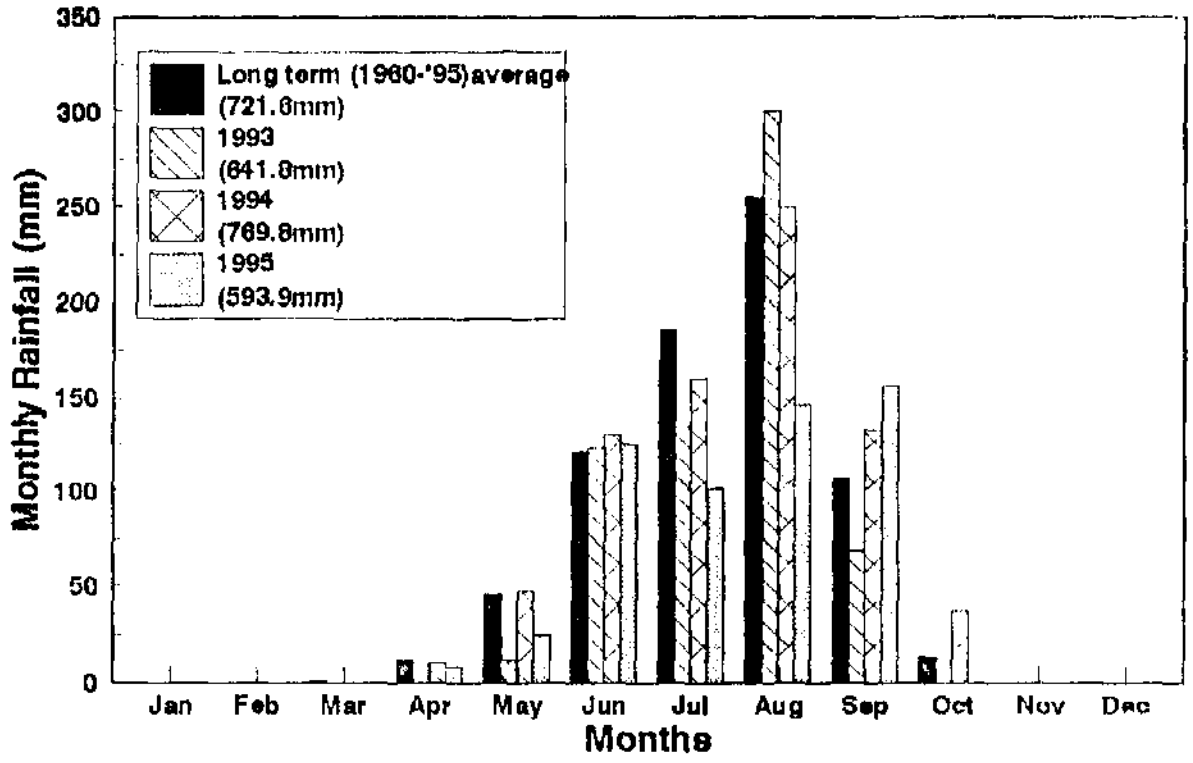


Fig. 4.1 Monthly total rainfall from 1993 to 1995, and long term snaverage, IAR/IITA Research farm, Kano, Nigeria.

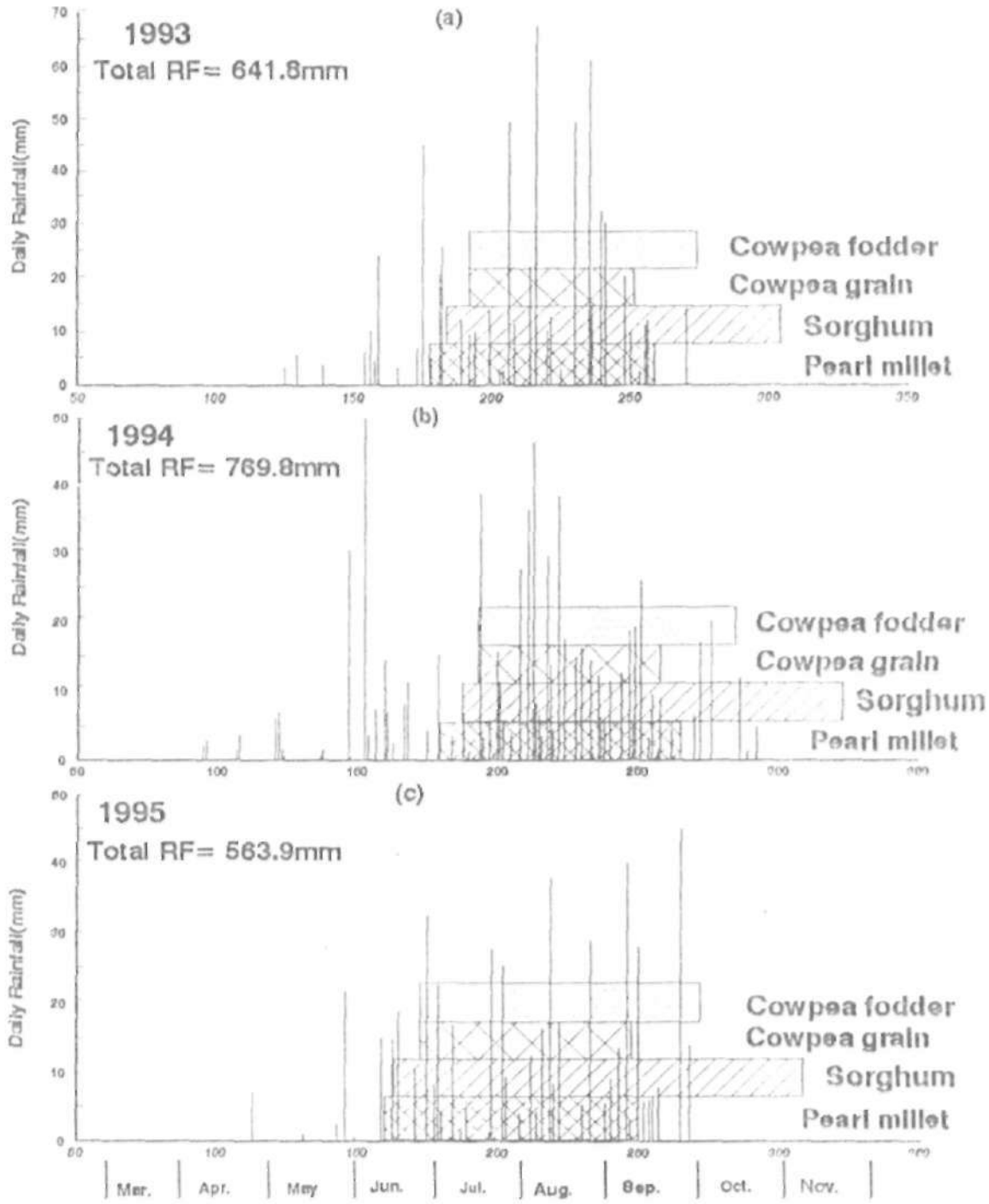


Fig. 4.2 Rainfall distribution in relation to component crops growth cycle in intercropping.

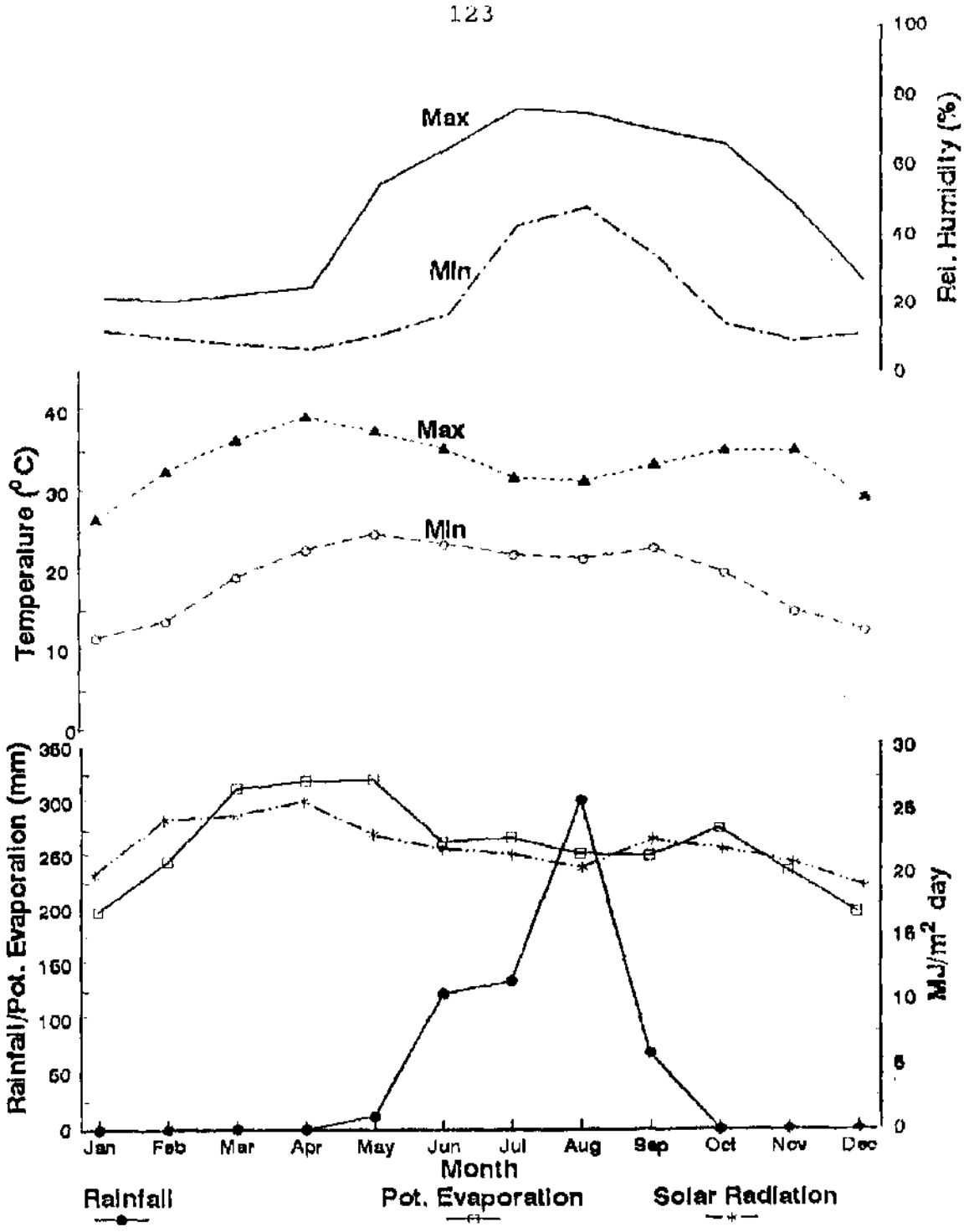


Fig. 4.3 Monthly totals/averages of weather variables for 1993 at IAR/IITA Research Farm, Kano, Nigeria.

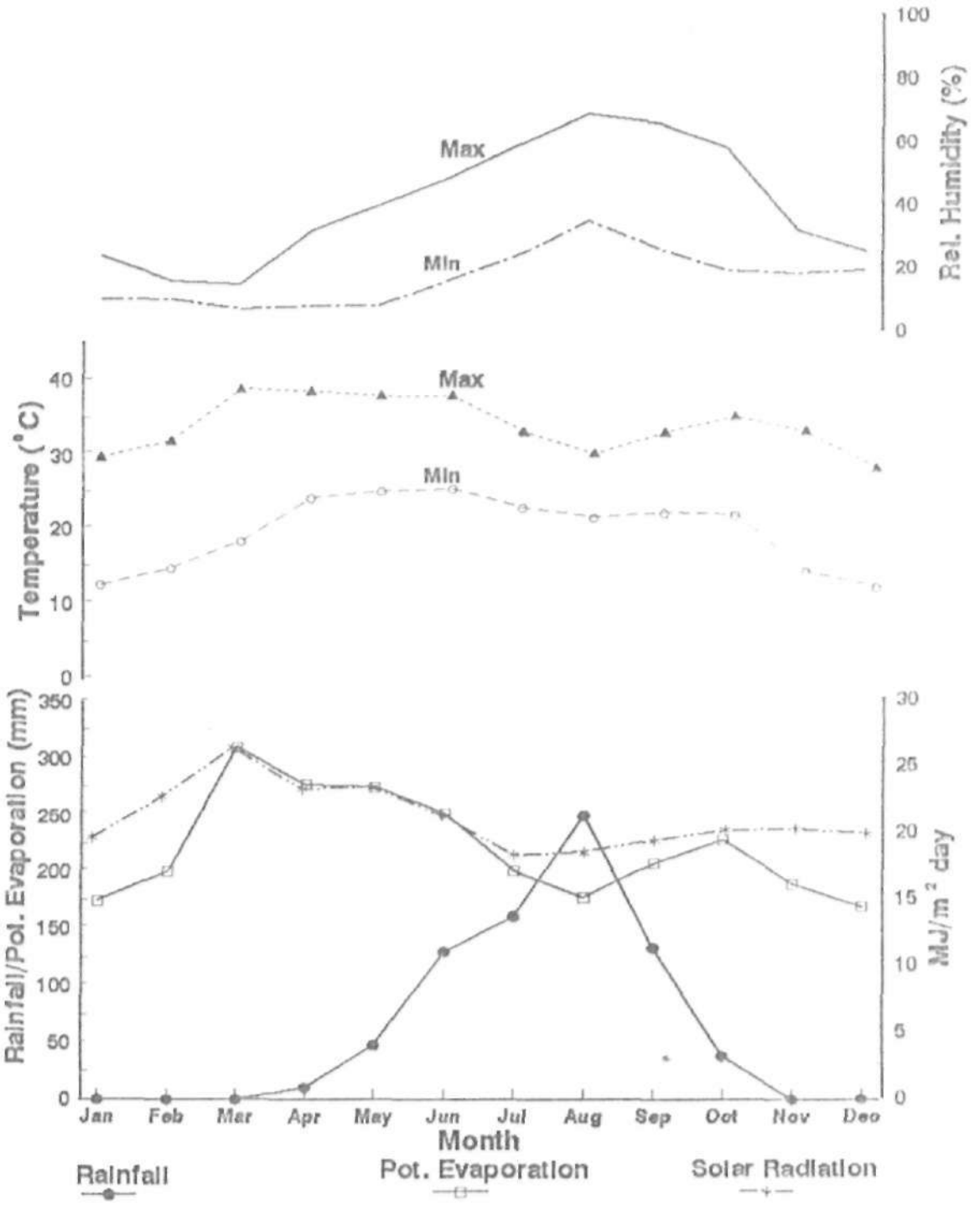


Fig. 4.4 Monthly totals/averages of weather variables for 1994 at IAR/IITA Research Farm, Kano, Nigeria.

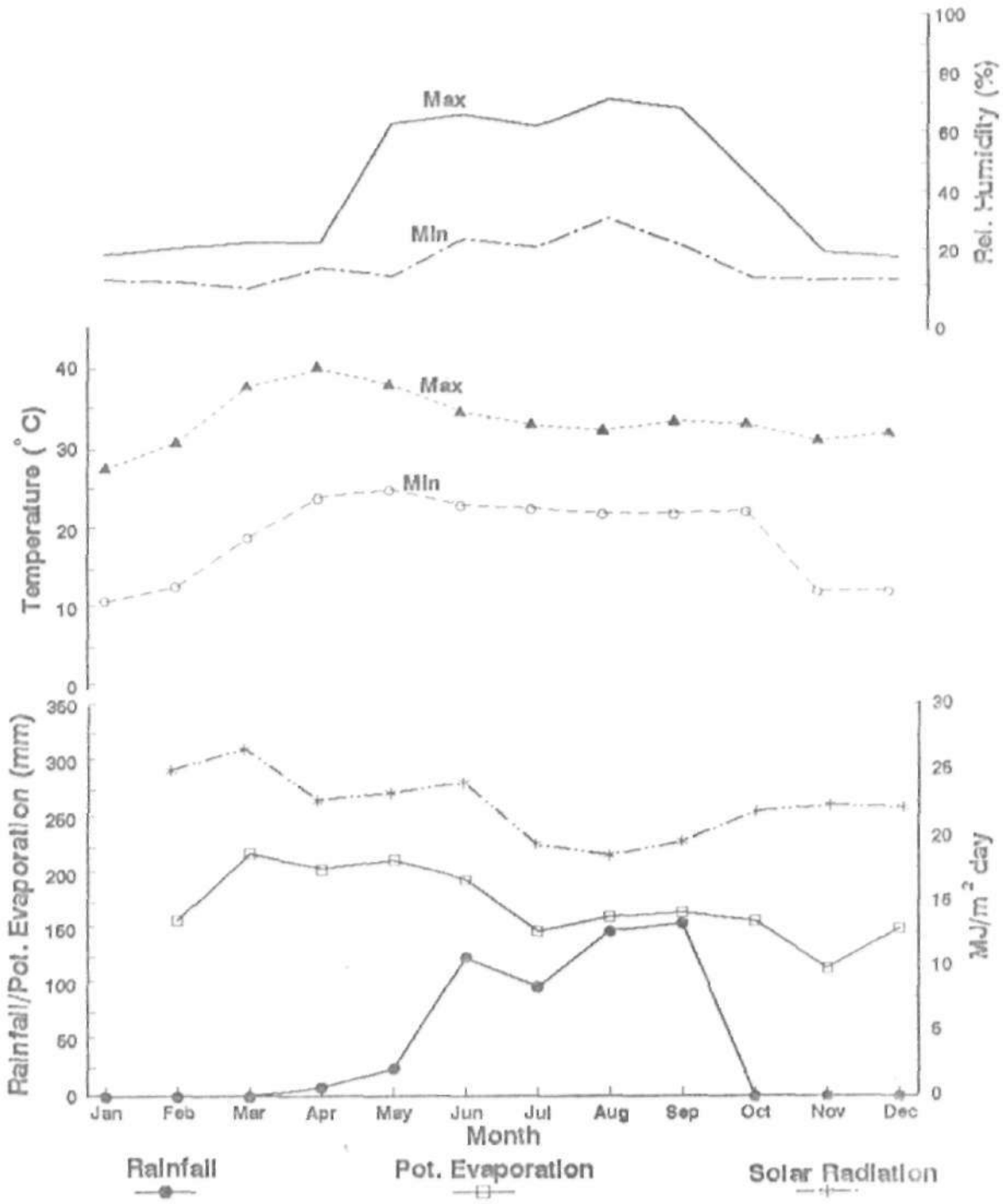


Fig. 4.5 Monthly totals/averages of weather variables for 1995 at IAR/IITA Research Farm, Kano, Nigeria.

i. the rainfall amount for 1993 (641.8 mm) was 11% less than the long term average for Kano,

ii. 1994 recorded the earliest rainfall and was the wettest year with an annual total rainfall of 769.8 mm, which was 7% above the long term average for Kano, and

iii. 1995 recorded the least annual rainfall of the three years with a value of 564 mm, 22% less than the long term average for Kano.

There were no clear departures from the annual trends of air temperature, solar radiation and relative humidity between the 1993, 1994 and 1995 weather situations when compared with the long term averages for Kano (Jagtap *et al.*, 1994). A comparison of the 1993, 1994 and 1995 weather data showed no major differences over these years in these parameters mentioned (Figs 4.3, 4.4 and 4.5).

Table 4.1

KANO WEATHER DATA (Long term averages and/or basic statistics)				
	Rainfall (mm) (1960-1995)	Solar Radiation ($MJ\ m^{-2}\ y^{-1}$) (1990-1995)	Avg. monthly *Air Temp.*(°C) (1973-1995)	Avg. monthly *Relative* Humidity.(%) (1973-1995)
Average	721.6	7671.82		
Standard Deviation	176.4	390.38		
Maximum	1141.5 (1962)	8117.88	27 (Jan)- >37 (Apr)	83 (Aug)
Minimum	374.2 (1974)	7110.23	12 (Dec)- 24 (May)	8 (Mar)
Range	767.3	1007.61		75

4.1.2 **Rainfall**

The onset of rains in 1993 was late, but became steady thereafter to allow the establishment and growth of crops by late June/early July (Fig. 4 a). During the 1994 season, the earliest useful rains experienced were prece· · d by a prolonged dry spell. Although the rains started in May, with adequate soil moisture for planting to start, most of the farmers waited for the end of the muslim 'Ramadan' festival and the periods of pilgrimage to Mecca (Saudi Arabia) before planting commenced in June. Planting with very early rains, before June, is anyway thought to be too risky and thus avoided by the farmers. However, the amounts of rainfall from early to mid June were not sufficient for the establishment and growth of crops until early July. Rainfall amount between early and mid-June could not meet the high evaporative demand from the environment during this period. Pearl millet and sorghum were resown three times between late June and early July before rains became steady (Fig. 4.2b). The 1995 rainfall ensured earlier sowing and establishment of crops in the sole and intercropped plots (Fig. 4.2c). Although the total amount of rainfall was 22% lower than the long term average, its distribution from July favoured the growth and development of the crops to maturity with good crop performance (Fig. 4.2c).

Rainfall distributions for 1993, 1994 and 1995 extended at least into the second week of September, hence ensured enough moisture for the maturity and good grain yields of pearl millet and grain type cowpea, which were harvested before the end of September (Fig. 4.2a,b and c). The fodder cowpea also performed well within the period under consideration. An exception was during 1994 season with a rainy season that extended into October which affected cowpea and sorghum yield qualities. The extended rainfall distribution into October was accompanied by a lot of cloud cover

and high relative humidity, which caused diseases and pest attacks and poor crop quality at maturation. On the other hand, the end of the rains in 1995 recorded relatively clearer sky, lower relative humidity and higher air temperature that favoured the drying process of grain at maturity and hence a better crop quality.

The rainfall in September, towards the normal end of the rainy season, is an important determinant of the amount of water stored in the soil when the rains ends. The fodder cowpea and especially the sorghum components mature using this stored water. While good sorghum yields were obtained in 1994 and 1995, lower yield was recorded in 1993, because the sorghum had to mature under moisture stress conditions (Fig. 4.2a).

4.2 Soil analysis

4.2.1 *1994 cropping season*

The seasonal details of the soil analysis results are in Appendix 4.1a and b, and the summaries of the soil analysis results are shown in Table 4.2. The particle size distribution of the 1994 pre-planting samples showed that the surface soils were in general loamy sand (USDA) in texture with the sand fraction (86% $\pm$ 1.3), dominated by the fine sand fraction, while clay and silt fractions were $<10\%$. The average surface soil bulk density was 1.5 Mg m^{-3}.

The soil pH in water varied from weakly acid to neutral with an average value of 6.1 $\pm$ 0.45. Based on the ratings for soil fertility classes in the Nigerian savanna (Esu, 1991 adapted from Hill and Rackham, 1973), soil total nitrogen was rated to be very low, its weight ranging from 0.03-0.06 % i.e between 6.3 and 12.6 kg

nitrogen per hectare (0-15 cm soil depth). The result of the organic manure analysis (Table 4.3) showed that it contained a high amount of nitrogen (about 0.7%) which added, in 4 t ha^{-1}, about 28 kg ha^{-1} nitrogen to the soil at planting. The percentage organic carbon present in the soils was very low (0.32 $\pm$ 0.05%). Soil available phosphorus ranged from medium to high, while the applied organic manure also contained some amount of P (about 2.0 kg ha^{-1}), thus supplementing the amount of P in the soil.

Soil Ca, Mg, K and Na were all low, with a resultant low Cation Exchange Capacity (CEC) which varied from 1.4 to 2.1 centimoles(+) per kilogram of soil (cmol(+)/kg). The very low clay and organic matter contents of the soil are responsible for the soil's low cations retaining ability, and hence its low capacity to hold nutrients against leaching during the cropping season.

The applied pre-planting organic manure increased the soil total cations by as much as 61.5 cmol(+) kg^{-1} (Table 4.3). The manure cations may improve soil fertility status appreciably if retained in the soil and when released for plant use. Soil extractable micronutrients Cu, Zn, Mn and Fe were above the critical levels reqiured for cereals growth (Lindsay and Norvell, 1978). The pre-planting organic manure application also added substantial amounts of these micronutrients to the soil (Table 4.3). The post-harvest soil particle size distribution analysis seem to have shown a slight improvement in soil textural classes in some plots associated with intercropping when compared with sole cereal systems. The sole cowpea treatments also experienced such a slight improvement in soil texture. Most of the textural improvements were associated with an increase in the silt and a reduction in the sand fractions of the soils (Appendix 4.1b).

Table 4.2 Some physical and chemical properties of the experimental plots at IAR/IITA Research farm,Minjibir,Kano.

Soil characteristics	1994 (pre) (9)[a]	1994 (post) (20)[a]	1995 (pre) (9)[a]	1995 (post) (18)[a]
Soil texture (%)				
Sand	84-88	80-90	86-88	86-90
Silt	4-8	4-12	6-10	2-4
Clay	8-10	4-10	4-7	6-10
pH				
Water (1:1)	5.6-7.1	5.0-6.9	6.6-7.3	5.9-7.4
$CaCl_2$ (0.01M)	4.9-5.8	4.9-6.1	*	*
Organic Carbon (%)	.24-.38	.12-.60	.22-.38	.26-.39
Total Nitrogen (%)	.03-.06	.01-.07	.03-.04	.02-.04
C:N ratio	4.6-9.1	2.1-12.9	6.5-11	8.5-18
Phosphorus				
Available P (Bray1) (mg kg^{-1})	10.7-22.4	8.1-32.3	10.7-19.7	9.8-24.7
Exchangeable cations (cmol(+) kg^{-1})				
Ca	.53-.84	1.2-2.9	1.1-2.2	1.3-2.4
Mg	.24-.41	.34-.83	.44-.89	.20-.50
K	.04-.08	.15-.35	.12-.28	.10-.40
Na	.01-1.0	.16-.37	.30-1.42	.20-.40
CEC (cmol(+) kg^{-1})	1.4-2.1	2.1-4.8	2.1-3.6	2.2-3.1
Extractable micronutrients (mg kg^{-1})				
Cu	.15-.30	.25-1.51	.20-.50	.4-1.3
Zn	.80-2.2	3.3-8.5	.30-1.9	1.6-4.0
Mn	5.6-8.7	*	18.6-30.2	15.0-25.6
Fe	6.9-9.5	2.2-17.7	*	5.5-10.3

pre - preplanting soil samples
post - post-harvest soil samples
* - data not available
a - Number of samples in parentheses.

Table 4.3 Some chemical properties of the organic manure (cow dung) applied to the experimental plots at IAR/IITA Research farm, Minjibir, Kano.

Manure characteristics	1994 Amounts applied (4000kg/ha)	1995 (6000kg/ha)
pH		
Water (1:1)	9.1	*
Total Nitrogen (%)	0.7	0.4
Phosphorus		
Total P (Bray1) (mg kg^{-1})	500	163
Total Bases (cations) (cmol(+) kg^{-1})		
Ca	29.0	13.4
Mg	13.0	6.3
K	11.5	13.3
Na	8.0	11.3
Total Micronutrients (mg kg^{-1})		
Cu	2.8	18.0
Zn	55.0	95.4
Mn	120.0	95.4

* - data not available

The soil pH slightly decreased towards the weakly acid (from 6.1 $\pm$ 0.45 to 5.8 $\pm$ 0.5) conditions, but the higher number of samples in the post-harvest case may be partly responsible for the larger ranges. Soil nitrogen (0.32 $\pm$ 0.05%) were on the average slightly lower than the pre-planting values and varied more widely, from 0.12 to 0.60%, again partly due to an increased number of samples (Table 4.2).

A decrease in soil available P (from 16 to 13 mg/kg) was generally observed in the sole cowpea plots lower than the soils from the intercropped (remaining 16 mg/kg) and sole cereals (20 mg/kg) treatments, which, received top dress fertilizer

in addition to the pre-planting manure application. The high soil P values observed were indeed associated with the sole cereal plots that received this additional fertilizer. In the intercropping plots, the influence of cereals and cowpea balanced (Appendix 4.1b).

A general increase in soil exchangeable cations was observed in the post harvest soil samples i.e Ca, from 0.67 ± 0.09 to 1.8 ± 0.4 cmol(+) kg^{-1} soil; Mg, from 0.30 ± 0.05 to 0.52 ± 0.2 cmol(+) kg^{-1} soil; K, from 0.06 ± 0.01 to 0.24 ± 0.06 cmol(+) kg^{-1} soil and Na, from 0.06 ± 0.03 to 0.26 ± 0.06 cmol(+) kg^{-1} soil (Appendix 4.1b). The resultant CEC of the soils also increased from 1.8 ± 0.2 to 2.7 ± 0.2 after harvesting and varied from 2.1 to 4.8 cmol(+) kg^{-1} soil but they were still at low levels for the soil as a whole. The release of nutrients from organic manure may not synchronise with the periods of their maximum release from soil for crop use, but organic manure was the main source of cations and micronutrients. The levels of soil extractable micronutrients were also observed to have generally increased in the post harvest soils sampled from all the treatments (Table 4.2).

4.2.2 *1995 cropping season*

The stovers and haulms of the 1994 cropping season were left on the fields and worked into the soil prior to ridge making in 1995, as was the practice on the research field at the IAR/IITA farm. In the values presented below, sample size has comparable influences as in 1994. Pre-planting soil sample analyses were observed to be sandy in texture with a sand fraction of 87 ± 1.0%, silt, 8 ± 1.1% and clay, 5 ± 1.0% (Table 4.2). Soil pH in water was higher in 1995 than in 1994 and neutral

(6.9 ± 0.2), while soil organic carbon (0.28 ± 0.04%) and total Nitrogen (0.03 ± 0.04%) were very low. The soil total N was about 6.3 kg N ha^{-1} of furrow slice (0-15 cm), while the pre-planting application of organic manure (6 t ha^{-1}), was able to supply an additional 24 kg N ha^{-1} to the soil. The C:N ratio (9.0 ± 2.4) was higher when compared with the 1994 post harvest soil analysis values of 6.4 ± 2.3 (Table 4.2). The relatively higher C:N ratio was as a result of the 1994 crop residues which were ridged into the soil before the planting of crops for the 1995 season. The soil available phosphorus at planting varied as in 1994 from low to medium fertility ratings, with a comparable average value of 15 ± 2.5 mg kg^{-1}. The moderate P value (1 kg ha^{-1}) from the organic manure applied also increased the soil P status.

The soil contained low levels of calcium (≤ 2.2 cmol(+) kg^{-1}), which were however double the values in 1994 at pre-planting, medium levels of Mg, also doubled compared to 1994, trebled K contents (compared to 1994) that varied from low to medium and a much higher Na content than in 1994 (0.46 ± 0.34 a against 0.06 ± 0.03 cmol(+) kg^{-1}). The Na was around 15% saturation of the CEC, thus conferring on the friable soil a poor structural development and had the tendency to disperse (Sanchez *et al.*, 1982). Soil CEC was still low (2.7 ± 0.60 cmol(+) kg^{-1}), while the extractable micronutrients fertility ratings were all above the critical levels required (Table 4.2). The incorporated stovers of the 1994 season and the organic manure applied to the field were the suggested sources of the increased quantities of cations observed on the field. The high rainfall intensity and amount in 1994 caused a rise in water table level our field that was close to the Jankara Lake (about 300 m). The water from the lake has been reported to be alkaline in reaction (water pH >8.0) (Craufurd, 1992, IITA Kano station, Kano, personal cummunication). This must have

caused the deposition of alkaline salts on the soil surface, when evaporation rates were high during the dry season period extending from November 1994 to June 1995. The higher values of cations observed on the surface soil in the pre-planting soil samples must have been an effect of these alkaline salt depositions. The applied manure also supplied appreciable levels of nutrient cations and micronutrients to the soil for the good growth and performance of crop components in the intercropped and sole crop treatments (Appendix 4.2a).

The post harvest soil analysis results for the 1995 treatments were all sandy (88 $\pm$ 1.0% sand), but with a general increase in the clay fractions (9 $\pm$ 1.4% as against 5 $\pm$ 1.0% pre-palnting) and a decrease in the silt fractions (3 $\pm$ 0.9% as against 8 $\pm$ 1.1% pre-planting) of the particle size distribution when compared with the 1995 pre-planting soil analysis results. Although the soil clay fractions were higher (10%) in the sole millet, sole sorghum (cv. Gaya Early) and the sole cowpea varieties Dan-illa, a local indeterminate spreading type and IT89KD-374, a semi erect improved but spreading type, this is within the accuracy limits of the measurements and therefore insignificant. Sole sorghum (cv. ICSV 400) plots had the lowest soil clay fractions (6%) and highest fractions of sand (90%), because of their open canopy structure. The relatively poor canopy development resulted in the exposure of the soil to the direct impact of raindrops that caused the leaching of clay and soil nutrients.

Soil pH in water varied from weakly acid (5.9) in the sole sorghum (cv. ICSV 400) to neutral in all other treatments with an overall soil pH average of 6.7 $\pm$ 0.30.

The observed soil organic carbon remained low (0.32 $\pm$ 0.07%). Total nitrogen remained low (0.03 $\pm$ 0.002%). The soil C:N ratio of 10.7 $\pm$ 3.0 was 20%

nitrogen remained low (0.03 ± 0.002%). The soil C:N ratio of 10.7 ± 3.0 was 20% higher than the pre-planting soil test value for 1995 (Table 4.2).

The soil available phosphorus (P), that kept the same average (now 16 mg/kg) throughout the two seasons varied from 9.8 mg/kg in one sole cowpea treatment to 24.7 mg/kg in the sole millet (Appendix 4.2b). The higher P values were observed in plots that received inorganic fertilizer. Phosphorus release in the soil is a slow process, hence some amounts are held within the soil for some time. The sole cowpea soils averaged lower P (12 mg/kg), the sole cereal crops higher (20 mg/kg), while in the intercrops, it was just like in 1994, a balance was struck (15 mg/kg). In terms of the soil levels of exchangeable bases at crop harvests, calcium was low, at values rather identical since post harvest 1994 soils, magnesium was medium, and lower than at planting, potassium low to medium comparable to that of post harvest soils of 1994, while sodium levels did not exceed 0.5 cmol(+) kg^{-1}, again similar to what was observed at the end of 1994 season (Table 4.2). The soil CEC was low (2.6 ± 0.3 cmol(+) kg^{-1}), and the same as at pre-planting soil analysis. Soil micronutrients present in the soil were above the critical levels of their requirements (Table 4.2).

The soil of the experimental site is hypothermic, typic ustipsamment comprising of >80% sand, ≤10% silt and ≤10% clay. The low amounts of the clay fractions in the analysed soil samples throughout the period of experiments explains the low nutrient retaining ability of the soil and hence the poor nutrient status. There seem to be a minor improvement in soil texture over a season, which reverted to a more sandy class at the begining of the subsequent season (Table 4.2). The seasonal influx of fine sand and silt through the Harmattan dust on the soil of this zone,

between the months of December and March prior to each year's onset of rains, is also suggested as a major reason for the change, although the larger number of samples analysed post harvest than in the pre-planting periods may have some influence on the textural classses. The strong winds associated with the Harmattan are also responsible for a lot of sand movement, especially where vegetation cover is sparse over some distance. Mϕberg *et al.* (1991) and Owonubi and Esu (1991) reported an influx of the Harmattan dust of about 1 tonne ha^{-1} $year^{-1}$ on the soil on which it fell. Rainfall pattern in terms distribution and intensity cause changes during the growing season.

Most soil nutrients required by plants at the observed soil pH range are readily available. The observed soil pH status between weakly acid and neutral, implied the ability of the soil chemical reaction release of required plant nutrients, when available in adequate forms and quantities. The application of organic manure also increased soil pH (near neutral) and enhanced the soil reactions that lead to the release of soil nutrients.

The main source of N is organic matter, and its low levels in the soils are reflected in the low total N values. While application of small amounts of N has been reported to be essential to ensure good nodulation of legumes (soybean and cowpea) in soils of low N status in the moist savannna (Kang *et al.*,1977), Agboola (1978) reported that there was no response to N in cowpea on soils with high levels of organic matter (>2%) in the same region. Farm yard manure (cow dung plus household waste) is the most common and relatively available source of organic manure reflecting the importance of livestock in the farming systems of this area. The analyses of the manures applied to the fields in 1994 and 1995 showed that they

contain high amounts of N; a major nutrient required at crop establishment. Manure application ensures the release of nutrients through the mineralization of the immobilized nutrients in the organic matter and thence their release in the soil for plant use. The organic manure also increases the nutrient retaining ability of the soil. Continous cultivation coupled with the annual application of organic manure and chemical fertilizers to farm land has raised soil P as observed from soil analyses results. P did not seem to be a limiting nutrient in the field and manure application also contributed modest amounts to the soil P pool.

The soil's low organic matter contents implied low nutrient absorption capacities due to their low buffering capacities. As a result the soil is expected to give good crop response to P when small quantities of P fertilizers are applied. The organic manure applied also increased soil exchangeable cations and micronutrients. High amounts of Zn and Mn were supplied to the soil (Table 4.3). Micronutrients in soils play very important roles in plant nutrition and also in the correction of macronutrients induced nutrient imbalances in soils especially when high analysis inorganic fertilizers are applied to supply large quantities of major plant nutrients. The soils Zn content is above critical levels with the contributions from the organic manure to the soil organic matter, and hence it may prevent any imbalance that can be induced by a high dose of P fertilization in the sandy soils.

4.3 Canopy development and dry matter production

4.3.1 Leaf area and leaf area index (LAI)

4.3.1 (a) *1993 cropping season*

Pearl millet canopy development was greatly affected by cropping systems. Leaf area accumulated faster, with the maximum leaf area indices (LAI) becoming greater in the millet crops within the millet/cowpea and millet/sorghum/cowpea intercrops when compared with the sole millet (Fig. 4.6). Maximum LAI were observed near 6 WAS millet at panicle initiation and varied from 2.36 to 3.87 over the range of 6667 to 53333 plants ha^{-1}. The higher LAI were associated with the higher number of tillers produced after thinning to two plants/stand by millet sown within the intercrops at lower densities. The maximum LAI of 3.87 and 3.20 of millet as shown in Figure 4.6 in millet/sorghum/cowpea and millet/cowpea intercrops respectively were statistically not significantly different (P= 0.32), but were both statistically different from the LAI of the sole millet (S.E. 0.715, P= 0.05). LAI remained > 1 throughout panicle development for all treatments, but declined thereafter at crop maturity in the millet/sorghum/cowpea and sole millet plots to 0.61 and 0.81 respectively.

The LAI of sorghum components within the various cropping systems over time showed the same trend. Sorghum variety, Gaya Early in the sole and intercrop plantings produced greater LAI than the sole sorghum cv. ICSV 400 from >30 DAS to the crop maturation periods (Fig. 4.7). There was no effect of cropping system on the LAI of sorghum variety, Gaya Early. Gaya Early grew taller and had better canopy development than ICSV 400 throughout the duration of crop growth. The two sorghum varieties used in the cropping systems maintained the two plants per hill

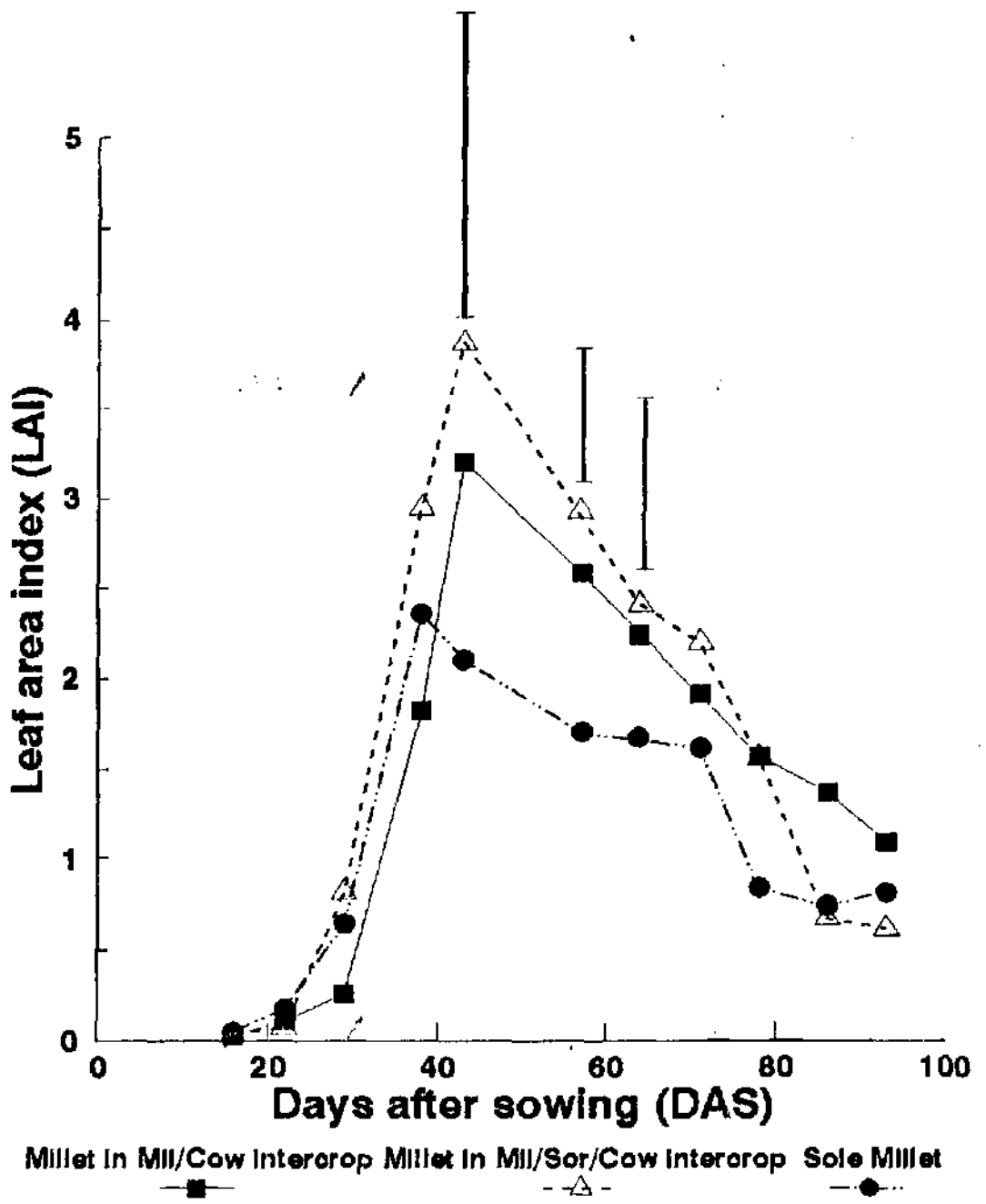


Fig. 4.6 The course of pearl millet leaf area index as affected by cropping systems during 1993 cropping season. Bars represent LSD $_{0.05}$.

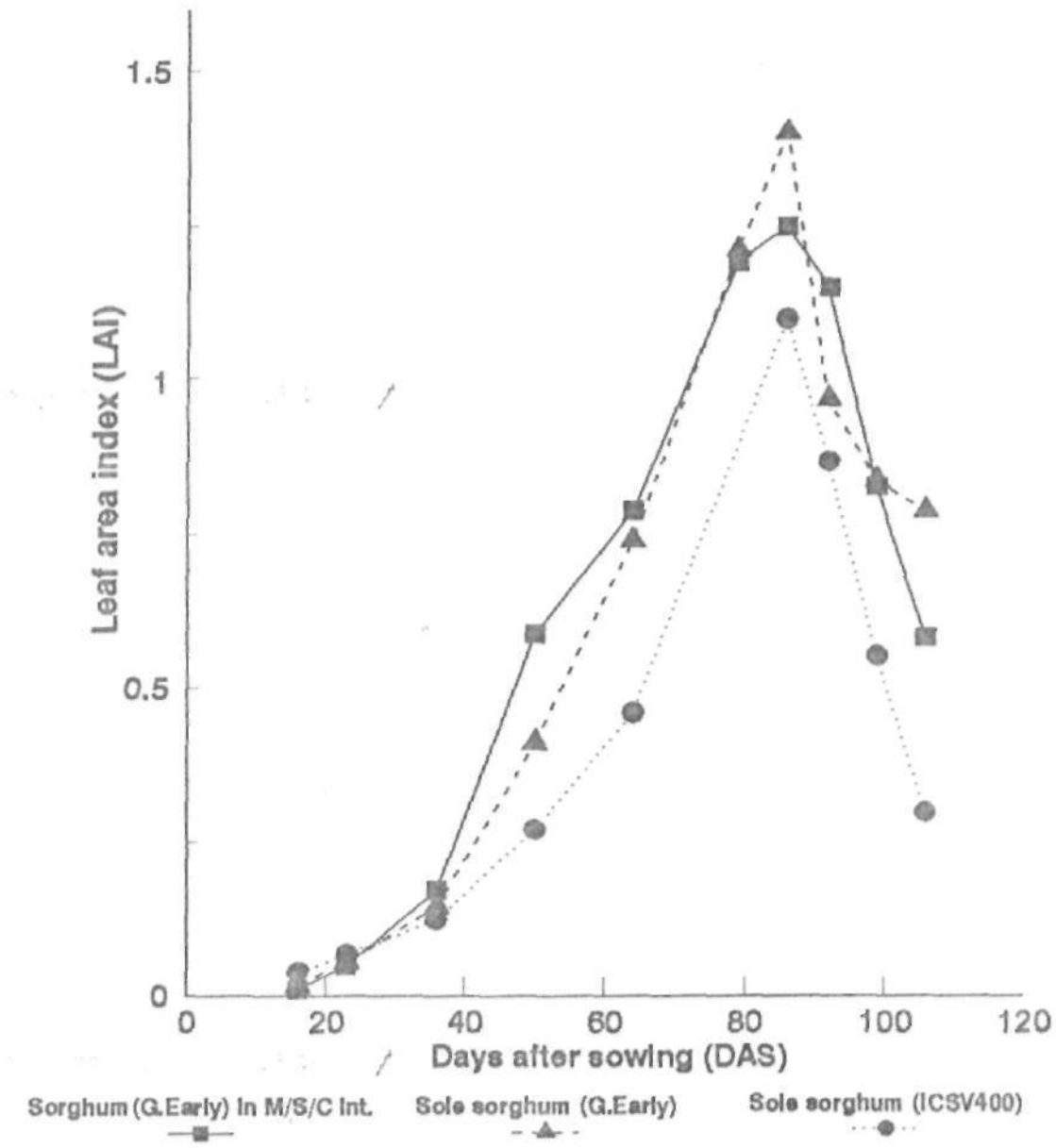


Fig. 4.7 The trends of sorghum leaf area index as affected by varietal difference and cropping system during 1993 cropping season.

from crop establishment to maturity and did not produce tillers as observed with the pearl millet components.

The various cropping systems adopted greatly affected the leaf area indices (LAI) and general canopy development of cowpea components in these systems. The cowpea components were sown 3 WAS millet and while substantial canopy development had taken place in pearl millet at 5 WAS millet, cowpea's canopy development was low. The LAI development of the different cowpea cultivars are shown in Figure 4.8. The canopy development of the determinate erect grain type cowpea variety, IT86D-719 was lower in the intercropping systems than in its sole crop planting. Maximum LAI for cowpea variety, IT86D-719 varied from 0.2 in the intercrop to 0.6 in the sole planting at flowering. Although $LSD_{0.05}$ values were generally higher than these differences on individual measuring days, the repetitive pattern make the overall pattern also statistically different especially between the period of pod filling ($\approx$ 50 DAS) to maturity ($\approx$ 65 DAS) using the DMRT as enumerated by Gomez and Gomez, 1984. The LAI never reached the value of 1, thus showing its poor biomass yield over time, but higher LAI may be obtained at higher plant densities than were adopted. The local cowpea variety, Dan-illa, prostrate with strong vegetative growth and indeterminate, within the intercrops also produced lower LAI than the sole planted treatment from 25 DAS cowpea throughout, but particularly from near flowering onwards (47 DAS cowpea). The maximum LAI of cowpea variety, Dan-illa varied from 0.7 to 2.0. Dan-illa reached its near maximum LAI value slightly earlier but flowered later in the intercrop situations than in sole cropping, and retained a substantial part of the canopy at crop maturity in October after the rains. The LAI of Dan-illa at maturity varied from 0.5 in intercrops to 1.5

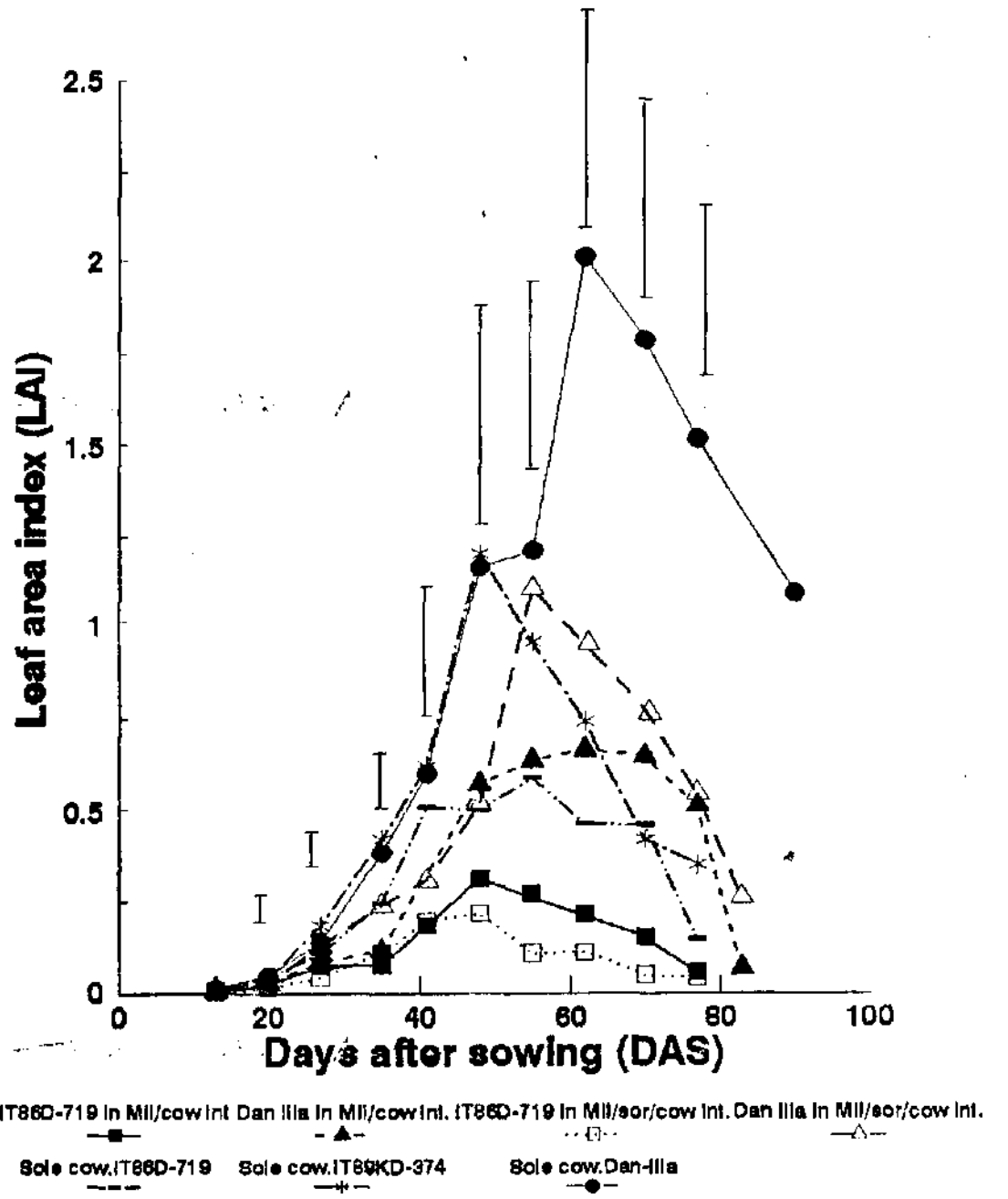


Fig. 4.8 Cowpea leaf area index in relation to cropping systems during 1993 cropping season. Bars represents LSD $_{0.05}$

in sole crop while the erect grain type cowpea shed most of its leaves at maturity.

The semi-erect determinate but improved cowpea variety, IT89KD-374 with potentials for higher grain production and sown sole, performed better than sole IT86D-719 in canopy development at low plant population. The population densities of IT86D-719 and IT89KD-374 sown sole were 53333 and 35555 plants ha^{-1} respectively. IT89KD-374 LAI compared well with Dan-illa until flowering and exceeded >1. IT89KD-374 LAI at pod filling ($\approx$ 60 DAS) to crop maturity decreased rapidly. The fast and comparable full canopy development of IT89KD-374 and Dan-illa as shown by their LAI development confers greater ground cover and hence tendency for a better soil protection. This IT89KD-374 performance as well as its performance at the Nationally Coordinated Cowpea Varietal Trial in 1992 and 1993 under intercropping situations in the Nigerian savanna formed the basis for its use to replace IT86D-719 as grain type cowpea in the subsequent years of our intercropping trials.

4.3.1 (b) *1994 cropping season*

The introduction of an additional top dress fertilizer application treatment on top of the pre-planting organic manure application in 1994 and 1995 experimental years had great effects on component crops canopy development. The LAIs of pearl millet components in the intercropped and sole plantings, as presented in Figure 4.9, show that millet canopy development was even for all treatments except the sole planted millet until 40 DAS. LAI accumulated fast and reached values >1 at 40 DAS for all treatments. Estimated crop nutrient requirements were applied to the millet components of intercrop and sole plantings in what we called OM + IF treatments,

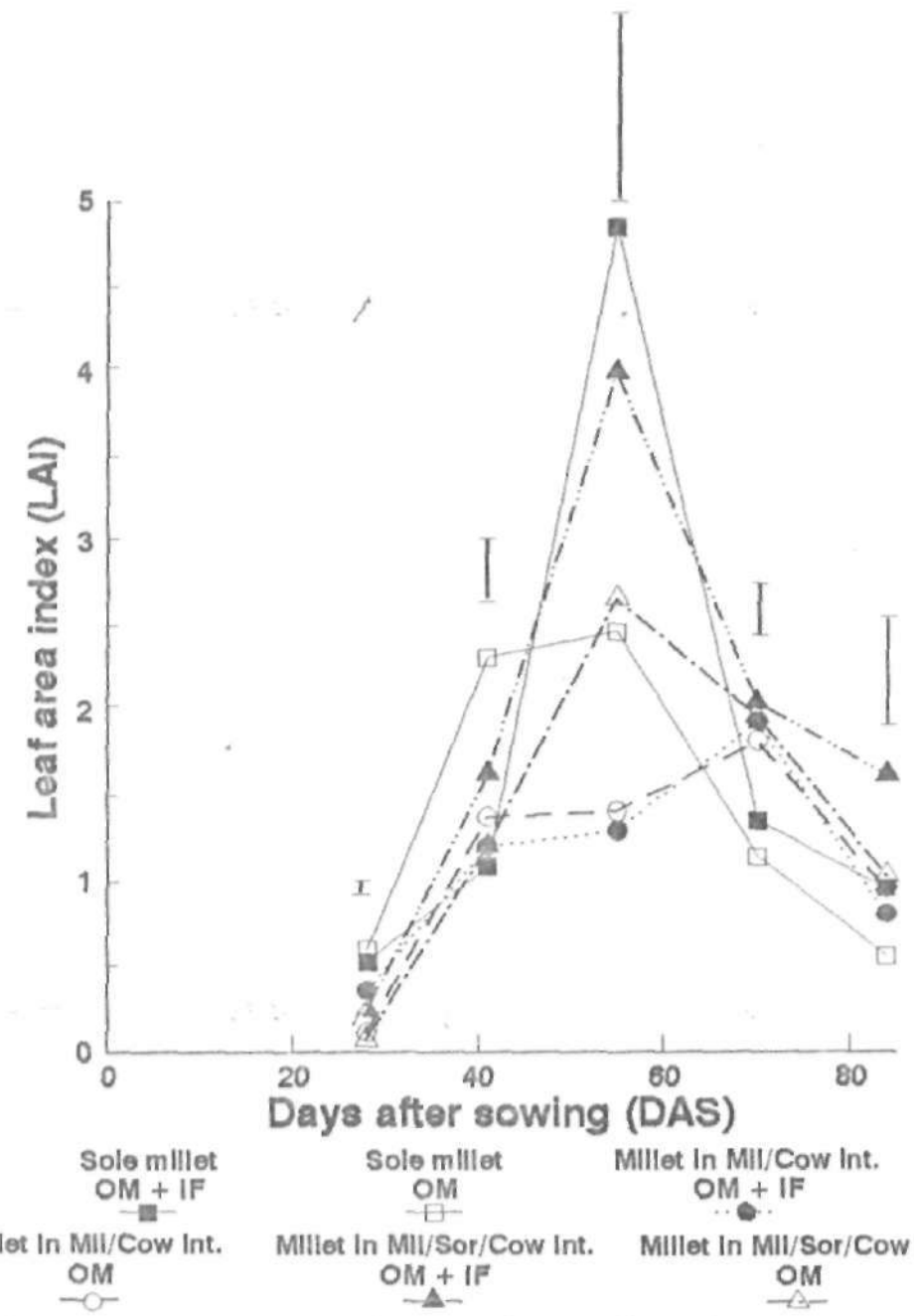


Fig. 4.9 The course of millet leaf area index as affected by cropping systems and soil fertility during the 1994 cropping season. Bars represent $LSD_{0.05}$. *OM represent pre-planting organic manure application only while* OM + IF represents organic manure plus top dress inorganic fertilizer application.

to make up for the recommended rate after 40 DAS. LAI reached a maximum at panicle initiation, about 55 DAS millet, in the sole millet and millet/sorghum/cowpea intercrops. Maximum LAI was reached in the millet/cowpea intercrops later, at about 70 DAS, although panicle initiation was still at 55 DAS.

The addition of top dress NPK applied in bands to millet significantly affected LAI as shown in Figure 4.9 from 55 DAS millet. The millet in millet/sorghum/cowpea and sole that received additional fertilizer application reached maximum LAIs of 4.0 and 4.8 respectively. These were significantly higher than the same treatments that received pre-planting organic manure only and the millet in millet/cowpea intercrops (S.E. 1.0, $P < 0.05$). The canopy development of millet in millet/cowpea intercrops is suppressed when compared with other treatments (Max. <2). LAI of millet planted sole, with and without inorganic fertilizer, declined rapidly to <1 through grain filling to crop maturity. Although a decline was observed in the LAI of intercropped millet in millet/sorghum/cowpea, in the OM+IF treatment it was still substantially $>$ 1 at crop maturity. LAI decline started in the millet/ cowpea intercrop after 70 DAS millet and was close to 1 at crop maturity. The rate of LAI decline was faster in the crops with higher LAIs.

The initial rate of canopy development of the sorghum components as shown by their LAI (Fig. 4.10) indicated a slower rate compared with pearl millet. Leaf area accumulation represented by the LAI was <0.7 for the faster growing sorghum within the first 60 DAS sorghum, in constrast to millet in that same intercrop that had attained the average LAI of >2.0 within the same period (Figs. 4.9 and 4.10). Of the two sole sorghum varieties sown, Gaya Early developed its canopy faster. The LAI of sole Gaya Early LAI (OM as well as OM+IF) were significantly different from

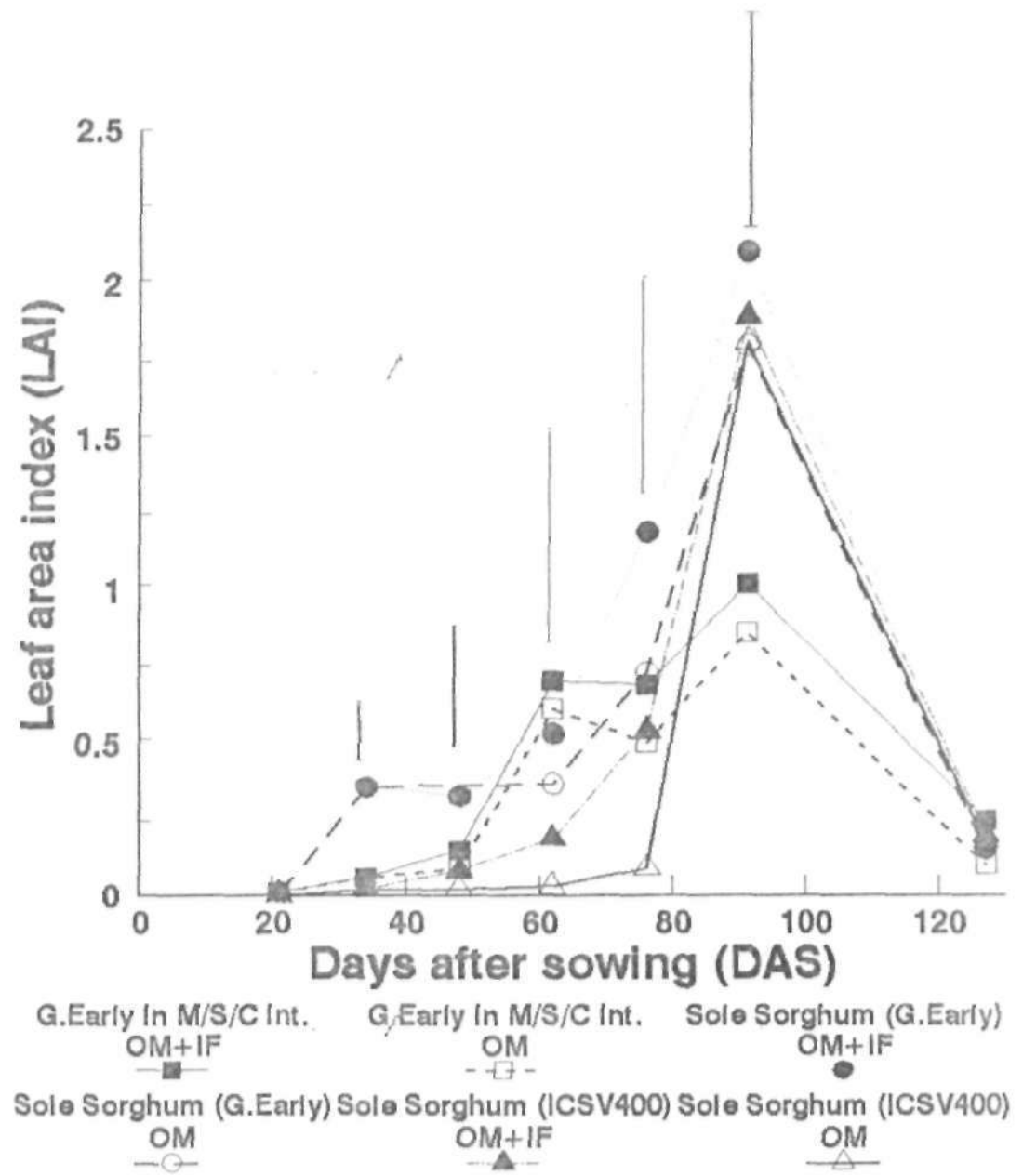


Fig. 4.10. The course of sorghum leaf area index as affected by cropping system and soil fertility level during the 1994 cropping season. Bars represent LSD $_{0.05}$

those of sole ICSV400 and intercropped Gaya Early after 30 DAS sorghum (S.E 0.04, $P<0.05$). LAI for the Gaya Early (OM+IF treatment) was also appreciably higher and significant higher at 75 DAS and 90 DAS than the intercropped sorghum.

At millet grain filling stage, sorghum components within the intercrops developed canopy at a rate comparable to the sole sorghum. This coincided with the end of the period of the rapid decline of millet LAI in all the cropping systems. Sole sorghum variety ICSV400, showed the least rate of canopy development, and more so under OM treatment, of all the systems until the start of the reproductive stage, when it grew faster, producing a canopy comparable to sole Gaya Early. From the reproductive until maturity, the rate of decline in LAI was similar in all treatments.

Additional fertilizer application to sorghum at 8 WAS generally improved canopy development but this did not reveal impressive differences in the LAI when compared with the same cropping systems that received pre-planting organic manure application alone. Maximum LAI reached at the initiation of reproductive stage varied from 0.86 for Gaya Early in the intercrop with OM, to 2.1 for sole Gaya Early with OM + IF. Sole Gaya early and ICSV400 under the two fertility treatments produced significantly higher LAI than Gaya Early within the intercrop (S.E. = 0.24, $P< 0.05$), indicating that the growth and development of sorghum within the intercrops was greatly affected by the other crops in the combination. Sorghum LAI from all the treatments declined rapidly during grain filling to crop maturity.

The LAI of the different cowpea cultivars over the season, within the various cropping systems and soil fertility levels are shown in Figures 4.11a and 4.11b. Cowpea canopy development in 1994 was poor in general (< 1.2) when compared with the two other years of experimentation. The enhanced canopy development of

the cereal components in intercropping favoured by the adequate supply of water may have suppressed the low growing cowpea components. The effects of the cereal components on cowpea performance was also affected by the soil fertility status resulting in a higher vegetative cover in OM only treatments as compared to OM+IF. The year 1994 was the wettest (769.8mm) with a record of 76 rainy days extending late into October. The vegetative and reproductive growth stages of cowpea therefore witnessed periods of relatively high average daily maximum humidity values. These were 60 ± 6.8% in July, 69 ± 4.1% in August, 66 ± 4.6% in September and 60 ± 5.3% by mid-October. The daily average air temperatures for July varied from 22.7 ± 1.1°C to 33.0 ± 1.7°C, while in August it was 21.4 ± 1.0°C to 30.0 ± 2.4°C. The periods of grain filling in cowpea and millet until crop maturity recorded a total rainfall of 165 mm and an average daily air temperature that varied from 22.0 ± 1.2°C to 33.0 ± 2.9°C in September and 22.2 ± 1.2°C to 34.2 ± 2.2°C by mid-October. The daily average wind speed of 3.21 ± 0.9 km hr in July was reduced to 2.0 ± 0.5 km hr in August and further reduced to 1.5 ± 0.4 km hr through September until mid October. These weather conditions favoured more periods of cloud covers, lower radiation and high moisture in the crop microclimate, which had adverse effects on crops performance, especially between cowpea flowering and maturity stages. The environmental conditions favoured the multiplication of disease organisms and insect pests which caused reduced canopy development (i.e photosynthetic capacity) and the eventual lower LAI than observed in years when the amounts of rainfall were lower and better distributed.

Cowpea varieties, IT89KD-374 and Dan-illa used in the millet/cowpea and millet/sorghum/cowpea intercrops with the high soil fertility treatments (of millet and

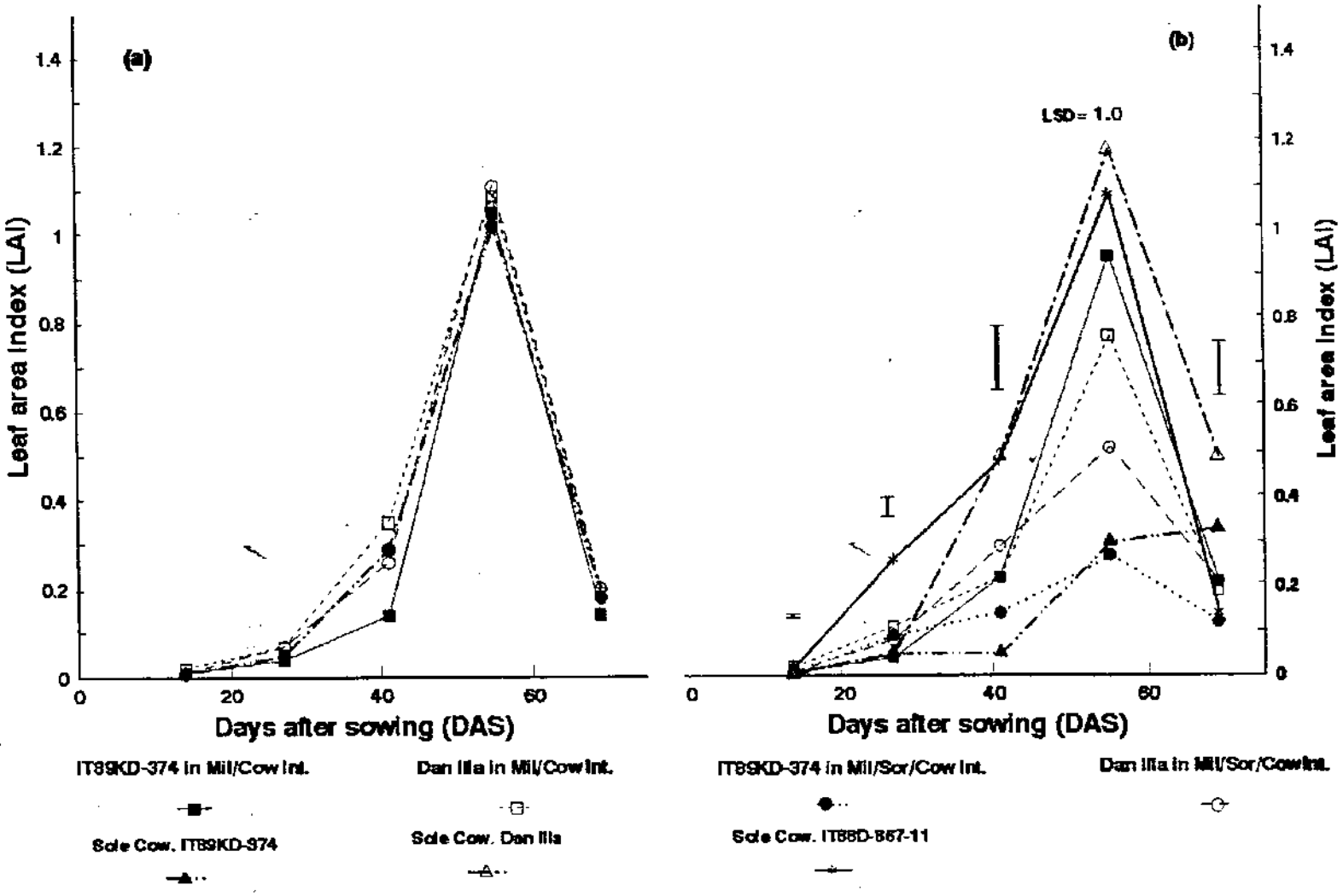


Fig. 4.11. The course of cowpea leaf area as affected by cropping systems during 1994 cropping season. (a) organic manure plus top dress inorganic fertilizer application (OM + IF) and (b) pre-planting organic manure application only (OM). Bars represent $LSD_{0.05}$.

sorghum components) retained their LAI development as a function of time throughout the duration of crop growth (Fig. 4.11a). The LAIs of sole cowpea Dan-illa and IT88D-867-11 were high but not different from the trend and accumulation rates observed in cowpea varieties within the intercropping systems with high soil fertility (Fig. 4.11a and b). In all the cropping systems, LAI reached a maximum at flowering and varied from 0.3 to 1.2 declining thereafter during pod filling until crop maturity. IT89KD-374 had the lowest maximum LAI in sole and intercropping system in combination with millet, sorghum and fodder cowpea (Dan-illa) at relatively, lower fertility rate of organic manure application alone. The sole cowpea varieties were more exposed and susceptible to the attacks of disease organisms and insects with little or no protection from the spread of these attack by any companion crop and hence their relatively poorer canopy development as compared to the intercrops over the season, the full insecticide protection not withstanding.

4.3.1.(c) *1995 cropping season*

The relatively faster rate of leaf area accumulation typical of pearl millet components of the various cropping systems was also observed for all treatments in 1995 (Fig. 4.12). The addition of inorganic fertilizers as top dress before panicle initiation of millet did not improve the leaf area accumulation of millet in the three cropping systems involved but, after a lower maximum only reduced the rate of LAI decline within grain filling periods. The LAI of millet components of the different cropping systems showed the same trend and with the exception of the intercrop with cowpea and without inorganic fertilizer, about the same rate until panicle initiation.

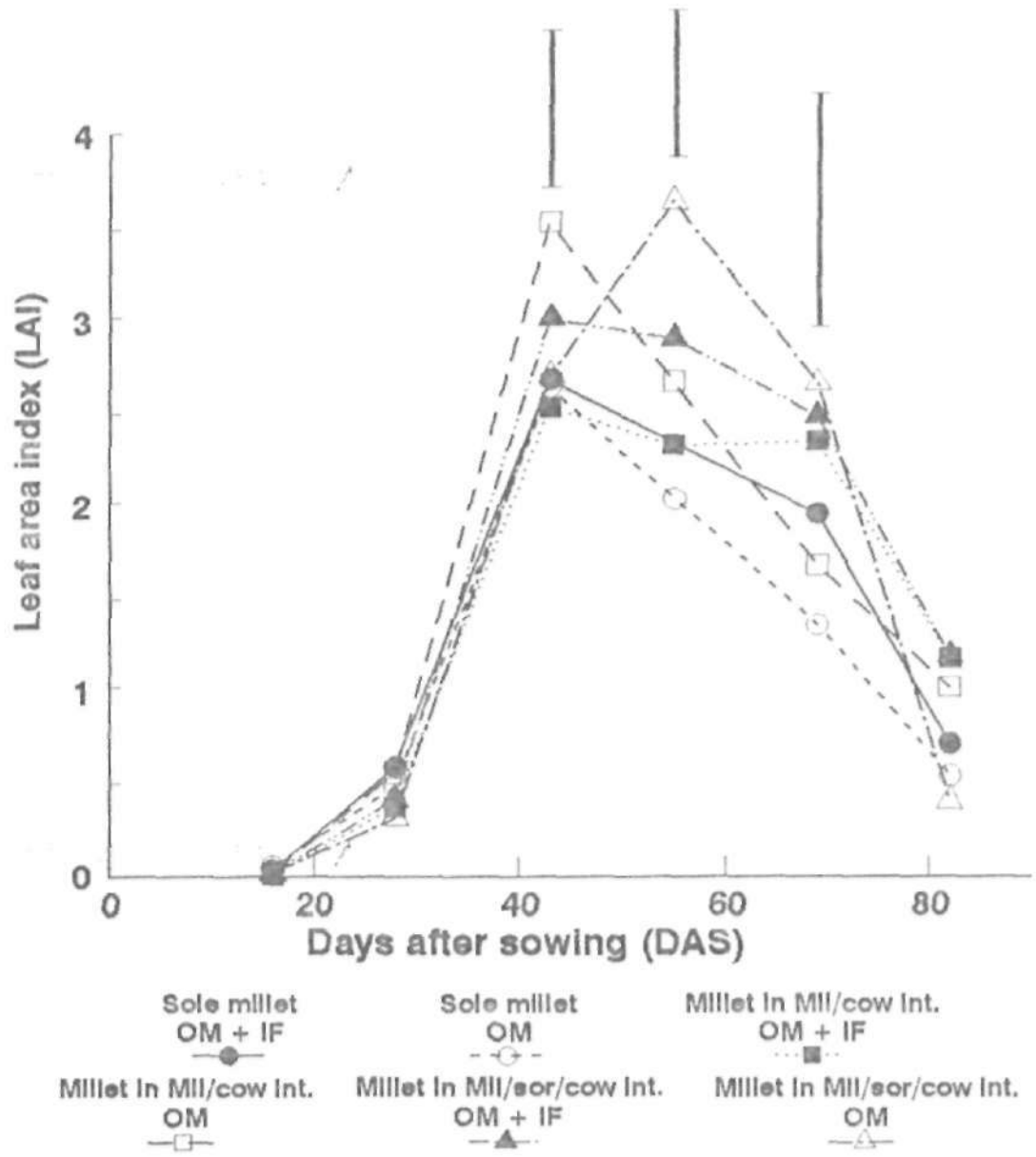


Fig. 4.12 Millet leaf area index as affected by cropping systems and soil fertility status during 1995 rainy season. Bars represent LSD $_{0.05}$

The maximum LAI periods of millet differ among the various cropping systems. The millet in millet/cowpea intercrops and both sole millets attained their maximum LAI of 3.5 and 2.7 respectively (Fig. 4.12) at the same period of growth. Maximum LAI of millet in the millet/cowpea intercrops without inorganic fertilizer was indeed higher, while millet in the millet/cowpea intercrop with pre-planting organic matter application alone was significantly different from the LAI of sole crop treatments ($S.E. = 0.80$, $P<0.05$). The maximum LAI of millet in the millet/sorghum/cowpea intercrop with the full soil fertility status was not different from those of the other cropping systems. A maximum millet LAI (3.7) in the relatively lower soil fertility treatment of millet/sorghum/cowpea intercrop was obtained at 55 DAS millet and was among the three highest of all the treatments. The ranking of LAI for millet at 55 DAS was for both fertilizer treatments, millet/sorghum/cowpea > millet/cowpea > sole millet. The differences in LAI among most cropping systems were statistically significant, but not within the same cropping system that received different soil fertility levels. An exception was the high fertility millet in millet/sorghum/cowpea which was not different from the two millets in millet/cowpea intercropping systems. While rapid LAI decline was observed in millet within the intercrops with pre-planting organic manure application alone after panicle initiation, such consistent trends were not noticed in the relatively high fertility treatments until a stage during grain filling to crop maturity. LAI was still higher during millet grain filling in millet/sorghum/cowpea intercrops, and in the full fertility treatment in millet/cowpea intercrop than in the other cropping systems, with a rapid decline thereafter until crop maturity in all treatments.

The leaf area accumulation of sorghum progressed slowly and without

difference in LAI for the first 40 DAS sorghum in all the cropping systems. Sorghum variety ICSV400, assessed at 75 DAS thereafter had an average faster canopy development than Gaya Early in sole and intercrop plantings (Fig. 4.13). The addition of inorganic fertilizer at 8 WAS sorghum improved the leaf area accumulation of sorghum in many of the cropping systems from the time of application through the reproductive stages to crop maturity, with the exception of ICSV 400 that had the normal decline at maturity because of its relative earliness, when compared with Gaya Early. Gaya Early at the relatively higher soil fertility level developed the highest LAI which was at about 60 DAS significantly different from those of the other sorghum based cropping systems. As also phenologically observed, ICSV400 attained its reproductive stage faster than Gaya Early and reached the maximum LAI that varied from 2.0 to 2.2 at about 75 DAS. The LAI at 75 DAS of ICSV 400 in the two fertility levels adopted differ statistically from those of Gaya Early in the sole and intercropping systems with pre-planting organic manure application alone, but not significantly different from the relatively high fertility Gaya Early in all the treatments (S.E. = 0.13, $P<0.05$). The LAI of ICSV 400 planted sole declined rapidly through the period of grain filling to crop maturity with consistently somewhat higher canopy development in the relatively higher soil fertility treatments.

The period of head formation in Gaya Early ($\approx$ 75 DAS and beyond) coincided with high LAI in sole and intercropped systems. At about 90 DAS, the high soil fertility treatments significantly improved canopy development in sole and intercropping systems compared to the organic manure fertility treatments (S.E. = 0.50, $P<0.05$). The periods after the harvest of millet ($\approx$ 95 DAS) and cowpea ($\approx$ 80 DAS for grain cowpea and 100 DAS for fodder cowpea) components of

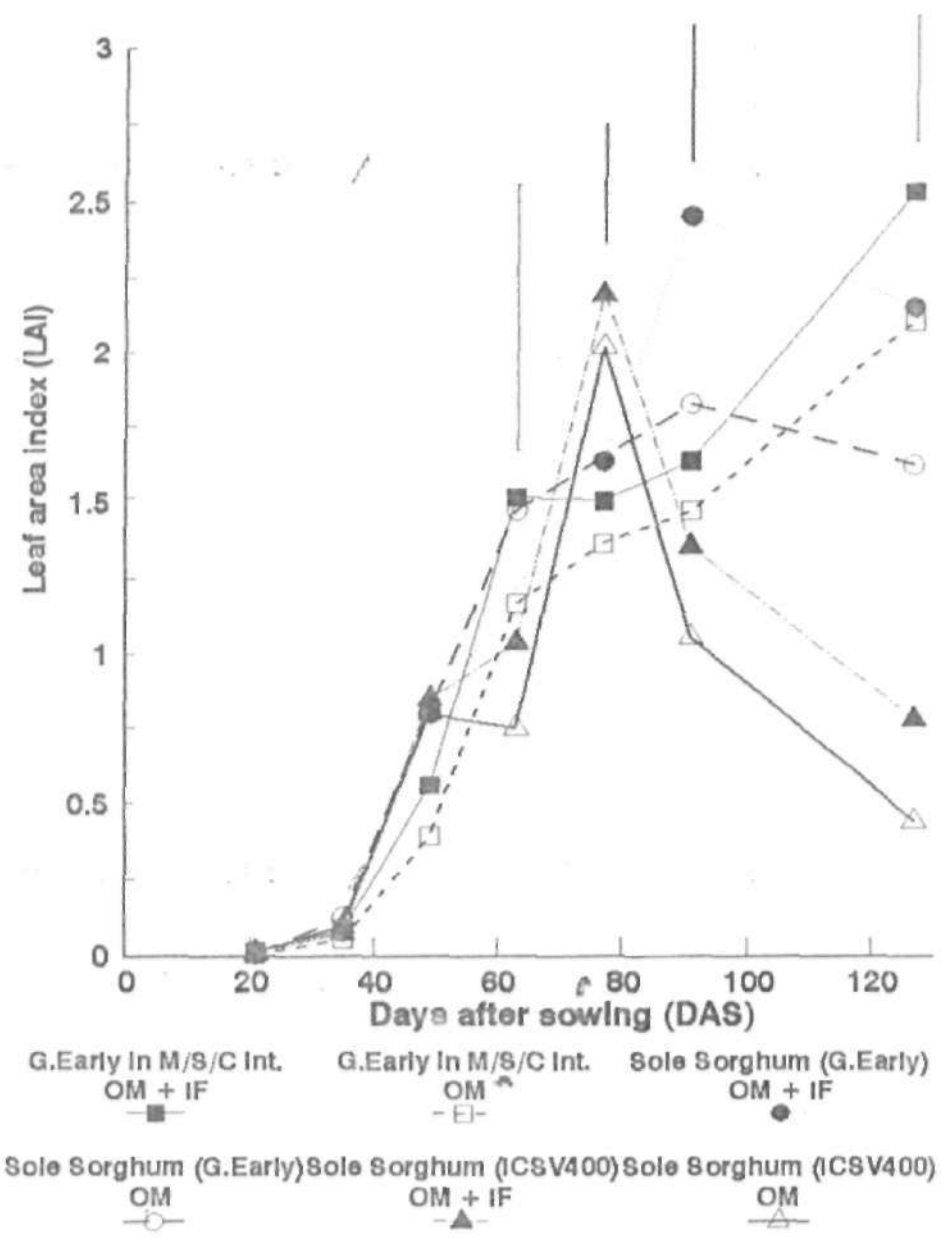


Fig. 4.13 Sorghum component leaf area index as affected by cropping systems during 1995 rainy season. Bars represent LSD $_{0.05}$

millet/sorghum/cowpea intercropping systems appear to show a rapid increase in sorghum LAI during the stages of head filling. The maximum sorghum LAIs were reached late in intercrops, later than in sole crops. The growth of sorghum at the beginning of the cropping season was initially slower than the other components within the intercrops and thus suppressed by the faster growing cowpea and especially millet. Sorghum (Gaya Early) being a later maturing crop (> 120 days) is able to recover and make use of resources for the remaining period of the growing season after millet and cowpea harvests, to achieve a better canopy development when environmental condition is favourable and so increase also its yield. Such intercrops share their resources more in time than in space (e.g. Stigter and Baldy, 1993), while millet and cowpea share resources more in space than in time.

The better rainfall distribution in 1995 when compared with 1994 favoured a better cowpea leaf area accumulation over time in all cropping systems. The time course of cowpea canopy development showed an initially higher LAI (≈ 30 DAS) in the sole, erect and determinate cowpea varieties, IT88D-867-11 and IT86D-719 than for the other varieties in sole and intercropping systems (Fig. 4.14a and b). The initial leaf area accumulation rate for sole and intercropped IT89KD-374 and Dan-illa within the first 30 DAS cowpea was not different for all the cowpea components in the different treatments. The maximum LAIs of early maturity sole cowpea varieties IT86D-719 and IT88D-867-11 appeared to be reached earlier, at 41 DAS during flowering. IT88D-867-11 (LAI 2.1) was a better leaf accumulator than IT86D-719 (LAI 1.3). LAI declined thereafter during pod filling to maturity < 60 DAS. All the sole planted cowpea varieties reached LAI values significantly higher than cowpea within intercropping systems with manure application alone (S.E.= 0.26, P> 0.01)

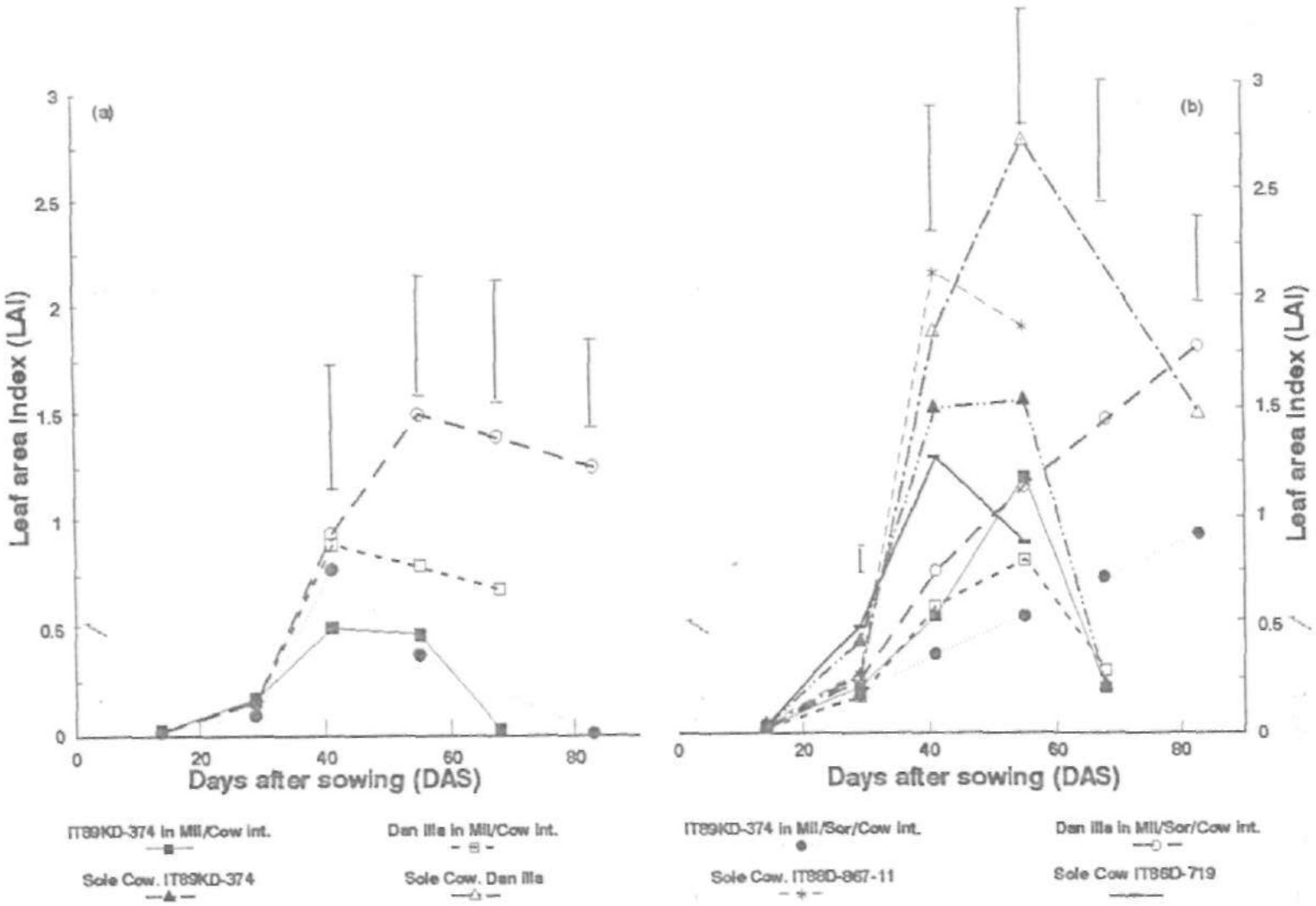


Fig. 4.14 The trend of cowpea component leaf area index as affected by cropping systems during 1995 rainy season. Bars represent LSD $_{0.05}$.
(a) organic manure plus top dress inorganic fertilizer application to the cereal components and (b) pre-planting organic manure application only.

(Fig. 4.14b). The maximum cowpea LAI of 2.7 for the season was from sole Dan-illa at 55 DAS which was significanty different from values for all the cowpea components within other cropping systems (S.E.= 0.25, P< 0.01).

The rate of leaf area accumulation of the cowpea varieties within the intercropping systems differ greatly (Fig. 4.14a and b). The prostrate and more vegetative fodder cowpea, Dan-illa developed higher and faster LAI than the semi erect grain type, IT89KD-374 within the intercrops for both fertility treatments. The LAI of Dan-illa and IT89KD-374 in the millet/sorghum/cowpea intercropping systems were higher than the values obtained within the millet/cowpea cropping systems, the different soil fertility treatments notwithstanding. The relatively slower growth rate of sorghum components in the millet/sorghum/cowpea systems as compared to the more aggressive and highly tillering millet created lesser competition for resources and hence a better canopy development of cowpea as against what obtained in the millet/cowpea systems. Dan-illa retained a substantial portion of its canopy at crop maturity which was generally LAI higher than 1 or close to it.

The cowpea variety IT88D-867-11, introduced in 1995 showed a faster leaf area accumulation rate than other improved grain cowpea, thus offering a potential for early ground cover during crop growth. The period of its maturity coincides with the rapid canopy formation of sorghum components, hence with a potential for reduced competition in intercropping systems. In addition, it is believed to offer some tolerance to cowpea *striga* (Striga generoides), which can reduce cowpea performance and yield drastically in the Nigerian savanna (Singh, 1994, personal communication). It is also considered a better grain cowpea because of the market preference for its large brown seeds with rough seed coat texture.

4.3.2 Dry matter production

4.3.2 (a) *1993 cropping season*

The trend of pearl millet dry matter accumulation was examined in the three contrasting cropping systems (millet/cowpea and millet/sorghum/cowpea intercrops and sole millet). The rate of the shoot dry matter production over time was rapid for all treatments when examined per plant stand of the millet crop, and the trend was about the same until millet panicle formation, about 55 DAS (Fig. 4.15a). Millet in the intercropping systems showed higher dry matter production per stand than in sole millet (S.E.= 33.7, $P< 0.05$). The higher number of tillers produced in the intercropped millet than in the sole crop is responsible for the higher dry matter production per stand from panicle initiation until crop maturity (after 85 DAS).

The effect of cropping systems on the systematic partitioning of assimilates to the reproductive organs in the millet components of these systems is shown in Table 4.4. The increase in dry matter production per plant associated with the higher number of tillers produced in the intercropped millet resulted in higher panicle number and total weight from grain filling to maturity. The trend of panicle biomass production at 64 DAS and thereafter was millet in millet/sorghum/cowpea > millet/cowpea > sole millet. The partitioning of assimilates to panicle grain filling 57 DAS, when more than 50% panicle formation has been achieved in all the cropping systems, showed that millet in millet/cowpea panicle weight was 11% of the total biomass accumulated. In the sole and intercropped millet in millet/sorghum/cowpea, the partitioning to panicle was 6% and 3% respectively. During grain filling to millet maturity, the fraction of assimilate partitioned to the harvestable parts increased more in the intercropped millet than sole crop. At 71 DAS panicles of the millet components of

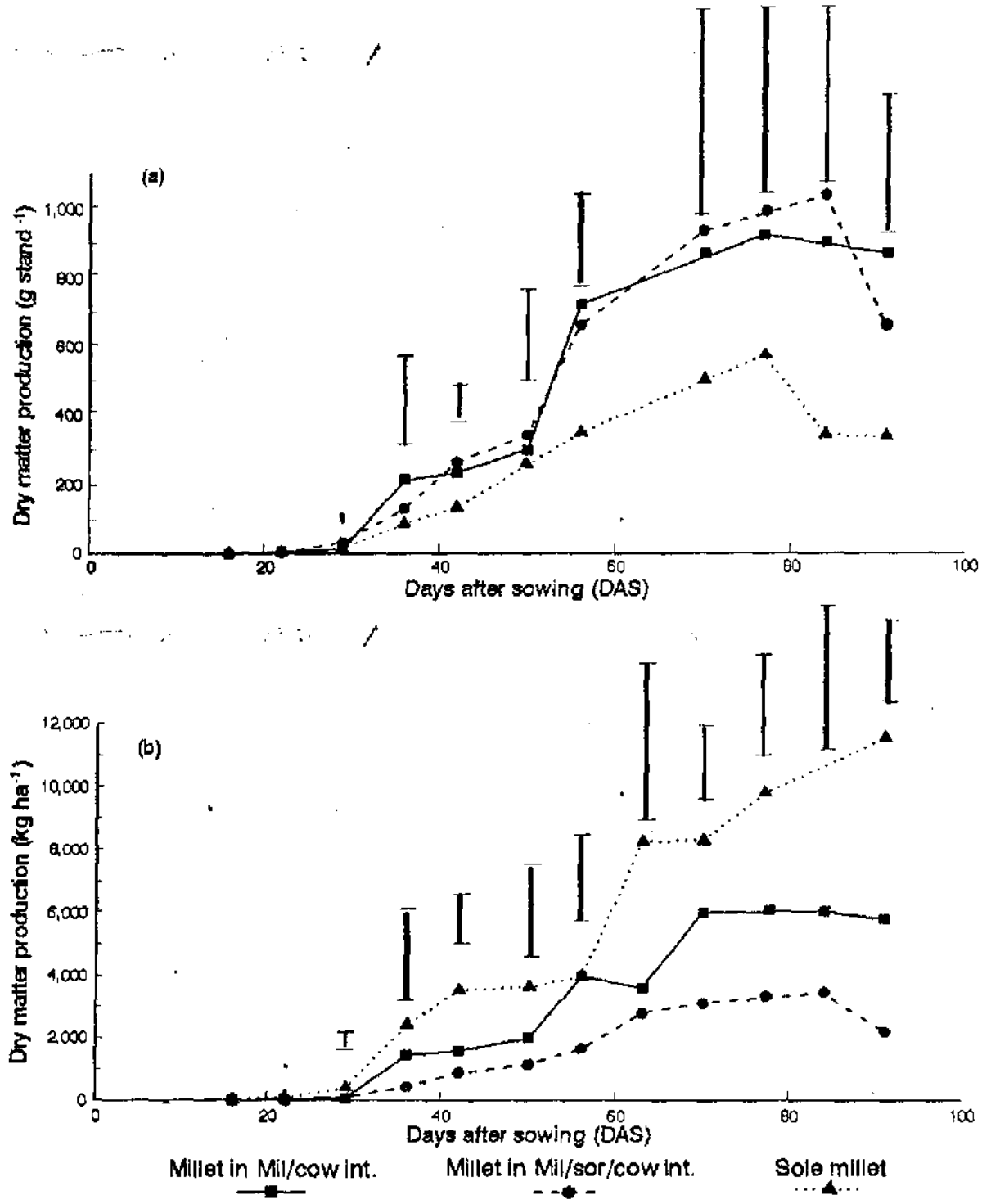


Fig. 4.15 The trend of millet dry matter accumulation in relation to cropping systems in (a) g stand (b) kg ha during 1993 rainy season. Bars represent $LSD_{0.05}$

millet/cowpea and millet/sorghum/cowpea acquired 21% and 25% respectively of the total dry matter production while in sole millet this was much less, with 6%. The highest rate of decline in leaf and stem weight during grain filling in the sole millet ensured a better partitioning at maturity hence the observed 21% of dry matter allocation. This was comparable to the 23% and 26% obtained for the millets in millet/cowpea and millet/sorghum/cowpea, indicating a better trend of assimilate partitioning than in sole millet.

Table 4.4: The effect of cropping systems on assimilates partitioning to reproductive organ of millet component.

Cropping system	Panicle dry weight per stand (g)					
	Days after sowing millet					
	51	57	64	71	78	93
Millet/cowpea intercrop	7.8	75.6	115	225	242	279
Millet/sorghum/cowpea intercrop	6.8	40.8	187	248	291	360
Sole millet	3.1	36.1	64.5	54.8	126	189
SE (df=4)	4.28	13.9	57.7	59.3	81.8	61.4

The total millet dry matter production within the various cropping systems during the growing season is examined in terms of millet component density within the millet based cropping systems. Millet sown sole at the recommended optimum density was 53333 plants per hectare (after thinning to 2 plants/stand), while millet components of millet/cowpea and millet/sorghum/cowpea were 13333 and 6667 plants per hectare respectively. The millet in millet/cowpea and millet/sorghum/cowpea intercrops were respectively 24% and 12.5% of the plant density of sole millet.

The higher density of the millet component in sole cropping compared with the

intercropping situations resulted in higher values of dry matter produced from sowing to maturity (Fig. 4.15b). The dry matter accumulation of millet in sole planting was significantly different from the intercropped millet until the period of peak canopy development in all cropping systems, 55 DAS when there was no significant difference between the sole millet and intercropped millet in millet/cowpea system. During grain filling ($\approx$ 57 to 75 DAS) to millet maturity ($\approx$ 90), the dry matter production in sole millet was much higher than in the intercropped situations, although millet components dry matter yield in millet/cowpea and millet/sorghum/cowpea were $\geq$ 50% and $\geq$ 20% respectively of the sole millet. The higher numbers of tillers produced in millet sown at relatively lower densities is responsible for the improvement observed in the intercropped millet.

The time course of sorghum dry matter production differs between the cropping systems and the sorghum varieties considered in this study. The total sorghum shoot weight per plant stand was highest in sole sorghum variety Gaya Early from about 70 DAS through reproductive stage to maturity (Fig. 4.16a). The sole crop of ICSV400 produced higher shoot dry matter than Gaya Early within millet/sorghum/cowpea intercropping system. Sorghum variety Gaya Early biomass production in the intercropping system was greatly suppressed when in association with millet and cowpea.

The partitioning of assimilate during sorghum reproductive stages also differs among the cropping systems and sorghum varieties. Sole ICSV400 started head formation before Gaya Early and the trend of dry matter production during sorghum head formation (until 87 DAS) indicated a higher head weight in the sole sorghum

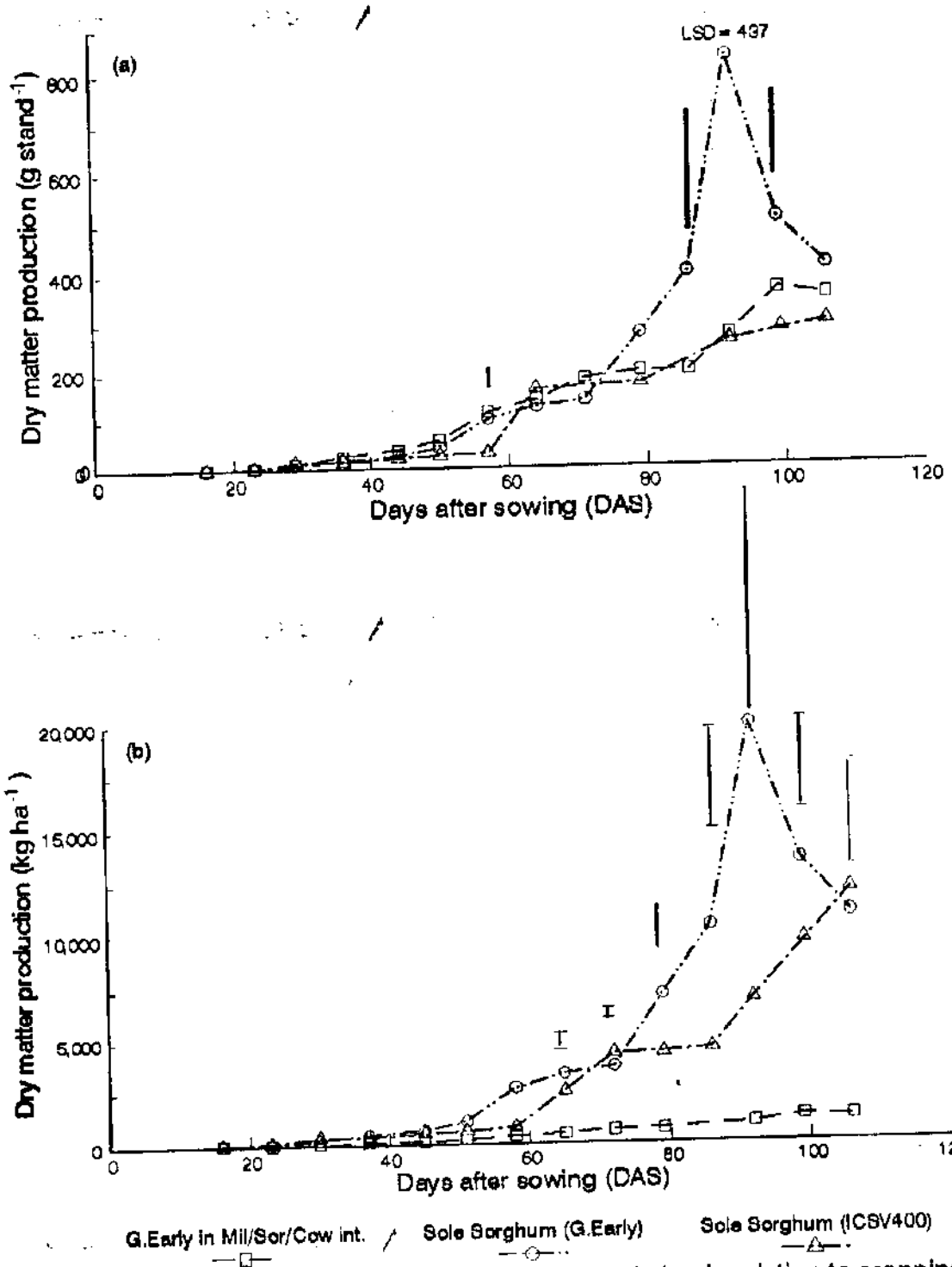


Fig. 4.16 The trend of sorghum dry matter accumulation in relation to cropping systems in (a) g stand $^{-1}$(b) kg ha^{-1} during 1993 rainy season. Bars represent $LSD_{0.05}$

varieties than in the intercrop (Table 4.5). The variation in partitioning reflected varietal differences in the timing of establishment of reproductive sinks (Table 4.5). ICSV 400 started head formation earlier than Gaya Early and produced the highest head weight from grain filling to crop maturity due to its earlier maturation. The reproductive stage of Gaya Early was earlier in the sole crop as compared to the intercrop situation. The late maturing Gaya Early sown sole and in intercropping experienced moisture stress as a result of early cessation of rain which affected dry matter partitioning during grain filling until maturity.

Table 4.5: Variation in sorghum head dry matter production as affected by cropping systems and sorghum varieties during 1993 cropping season.

Cropping system	*Head dry weight per stand (g)*				
	Days after sowing sorghum				
	72	80	87	93	107
Millet/sorghum/cowpea intercrop (Gaya Early)	0.0	0.0	3.8	70.8	96.8
Sole Sorghum (Gaya Early)	0.0	6.2	10.2	54.4	81.3
Sole sorghum (ICSV 400)	3.7	8.6	20.2	81.7	148
SE (df=4)	2.16	5.45	4.82	16.97	35.8

The initially lower rate of head dry matter accumulation in intercropped sorghum compared to sole, improved after the harvest of millet and cowpea components (85 DAS) in intercropping and was thereafter higher than sole Gaya Early at crop maturity (Table 4.5). This indicates an improvement in the availability and better use of resources at the lower plant density of sorghum remaining on the ground. The fraction of assimilate partitioned to the head at maturity was 55% for ICSV400 and 30% and 20% for Gaya Early in intercrop and sole respectively. ICSV400

produced higher head dry matter than Gaya Early showing a better partitioning of assimilate to the grain (Table 4.5).

Plant population density of sorghum components within the different cropping systems created variations in dry matter production. Sorghum within the millet/sorghum/cowpea intercropping system was 6667 plants ha^{-1}, while the plant densities of Gaya Early and ICSV 400 sown sole were the same (53333 plants ha^{-1}). The trend of sorghum component shoot dry matter yield per hectare was sole Gaya Early > Sole ICSV 400 > Gaya Early in millet/sorghum/cowpea. Sole Gaya Early grew taller and produced greater canopy and dry matter than ICSV 400. Gaya Early at relatively lower density in millet/sorghum/cowpea produced the least shoot dry matter which differed greatly from that of sole crop Gaya Early and ICSV 400 from crop establishment to maturity (Fig. 4.16b).

The trend and rate of cowpea shoot dry matter accumulation per plant stand was affected by the growth rate of the different genotypes. The different cropping systems considered were also important sources of shoot dry matter yield variation among cowpea cultivars. The dry matter accumulation pattern in all the sole planted cowpea cultivars indicated a significantly ($P < 0.05$) higher rate than in the same cowpea genotypes within the intercropping systems during most periods of crop growth (Fig. 4.17a). The cereals in association with cowpea components in the intercrops seem to have caused growth suppression of the cowpea cultivars. The time course of dry matter accumulation was consistent among the cultivars. The prostrate and more vegetative local cowpea cultivar Dan-illa in sole and intercropping systems produced higher shoot dry matter than the erect and earlier maturing grain cowpea varieties IT89KD-374 and IT89D-719. A rapid decrease in shoot dry matter

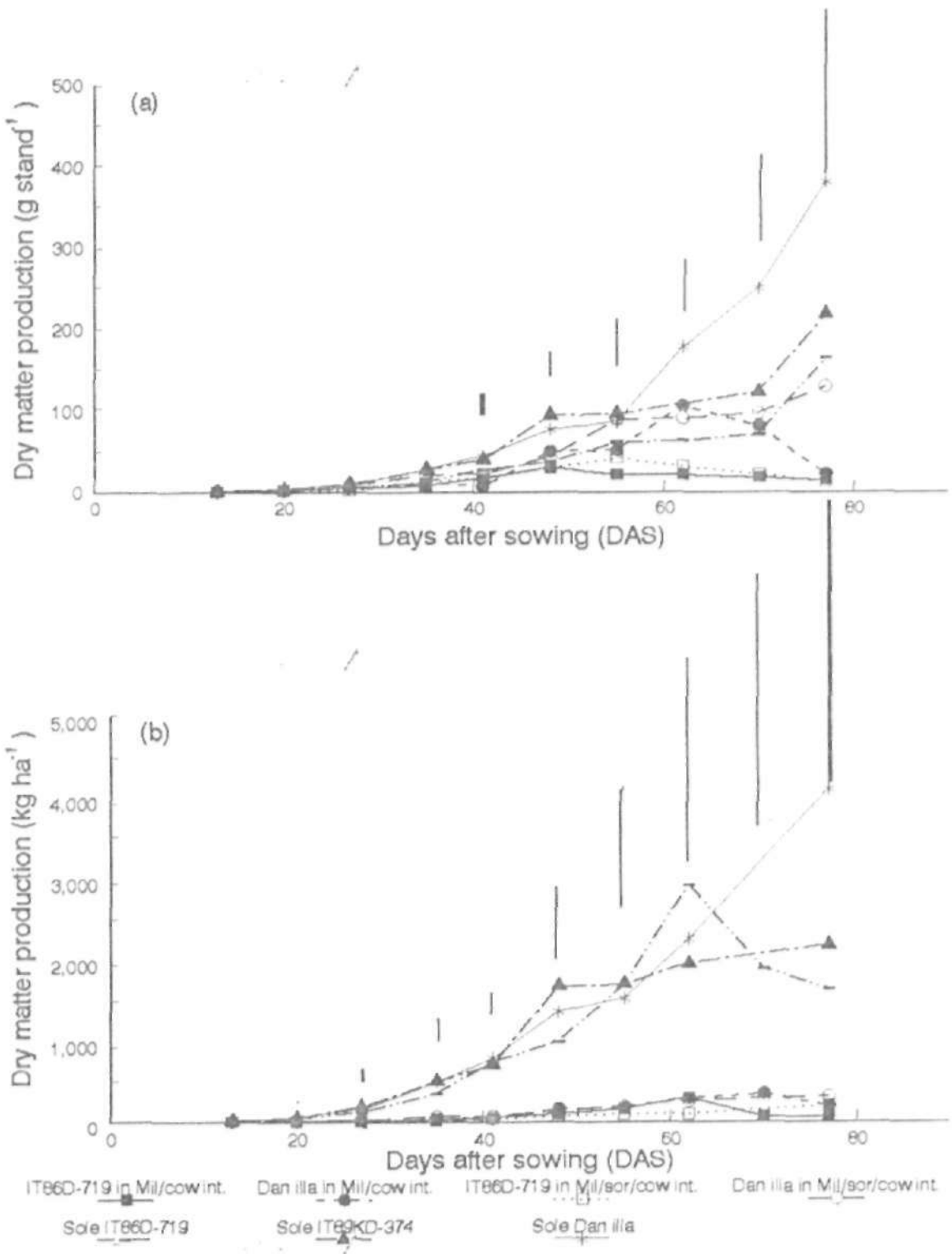


Fig. 4.17 The trend of cowpea dry matter accumulation as affected by cultivars and cropping systems in (a) g stand $^{-1}$,(b) kg ha $^{-1}$ during 1993 rainy season. Bars represents $LSD_{0.05}$

accumulation was noticed in the sole grain cowpea IT89D-719 (Fig. 4.17b) from pod filling (after 60 DAS) to crop maturity (≈ 75 DAS) as against the grain component in the intercrop where little increases in shoot dry matter production was noticed. The higher partitioning of assimilate during the reproductive stage in the sole grain cowpea cultivars (Table 4.6) is accompanied by the loss of foliage (Fig. 4.8) which is indicative of a sufficient accumulation of assimilate for subsequent partitioning to the development of reproductive organs and harvestable seeds. The slower growth rate and the resultant lower biomass produced by intercropped cowpea is a result of the competition from cereal components in intercrops and hence insufficient assimilate for both vegetative growth and reproduction.

Although the erect grain type cowpea cultivars (IT89D-719 and IT89KD-374) started their reproductive stages earlier than the indeterminate and more vegetative fodder cowpea (Dan-illa), the different cropping systems greatly affected assimilate partitioning from flowering to pod maturity. Pod formation was better enhanced in the sole cowpea cultivars than their intercropped counterparts (Table 4.6), with the exception of Dan-illa at maturity, and particularly in the millet/sorghum/cowpea intercrops. The improved semi-erect grain cowpea (IT89KD-374) planted sole was superior to other cowpea cultivars in terms of pod production. The fraction of assimilates partitioned to pod development in relation to total shoot dry matter production 62 DAS for the grain type cowpea IT89D-719 in sole and millet/sorghum/ cowpea intercrop system was the same (52%), while in the millet/cowpea intercrop it was 40%. The percentage dry matter partitioned to pods in the improved sole IT89KD-374 was 60%. The pod weight per plant of IT89KD-374 was greater than was recorded for IT89D-719 and Dan-illa at crop maturity (Table 4.6).

Table 4.6: Changes in dry matter of reproductive organs of sole and intercropped biomass as affected by cropping systems and cowpea cultivars during 1993 cropping season.

Cropping system	Reproductive (Flower and pod) organs dry weight per stand (g)						
	Cowpea Cultivar	Days after sowing cowpea					
		41	48	55	62	70	77
Millet/cowpea intercrop	IT89D-719	0.07	0.37	1.90	10.2	13.9	9.10
	Dan-illa	0.0	0.03	0.03	2.97	15.1	19.0
Millet/sorghum/cowpea int.	IT89D-719	0.43	0.78	4.97	12.0	12.8	17.1
	Dan-illa	0.0	0.03	0.67	5.43	6.40	30.6
Sole cowpea	IT89D-719	0.47	0.67	5.40	44.4	22.0	30.7
	IT89KD-374	0.07	0.57	1.53	38.2	18.4	67.8
	Dan-illa	0.07	0.03	0.07	7.23	15.5	27.2
SE (df=11)		0.09	0.18	1.41	9.44	5.89	18.9

Assimilate partitioned to pod at crop maturity for the prostrate and more vegetative Dan-illa sown sole was 47% as compared to 28% and 16% in millet/sorghum/cowpea and millet/cowpea systems respectively. The pod yield of cowpea cultivars per plant stand were reduced by the other component crops in intercropping as compared to their sole crops, with the exception of Dan-illa in the millet/sorghum/cowpea intercrop. The competitive effects of the cereal component on the final pod yield were more in the millet/cowpea than millet/sorghum/cowpea system as a result of the lower density of the faster and more aggresive millet component in the millet/sorghum/cowpea intercropping treatment.

Cowpea shoot total dry matter accumulation within the various cropping systems differ with plant densities. The grain cowpea component of the intercropping systems was 12.5% of the density of sole IT89D-719 (53333 plants ha^{-1}), while the

prostrate vegetative cowpea, Dan-illa within the intercropping system was 19% of the sole crop density. Sole cowpea cultivars dry matter accumulation per hectare were significantly different ($P < 0.05$) and much higher than those within intercrops throughout the duration of crop growth (Fig. 4.17b). The highest shoot dry matter production observed was at the end of the growing season with the indeterminate and vegetative cowpea cultivar Dan-illa.

4.3.2 (b) *1994 cropping season*

The trend of millet shoot dry matter accumulation per stand was affected by the various cropping systems. During panicle initiation ($\approx$ 55 DAS), after top dress fertilizer was applied for the complete fertility requirement of millet, soil fertility created an increase in dry matter accumulation through grain filling (Fig. 4.18a). At millet maturity ($\approx$ 85 DAS), soil fertility resulted in high dry matter production in the relatively high fertility treatments, except in millet/cowpea OM treatment which was higher than the OM+IF treatment. With the sampling density adopted, the fertility treatments, however, did not produce any statistically significant difference in shoot dry matter accumulation within cropping systems (Fig. 4.18a). On the other hand, shoot dry matter accumulation over time was significantly affected by cropping system from grain filling (S.E. = 67.9, $P<0.03$) at 69 DAS millet to millet maturity at about 85 DAS (S.E. = 139.4, $P<0.02$)[Fig. 4.18a]). The highest number of tillers was produced in the millet/sorghum/cowpea intercrops (13 $\pm$ 2), which produced per stand a lot of dry matter more than the millet within millet/cowpea intercrops ($\approx$ 11 tillers) sown at a relatively higher plant density and the high density sole millet

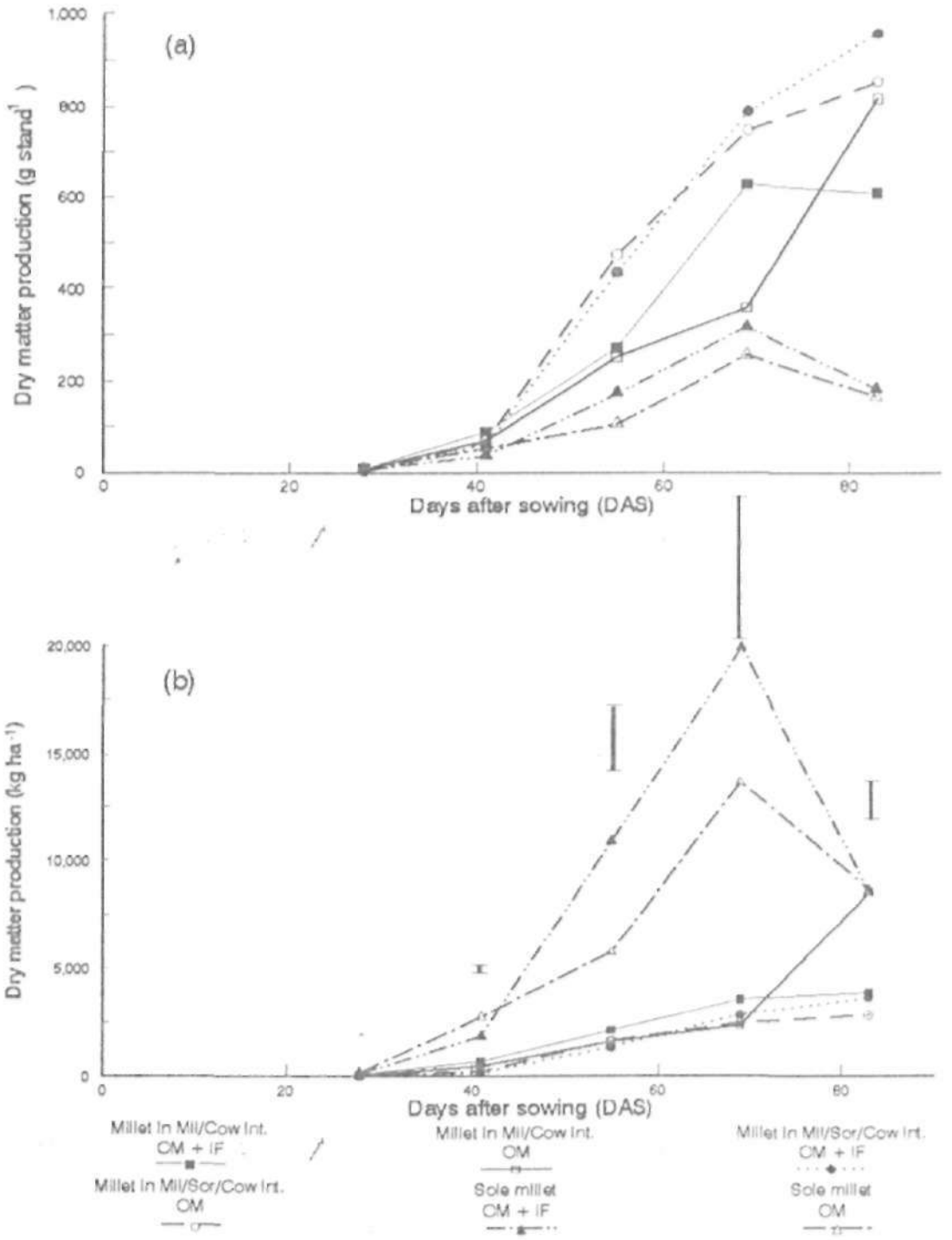


Fig. 4.18 The trend of millet dry matter accumulation as affected by cropping systems in (a) g stand^{-1} and (b) kg ha^{-1} during 1994 rainy season. Bars represent LSD $_{0.05}$.

(≈ 9 tillers), hence compensating for the loss resulting from the lower plant density.

The partitioning of dry matter into leaf, stem and panicle components among the treatments is presented in Table 4.7. The active vegetative growth stage favoured the accumulation of dry matter in the leaf component which was the photosynthetic part responsible for crop development until about 55 DAS millet. At panicle initiation, 55 DAS, there were more assimilates stored in the stem component, while dry matter partitioning to panicle increased during grain filling (69 DAS) until crop maturity (≈ 83 DAS). At the cropping system level, the proportion of total dry matter partitioned to different components was affected significantly. At 27 DAS millet, the treatment average leaf dry weight per plant stand were 7.1, 7.0 and 5.8g in the full soil fertility (OM+IF) treatment and 6.3, 7.2 and 2.0 g in OM only treatments for sole millet, millet/cowpea and millet/sorghum/cowpea intercrops, respectively (Table 4.7). The millet leaf weight in the sole millet and millet/cowpea were higher, but not significantly different from the millet in millet/ sorghum/cowpea intercrops. The trend in dry matter accumulation observed at 41 DAS showed that, the leaf dry matter accumulation of millet in the three cropping system did not differ significantly, but the stem components were different in their dry matter accumulation. Millet stem dry matter accumulation in the millet/sorghum/cowpea intercrops were significantly higher than sole millet (S.E. = 5.09, $P < 0.05$) and higher than in millet/cowpea intercrops, but this was not significant statistically. At 55 DAS when millet attained 50% head formation in all treatments, the general trend of dry matter partition to components was millet in millet/sorghum/cowpea > millet in millet/cowpea > sole millet. Assimilate partitioned at millet maturity was higher in the intercropped millet than in the sole crop as a result of the higher number of tillers per stand observed in the

Table 4.7: Variation in dry matter fractions of sole and intercropped millet in relation to soil fertility during 1994 cropping season.

CROPPING SYSTEM	FERTILITY TREATMENT	Dry matter production g/plant stand														
		27 DAS			41 DAS			55 DAS			69 DAS			83 DAS		
		LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD
SOLE MILLET	ORG.MAN+ INORG.FERT	7.1	*	0.0	23.5	12.2	0.0	60.7	100.2	13.75	66.2	181.2	70.8	29.1	78.4	77.3
	ORG.MAN ONLY	6.3	*	0.0	39.6	13.5	0.0	38.0	57.0	11.9	42.9	152.0	62.1	21.0	79.9	66.7
MIL/COW INTERCROP	ORG.MAN+ INORG.FERT	7.03	*	0.0	44.0	45.2	0.0	70.6	174.2	27.45	108.1	426.2	94.9	81.9	363.9	165.0
	ORG.MAN ONLY	7.2	*	0.0	35.1	34.1	0.0	82.9	148.9	20.8	67.0	205.4	87.8	109.0	487.5	221.0
MIL/SOR/COW INTERCROP	ORG.MAN+ INORG.FERT	5.8	*	0.0	40.0	20.3	0.0	143.7	243.1	50.5	156.2	431.1	202.4	118.7	568.0	274.9
	ORG.MAN ONLY	2.0	*	0.0	40.1	26.7	0.0	136.1	316.2	23.7	167.0	428.1	153.4	141.0	426.7	288.6
STANDARD ERROR (D.F=6)		2.12			4.25	5.09	0.0	35.5	58.3	6.51	11.5	35.7	54.1	26.3	84.1	111.0

intercrops, but soil fertility treatment did not produce a significant difference in dry matter production in the same cropping system.

The overall pattern of millet dry matter accumulation indicated a great difference between sole and intercropped millet, with the exception of millet in millet/cowpea intercrop (OM only) at maturity (Fig.4.18b). Sole millet at optimum density (53333 plants ha^{-1}) differs significantly from the millet components in the intercrops sown at relatively lower densities throughout the duration of crop growth ($P<0.05$). There was no difference in the time course of millet dry matter accumulation between millet/cowpea (13333 plants ha^{-1}) and millet/sorghum/cowpea (6667 plants ha^{-1}). The higher rate of biomass accumulation and partitioning resulting from the higher number of tillers produced in millet/sorghum/cowpea facilitated this contribution.

There was a variation in the trend of sorghum dry matter accumulation per stand as affected by cropping system, soil fertility status and sorghum variety (Fig. 4.19a). The relatively higher soil fertility treatment in all the cropping systems produced higher sorghum shoot dry matter per stand from about 85 DAS through to the duration of crop growth. The rate of dry matter accumulation was significantly greater in the sorghum sown sole than in intercrops ($P<0.05$). Sole Gaya Early was the higher dry matter accumulator of the two sole sorghum varieties used in these studies. The millet and cowpea cultivars in mixture actively competed with sorghum component in the relatively lower fertility intercrop consequently reducing the rate of biomass accumulation and partitioning. Sorghum variety and growth rate are important sources of variation in dry matter partitioning within a cropping system.

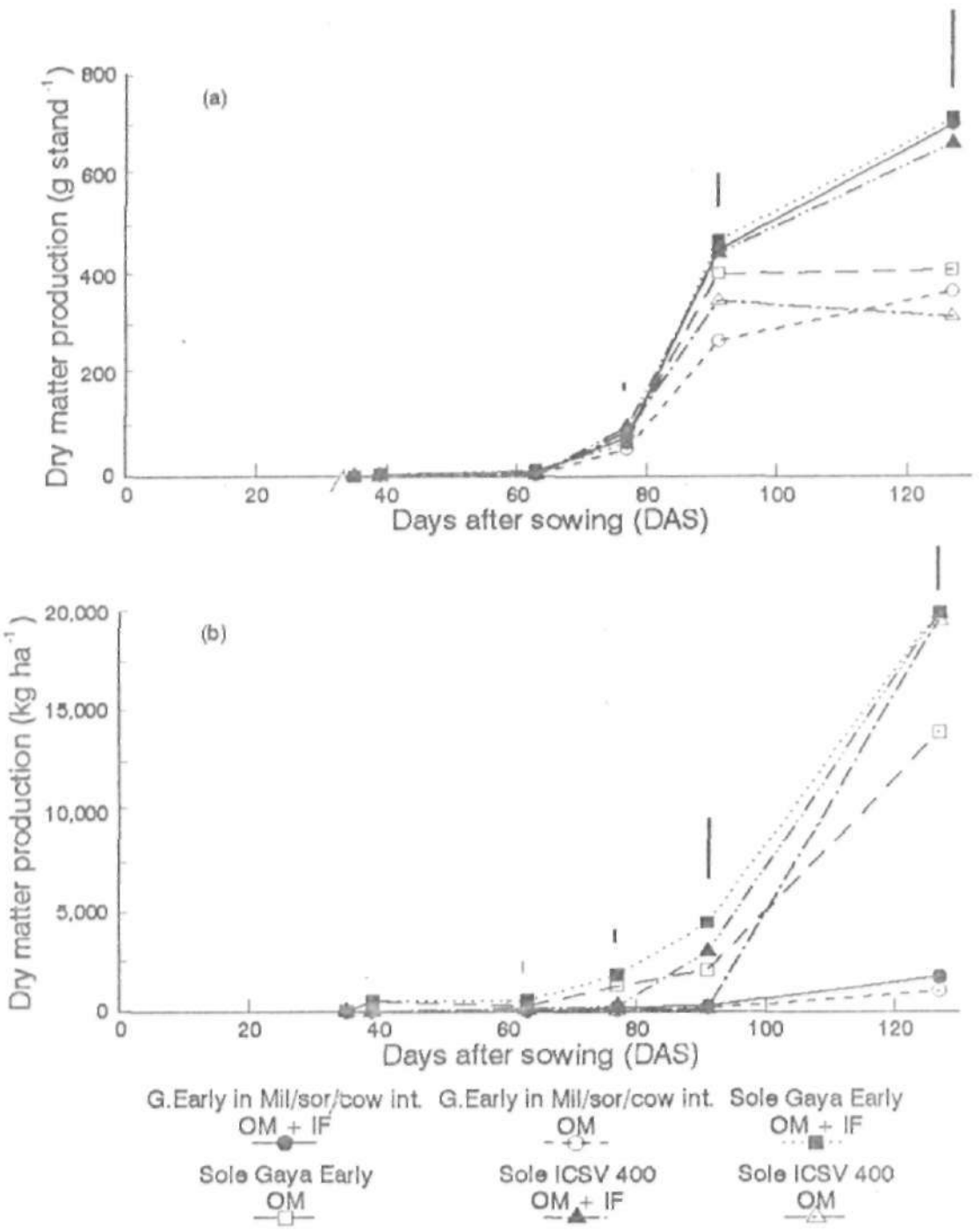


Fig. 4.19 The time course of sorghum dry matter accumulation as affected by cropping systems and soil fertility status in (a) g stand^{-1} and (b) kg ha^{-1} during 1994 rainy season. Bars represent $LSD_{0.05}$.

ICSV 400 was earlier in maturity than Gaya Early, but accumulated dry matter about the same rate with Gaya Early when soil fertility status was high enough. A decline in dry matter accumulation from grain filling to maturity was a feature of the sorghum varieties at the relatively lower soil fertility level (OM), while an increase in dry matter was observed at this time under the high fertlity sole and intercropped sorghum.

The pattern of assimilate partitioning varied with respect to the cropping systems and the sorghum variety involved. In all the treatments, sorghum plant stand m^{-2} assimilate partitioning to the leaf component of plant shoot was near or slightly above those partitioned to the stem until the initiation of heading (Table 4.8). A rapid decrease in leaf weight in favour of stem and head dry matter accumulation was the trend from grain filling to maturity. The sorghum sown within the relatively higher soil fertility cropping systems produced higher masses of assimilates partitioned to shoot components after top dress fertilizer application from 9 WAS sorghum. The effect of the additional fertilizer was only significant in the sole ICSV 400, 77 DAS (leaf, SE= 14.6, $P<0.01$). Gaya Early in sole and intercrop grew taller and produced greater biomass than ICSV 400 at crop maturity.

The time course of sorghum total dry matter production on hectarage basis showed the significance of plant density and soil fertility status among the cropping systems (Fig. 4.19b). The sole sorghum treatments at high population density (53333 plants ha^{-1}) accumulated significantly higher ($P< 0.01$) dry matter than intercropped sorghum (6667 plants ha^{-1}) throughout the duration of crop growth. The relatively higher fertility treatments also increased the trend of dry matter accumulation but this was only statistically significant at grain filling period in the sole Gaya Early (S.E. =

Table 4.8: Variation in the dry matter fractions of sole and intercropped sorghum as affected by soil fertility status during 1994 cropping season.

CROPPING SYSTEM	FERTILITY TREATMENT	Dry matter production g/plant stand																	
		35 DAS			39 DAS			63 DAS			77 DAS			91 DAS			127 DAS		
		LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD
SOLE SORGHUM (G.EARLY)	ORG.MAN+ INORG.FERT	3.39	1.09	0.0	5.5	5.0	0.0	10.7	6.9	0.0	22.1	42.6	0.0	102	308	61	48.4	580	84.2
	ORG.MAN ONLY	3.04	0.63	0.0	2.4	2.08	0.0	11.1	4.4	0.0	41.0	34.2	0.0	74.7	283	48	42.8	302	69.4
SOLE SORGHUM (ICSV400)	ORG.MAN+ INORG.FERT	0.84	0.30	0.0	1.65	1.35	0.0	5.7	5.26	0.0	55.7	40.4	0.0	94.0	294	59.4	24.5	576	63.8
	ORG.MAN ONLY	0.96	0.10	0.0	0.69	1.05	0.0	1.8	0.83	0.0	54.8	31.5	0.0	67.2	247	34.5	19.3	298	38.2
MIL/SOR/COW INTERCROP (G.EARLY)	ORG.MAN+ INORG.FERT	2.12	0.90	0.0	5.06	3.53	0.0	31.0	18.0	0.0	31.9	44.1	0.0	109	284	60.9	51.4	572	78.0
	ORG.MAN ONLY	1.26	0.71	0.0	1.84	0.96	0.0	17.4	4.64	0.0	26.0	27.0	0.0	82.2	174	11.7	32.7	294	43.7
STANDARD ERROR (D.F=4)		0.57	0.03	0.0	1.19	0.63	0.0	4.8	8.6	0.0	14.6	30.9	0.0	6.69	45.4	45.2	9.8	123	41.1

602.3, $P < 0.05$).

There was considerable variation in the rate of dry matter accumulation per stand of cowpea cultivars within the different cropping systems and soil fertility levels (Fig. 4.20a and b). The relatively higher amount and poor distribution of rainfall in 1994 coupled with generally higher relative humidity and low wind speed during the active vegetative and flowering periods greatly affected dry matter accumulation and partitioning of all the cowpea varieties. All the cowpea cultivars were affected by fungal and bacterial foliage diseases and insect pests, but the severity of the attacks was more in the sole cowpea and in the intercropped cowpea cultivars with the relatively lower soil fertility status (on the cereal components). The trend of dry matter accumulation was higher in the prostrate and more vegetative local cowpea, Dan-illa than in the other cowpea cultivars at cropping system level. Cowpea cultivars within intercrops at relatively higher soil fertility status showed higher trend of shoot dry matter accumulation than in intercrops that recieved pre-planting organic manure application alone. The more vigorous growth of the two cereal components resulting in greater canopy formation in such intercrops at higher soil fertility may have offered some barrier to the movement and propagation of disease organisms at the prevailing weather condition (Fig 4.20a and b).

The pattern of cowpea dry matter partitioning per plant stand varied among cultivars and cropping systems (Table 4.9). The trend of assimilate partitioning showed Dan-illa ahead of other cowpea cultivars at the flowering stage (40 DAS) in the intercropping systems. The trend in the sole cowpea treatments was IT88D-867-11 > Dan-illa > IT89KD-374. Dan-illa within the millet/sorghum/cowpea intercropping system and under full fertility treatment, produced higher dry matter than in the

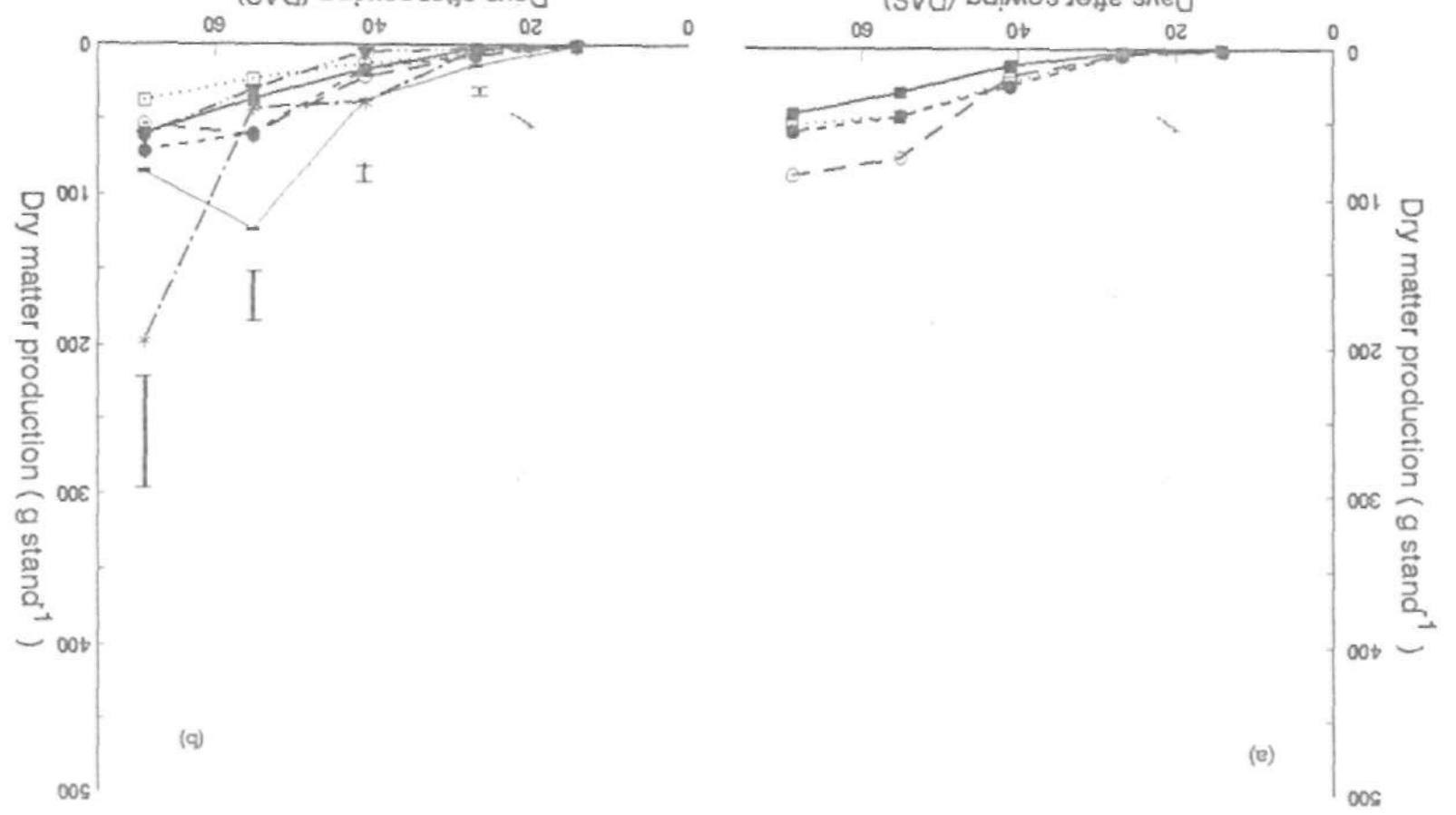


Fig. 4.20 The time course of cowpea dry matter accumulation as affected by cropping systems in (a) organic manure plus inorganic fertilizer application to cereal components and (b) organic manure application only to whole plot during 1994 cropping season. Bars represent $LSD_{0.05}$

millet/cowpea intercrops, particularly from 66 to 80 DAS. The relatively fewer stands of the fast growing millet and slower development rate of sorghum in the millet/ sorghum/cowpea systems reduced competition for resources and hence the better growth and development recorded. Although the trend of dry matter partitioning was the same for all cultivars, the fraction to fruits at maturity differ across cultivars and cropping systems [Table 4.9 (S.E. = 10.5, $P < 0.05$)]. Leaf, stem and pod yields of sole Dan-illa were higher and significantly different from sole IT89KD-374 and IT88D-867-11. Dan-illa in intercropping produced more seeds than the improved grain type cowpea as a result of the prolonged season with enough available soil moisture for later maturity crops.

The total dry matter accumulation of cowpea cultivars per hectare was significantly greater in the sole crops with higher plant densities than in intercrops (Fig. 4.21a and b). Sole grain type cowpea, IT88D-867-11, was a better dry matter accumulator than IT89KD-374 throughout the vegetative phase of crop growth up to 55 DAS. The trend of dry matter accumulation at crop maturity was Dan-illa > IT88D-867-11 > IT89KD-374. More dry matter was accumulated in the intercropped cowpea cultivars in the millet/sorghum/cowpea system within the relatively high soil fertility status plots, but this was not significant. The somewhat better performance of IT88D-867-11 over IT89KD-374 in the relatively unfavourable weather conditions of 1994, showed its potential as a possible replacement and inclusion as grain cowpea in intercropping systems.

The combined component crops TDM production of the intercropping systems compared with the sole millet up to 69 DAS, was significantly higher ($P < 0.01$) in the sole millet than that of intercropping systems (Table 4.10). However, at crop

Table 4.9: Dry matter partitioning in sole and intercropped cowpea cultivars during 1994 cropping season.

CROPPING SYSTEM	FERTILITY TREATMENT	COWPEA VAR.	Dry matter production g/plant stand														
			25 DAS			40 DAS			52 DAS			66 DAS			80 DAS		
			LEAF	STEM	POD	LEAF	STEM	POD	LEAF	STEM	POD	LEAF	STEM	POD	LEAF	STEM	POD
MIL/COW INT.	ORG.MAN+ INORG.FERT	IT89KD-374	0.55	*	0.0	1.26	0.50	0.0	5.13	2.73	0.2	10.8	8.96	2.0	9.34	8.72	15.2
		DAN ILLA	1.25	*	0.0	2.13	0.80	0.0	11.9	6.60	0.3	17.4	13.6	3.1	12.0	9.76	20.1
	ORG.MAN ONLY	IT89KD-374	0.55	*	0.0	1.57	0.50	0.0	8.78	3.80	0.2	15.5	10.9	1.7	18.4	11.9	14.9
		DAN ILLA	0.90	*	0.0	3.47	1.20	0.0	7.93	4.47	0.2	23.3	19.2	2.42	20.1	14.7	24.5
M/S/C INT.	ORG.MAN+ INORG.FERT	IT89KD-374	0.46	*	0.0	1.70	0.63	0.0	11.0	5.50	0.1	17.2	14.8	1.95	9.66	11.4	17.2
		DAN ILLA	0.60	*	0.0	2.23	0.86	0.0	9.3	4.20	0.1	24.5	24.5	6.30	17.8	16.0	30.3
	ORG.MAN ONLY	IT89KD-374	0.45	*	0.0	2.53	1.27	0.0	6.18	3.36	.02	9.26	7.28	1.20	7.02	8.69	13.1
		DAN ILLA	0.75	*	0.0	4.00	1.40	0.0	10.5	5.37	0.2	17.8	21.9	6.31	13.4	12.3	14.8
SOLE COWPEA	ORG.MAN ONLY	IT89KD-374	0.45	*	0.0	0.97	0.28	0.0	3.12	0.78	0.1	10.7	6.56	0.46	13.6	9.50	11.9
		DAN ILLA	0.70	*	0.0	0.92	0.58	0.0	12.7	8.03	0.4	12.9	10.3	1.26	31.5	32.6	48.3
		IT98D-867-11	0.35	*	0.0	3.42	1.53	0.0	7.84	4.48	0.1	21.9	20.3	3.63	5.56	11.5	14.8
STANDARD ERROR (D.F=17)			0.16	*	0.0	0.56	0.23	0.0	2.08	1.28	0.1	4.3	4.44	1.70	5.61	5.09	10.5

* - Data not available

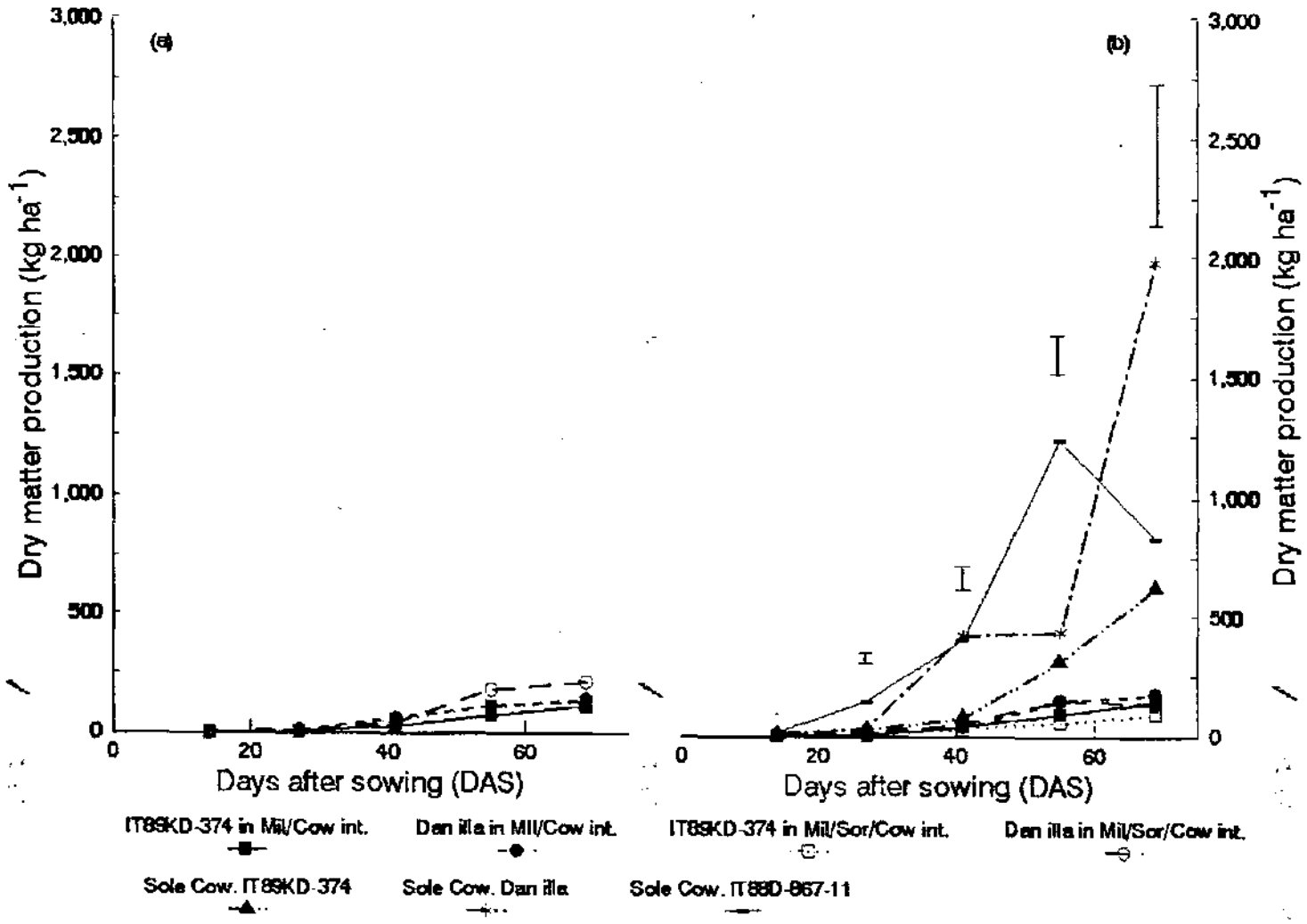


Fig. 4.21 The time course of total dry matter accumulation of cowpea as affected by cropping systems in (a) organic manure plus inorganic fertilizer application and (b) organic manure application only during 1994 rainy season.
Bars represents $LSD_{0.05}$

maturity (83 DAS) when millet had reached senescent maturity, TDM production was not significantly different statistically among the cropping systems. The effect of Soil fertility treatment on cropping systems was not significant, hence an assessment of the combined average TDM production for sole millet (6934 kg ha^{-1}), showed that it was 7 and 23% greater than the total dry matter produced in millet/cowpea and millet/ sorghum/cowpea cropping systems respectively.

Table 4.10: Variation in the trends of combined crop components total dry matter accumulation of millet based cropping systems as affected by cropping system in 1994.

	Total dry matter production (kg ha^{-1})						
	Sole millet		millet/cowpea		millet/sorghum/cowpea		
DAS	OM+IF	OM	OM+IF	OM	OM+IF	OM	SE (df=6)
28	379	225	45	74	15	19	32.0
41	2770	1884	497	738	279	231	98.5
55	5726	10842	1724	2244	1768	1476	745.5
69	13618	19813	2626	3727	2744	3379	1732.4
83	4470	8599	8813	4038	4350	3235	4470.1

4.3.2 (c) *1995 cropping season*

Dry matter accumulation of millet stands was significantly affected by the different cropping systems (Fig. 4.22). Millet in millet/sorghum/cowpea with the OM+IF treatment at 28 DAS produced higher shoot dry matter than was observed in the sole and intercropped millet with cowpea. From 43 DAS millet, when most tillers have developed, the intercropped canopies produced significantly higher shoot

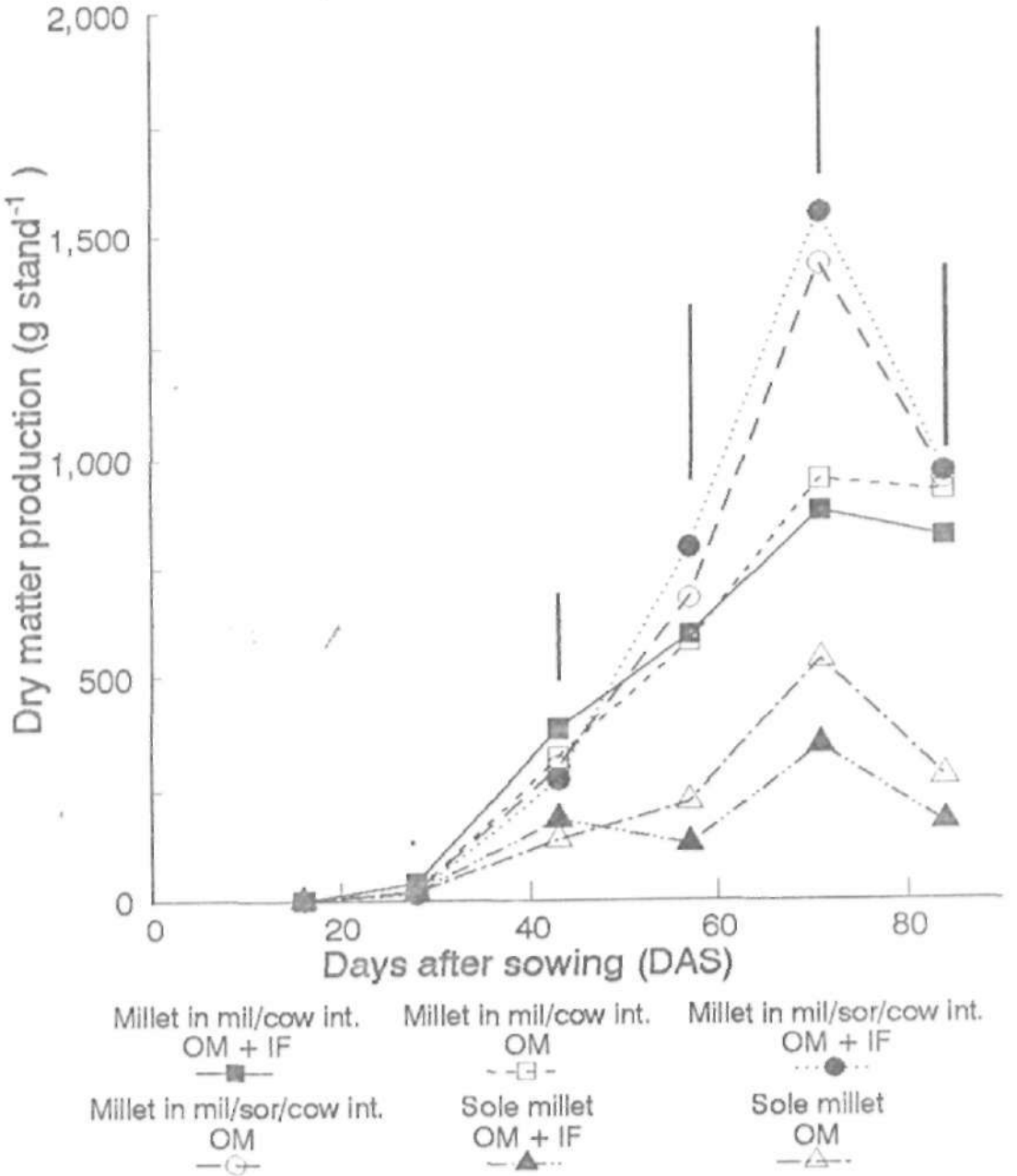


Fig. 4.22 The trend of millet stands dry matter accumulation as affected by cropping systems and soil fertility status during 1995 rainy season. Bars represent $LSD_{0.05}$

dry matter than the sole millet treatments until maturity. Dry matter accumluation was similar in the two soil fertility levels in all treatments ($P > 0.2$). However, cropping systems affected the rate of assimilate accumulation. The trend of dry matter accumulation per stand from panicle initiation (57 DAS) through grain filling to crop maturity was millet within millet/sorghum/cowpea intercrops > millet within millet/cowpea > sole millet (Fig. 4.22). Millet dry matter production decreased during grain filling in all the cropping systems until crop maturity, but this trend was more pronounced in the millet/sorghum/cowpea intercrops and sole millet under the two fertility treatments adopted (Fig. 4.22).

The sum of the partitioned assimilates to components parts of leaf, stem and panicle was higher in the intercropped millet than in sole. The higher number of tillers per stand in intercropped millet facilitated higher biomass production and hence a higher partitioning to components parts (Table 4.11). The trend of dry matter partitioning from millet panicle initiation to maturity was millet/sorghum/cowpea > millet/cowpea > sole millet.

The trend of millet total dry matter accumulation per hectare was greatly affected by plant population densities of cropping systems within the first 43 DAS (Fig. 4.23). Sole millet with the highest plant density accumulated significantly higher dry matter than the millet within intercrops ($P < 0.05$).The trend of assimilate accumulation was sole millet > millet in millet/cowpea > millet in millet/sorghum/ cowpea. The higher number of tillers produced in intercropped millet and additional fertility altered the trend of assimilate accumulation to favour the intercropped millet at panicle initiation through grain filling to crop maturity. The additional fertilizer to millet components of the higher fertility treatment increased dry matter accumulation

Table 4.11: Variation in dry matter fractions of sole and intercropped millet in relation to soil fertility during 1995 cropping season.

CROPPING SYSTEM	FERTILITY TREATMENT	Dry matter production g/plant stand																	
		16 DAS			28 DAS			43 DAS			57 DAS			71 DAS			84DAS		
		LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD
SOLE MILLET	ORG.MAN+ INORG.FERT	1.23	0.57	0.0	13.7	3.63	0.0	70.3	112	3.05	40.1	75	13.8	31.4	222	92	37.6	41.9	95.3
	ORG.MAN ONLY	0.75	0.27	0.0	14.1	4.87	0.0	62.4	76	1.25	47.6	160	15.1	84.2	355	98	38.9	165	70.5
MIL/COW INTERCROP	ORG.MAN+ INORG.FERT	0.80	0.30	0.0	30.2	9.77	0.0	157	228	0.0	155	377	62.4	136	527	216	104	398	317
	ORG.MAN ONLY	0.87	0.26	0.0	14.9	5.76	0.0	127	193	0.0	141	356	81.9	148	624	179	139	505	280
MIL/SOR/COW INTERCROP	ORG.MAN+ INORG.FERT	1.07	0.33	0.0	12.0	3.87	0.0	135	138	0.0	190	564	42.6	187	902	464	173	433	361
	ORG.MAN ONLY	0.93	0.37	0.0	16.1	6.68	0.0	144.	156	0.0	141	434	104	167	832	434	140	462	349
STANDARD ERROR (D.F=6.cropping system)		0.11	0.07	0.0	3.6	1.03	0.0	16.9	45.8	0.84	16.9	73.5	14.7	27.3	118	54.5	22.0	45.2	46.0

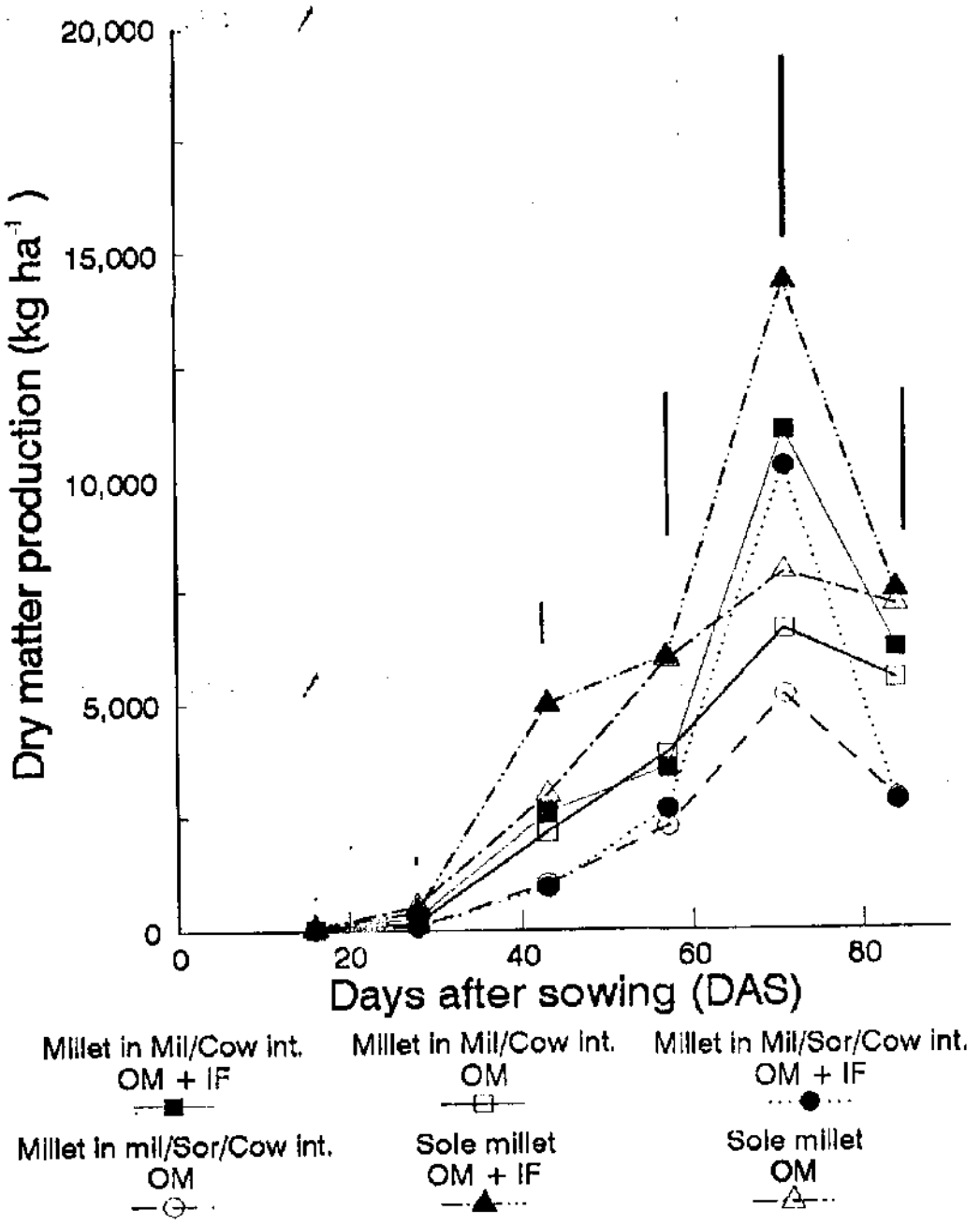


Fig. 4.23 The trend of total millet dry matter accumulation as affected by cropping systems and soil fertility status during 1995 rainy season. Bars represent $LSD_{0.05}$.

in all cropping systems. However, there was a decrease in dry matter accumulation during grain filling to crop maturity in all the cropping systems.

The pattern of sorghum dry matter accumulation per stand varied between the two sorghum varieties but not within cropping systems (Fig. 4.24a). Sole Gaya Early consistently produced higher dry matter than ICSV 400 at the two fertility levels of this study until 66 DAS. At about 80 DAS, when ICSV 400 had reached its peak canopy development, the high fertility treatment produced higher dry matter than Gaya Early sown sole and intercropped. The additional fertilizer to sorghum components in all the cropping systems also seem to improve dry matter accumulation through grain filling to crop maturity, except in the intercropped Gaya Early with OM fertility level.

The pattern of variation in the sorghum component dry matter partitioning as affected by cropping system and soil fertility status is presented in Table 4.11. Although Gaya Early in sole and intercropping system seem to be the better dry matter accumulator when compared with ICSV 400 (40 DAS), this trend was not consistent during the period of assimilate partitioning at the start of reproductive phase (79 DAS). Sole ICSV 400 (OM+IF) and intercropped Gaya Early initiated head formation earlier than sole Gaya Early. The dry matter production and partitioning was higher in Gaya Early than ICSV 400 at crop maturity, while intercropped Gaya Early gave higher fractions of partitioned assimilates than the sole crop (Table 4.12).

Total dry matter production per hectare of sorghum components of the various cropping systems was related to plant population density per hectare and sorghum variety. Sole Gaya Early with better canopy development and at high density was a better dry matter accumulator than ICSV 400 and intercropped Gaya Early through

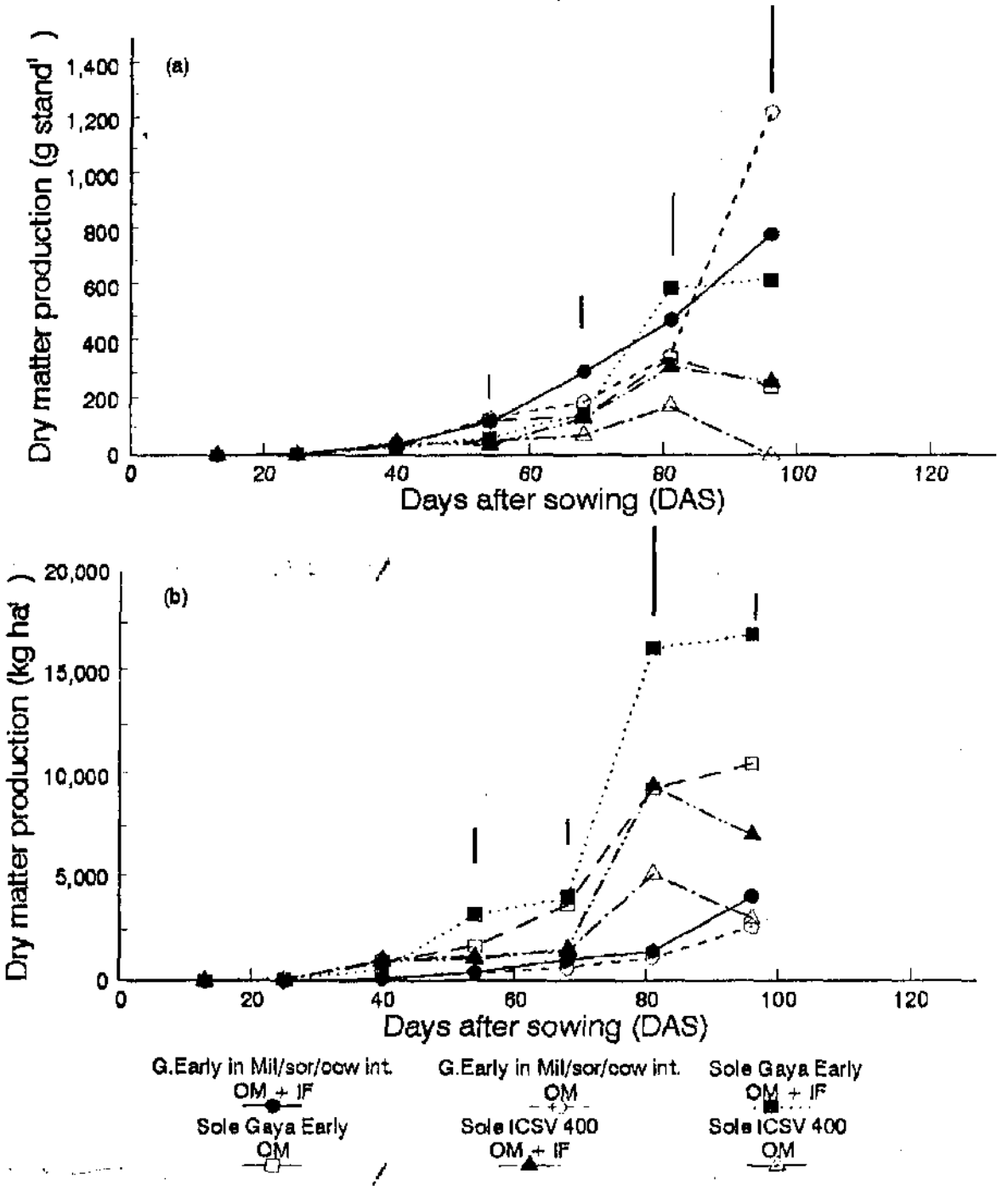


Fig. 4.24 The trend of sorghum dry matter accumulation as affected by cropping systems and soil fertility status in (a) g stand^{-1} and (b) kg ha^{-1} during 1995 rainy season. Bars represent $LSD_{0.05}$

Table 4.12: Dry matter partitioning of sorghm components as affected by cropping system and soil fertility status during 1995 cropping season.

CROPPING SYSTEM	FERTILITY TREATMENT	Dry matter production g/plant stand																	
		25 DAS			40 DAS			52 DAS			66 DAS			79 DAS			125 DAS		
		LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD	LEAF	STEM	HEAD
SOLE SORGHUM (G.EARLY)	ORG.MAN+ INORG.FERT	2.88	1.32	0.0	18.6	9.4	0.0	36.9	27.4	0.0	50.0	104	0.0	112	486	0.0	160	47.5	423
	ORG.MAN ONLY	3.20	1.19	0.0	18.2	14.4	0.0	56.5	65.2	0.0	53.8	86	0.0	111	240	0.0	93	22.6	135
SOLE SORGHUM (ICSV400)	ORG.MAN+ INORG.FERT	2.36	0.71	0.0	25.6	21.8	0.0	20.7	15.6	0.0	26.8	109	0.0	76	234	9.20	69	79.4	117
	ORG.MAN ONLY	1.21	1.04	0.0	21.4	15.1	0.0	27.6	27.1	0.0	33.7	39	0.0	44	136	0.0	26	30.0	*
MIL/SOR/COW INTERCROP (G.EARLY)	ORG.MAN+ INORG.FERT	3.95	1.24	0.0	26.7	15.5	0.0	58.3	63.6	0.0	69.5	233	0.0	124	315	45.9	157	54.5	580
	ORG.MAN ONLY	2.74	1.0	0.0	21.0	14.2	0.0	67.4	68.1	0.0	79.4	114	0.0	114	232	13.2	222	115	895
STANDARD ERROR (D.F=4)		1.74	0.63	0.0	10.2	8.46	0.0	5.68	9.12	0.70	26.2	41.6	0.0	25.8	121		38.6	4.79	136

* - missing data

grain filling to crop maturity (Fig. 24b).

The time course of cowpea component dry matter accumulation within the different cropping systems varied considerably (Table 4.13 and Fig. 4.25). Dry matter production of cowpea cultivars in intercropping systems indicated a higher rate in the millet/sorghum/cowpea intercrops than millet/cowpea system. Dan-illa was the better dry matter accumulator in intercropping and sole planting (Fig 4.25a and b). The sole cowpea crops of Dan-illa, IT89KD-374, IT86D-719 and IT88D-867-11 significantly accumulated higher dry matter than cowpea cultivars within millet/cowpea intercrops. The three earlier maturing grain type cowpea, IT89KD-374, IT88D-867-11 and IT86D-719 reached their peak biomass accumulation about the same time with IT88D-867-11 producing the highest thus in agreement with 1994 observation. However, the rate of dry matter decline at grain filling to maturity was highest in IT88D-867-11 when compared with the other sole grain cowpea cultivars (Fig. 4.25b).

Cowpea growth rate in the different cropping systems is an important source of assimilate partitioning variation which is related to the cultivar genotypes. The higher weight of assimilates, partitioned to leaf and stem in Dan-illa from 41 DAS until flowering, than other cultivars is consistent with its growth and dry matter accumulation (Table 4.13). The variation in the partitioning of assimilate reflected cultivar differences influenced by cropping systems in the timing of establishment of reproductive sinks. The grain cowpea cultivars commenced reproductive stage earlier than intercropped and sole Dan-illa and hence indicated relatively higher ratio of assimilate partitioning to flowers and pods development at 41 DAS. The rate of dry matter accumulation and partitioning at 68 DAS was lowest for Dan-illa in millet/cowpea intercrops where the more vigorous millet produced faster canopy and

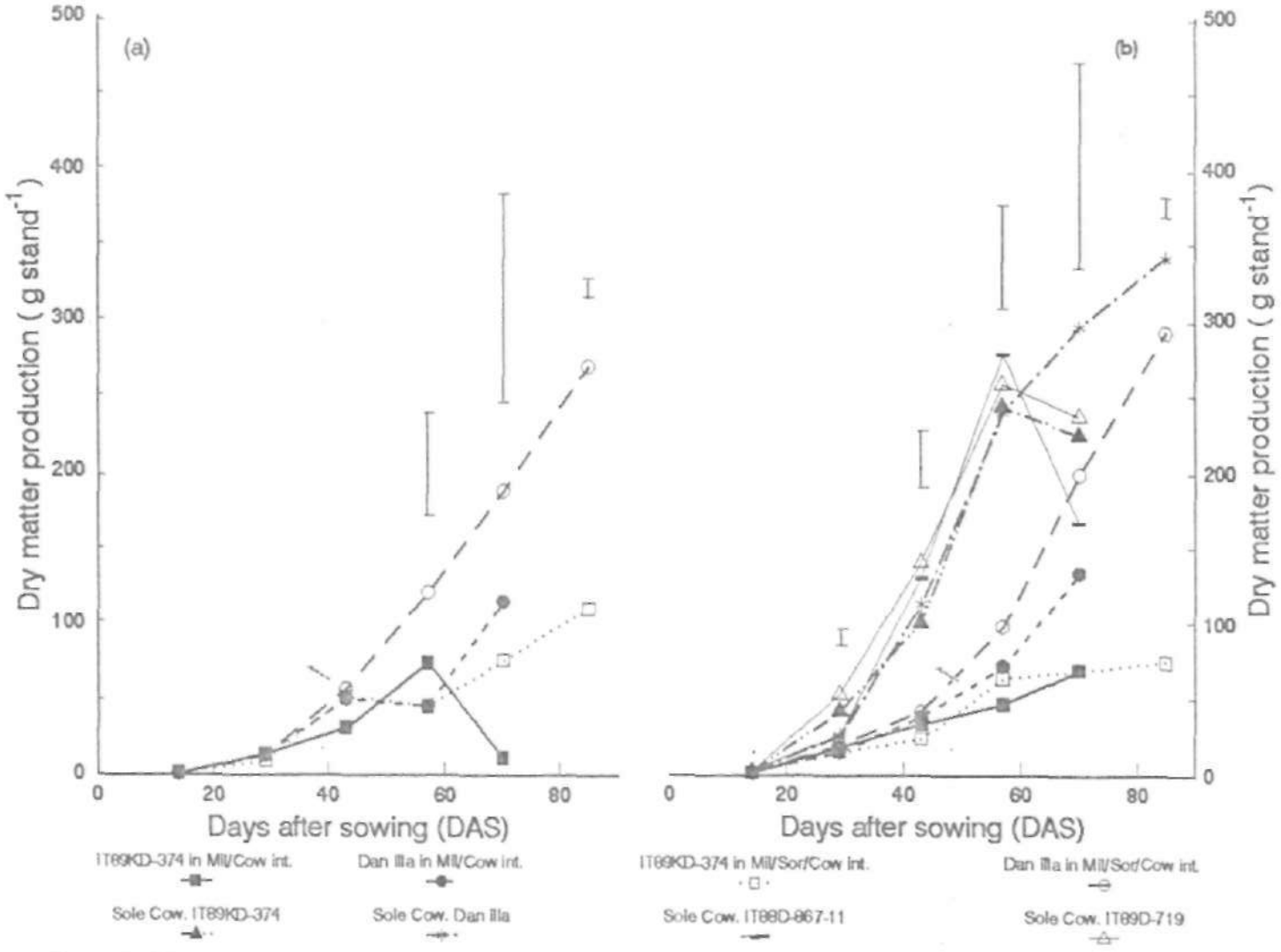


Fig. 4.25 The trend of cowpea stands dry matter accumulation as affected by cropping system in (a) organic manure plus inorganic fertilizer application to cereal components and (b) organic manure application only. Bars represent $LSD_{0.05}$.

Table 4.13: Dry matter partitioning of cowpea cultivars as affected by different cropping systems during 1995 cropping season.

CROPPING SYSTEM	FERTILITY TREATMENT	COWPEA VAR.	Dry matter production d/plant stand																	
			14 DAS			29 DAS			41 DAS			55 DAS			68 DAS			83 DAS		
			LEAF	STEM	POD	LEAF	STEM	POD	LEAF	STEM	POD	LEAF	STEM	POD	LEAF	STEM	POD	LEAF	STEM	POD
MIL/COW INT.	ORG.MAN+ INORG.FERT	IT89KD-374	0.73	0.20	0.0	6.80	3.63	0.0	13.2	10.4	0.1	28.1	23.1	3.0	17.0	16.9	6.8	0.0	0.0	0.0
		DAN ILLA	0.73	0.24	0.0	6.90	3.03	0.0	21.2	16.8	0.0	30.0	21.5	0.1	59.1	58.9	2.1	0.0	0.0	0.0
	ORG.MAN ONLY	IT89KD-374	0.86	0.16	0.0	9.50	4.23	0.0	14.6	10.8	0.0	17.9	20.1	4.4	23.5	28.2	1.5	0.0	0.0	0.0
		DAN ILLA	0.98	0.30	0.0	7.97	3.73	0.0	15.5	13.2	0.0	25.6	24.2	2.7	45.9	46.3	2.2	0.0	0.0	0.0
M/S/C INT.	ORG.MAN+ INORG.FERT	IT89KD-374	0.83	0.24	0.0	4.97	2.27	0.0	22.2	16.6	0.2	11.6	13.0	6.4	10.6	11.8	19.0	21.1	44.6	80.7
		DAN ILLA	0.51	0.16	0.0	6.40	3.57	0.0	23.3	19.6	0.0	47.5	43.1	0.1	65.5	87.7	18.6	43.4	77.7	37.5
	ORG.MAN ONLY	IT89KD-374	0.90	0.34	0.0	7.83	3.53	0.0	10.9	6.45	0.4	17.9	19.0	7.3	5.8	13.5	7.1	3.7	30.3	21.9
		DAN ILLA	0.91	0.26	0.0	9.63	5.20	0.0	17.8	13.7	0.0	32.8	37.9	2.0	75.8	103	22.1	48.2	102	68.0
SOLE COWPEA	ORG.MAN ONLY	IT89KD-374	0.99	0.28	0.0	17.3	6.50	0.0	31.2	25.1	0.4	38.6	59.2	25.9	30.5	58.5	42.0	*	*	34.4
		DAN ILLA	0.78	0.24	0.0	10.2	4.60	0.0	34.3	29.4	0.0	62.6	71.4	0.60	89.1	105	20.2	37.3	53.3	101
		IT89D-719	0.57	0.25	0.0	13.7	6.85	0.0	22.0	29.8	0.2	16.4	35.1	15.1	38.0	31.6	15.5	*	*	34.5
		IT88D-867-11	0.51	0.42	0.0	7.20	3.10	0.0	28.6	19.9	0.6	30.8	50.4	30.2	33.8	64.7	13.2	*	*	34.4
STANDARD ERROR (D.F= 18)			0.17	0.07	0.0	1.87	0.94	0.0	5.45	3.99	0.2	5.84	7.94	6.54	3.97	17.3	9.48	2.59	5.54	2.1

*- missing data

created resource competition problems for cowpea. The 1995 cropping season provided favourable condition for cowpea growth and development. The highest biomass and seed yield per plant stand was obtained in the sole Dan-illa (Table 4.13). Total dry matter accumulation per hectare was much higher in the sole than in the cowpea components within intercrops ($P < 0.001$) throughout crop duration on the field (Fig. 4.26a and b). The higher plant population density in the sole cowpea plots produced more shoot dry matter. Dry matter accumulation was not significantly different among the sole cowpea crops, but Dan-illa that reached maturity later produced the most dry matter, while the initial advantage of IT88D-867-11 was lost as a result of senescence towards physiological maturity .

An analysis of the combined TDM production of the intercropped systems compared with sole millet showed that the different soil fertility treatments did not affect the rate of TDM accumulation at cropping system level (Table 4.14). On this basis, the combined TDM up to 43 DAS millet was significantly ($P < 0.01$) different among the systems. The trend of combined TDM up to 43 DAS millet, was sole millet > millet/cowpea > millet/sorghum/cowpea cropping systems. At the period of maximum canopy development in millet and cowpea components (57 DAS), TDM of combined millet/sorghum/cowpea intercrop was higher by 23 and 15% than that of mille/cowpea and sole millet respectively. The TDM of sole millet was slightly higher (9%) than the millet/cowpea intercrop. The TDM production from 57 DAS up to the stage of grain filling and rapid linear growth in the sorghum components, 71 DAS, among the cropping systems did not differ significantly. However, at millet and cowpea maturity, while sorghum was still actively growing on the field, TDM in the millet/sorghum/cowpea system (16400.5 kg ha^{-1}) was significantly higher ($P < 0.05$)

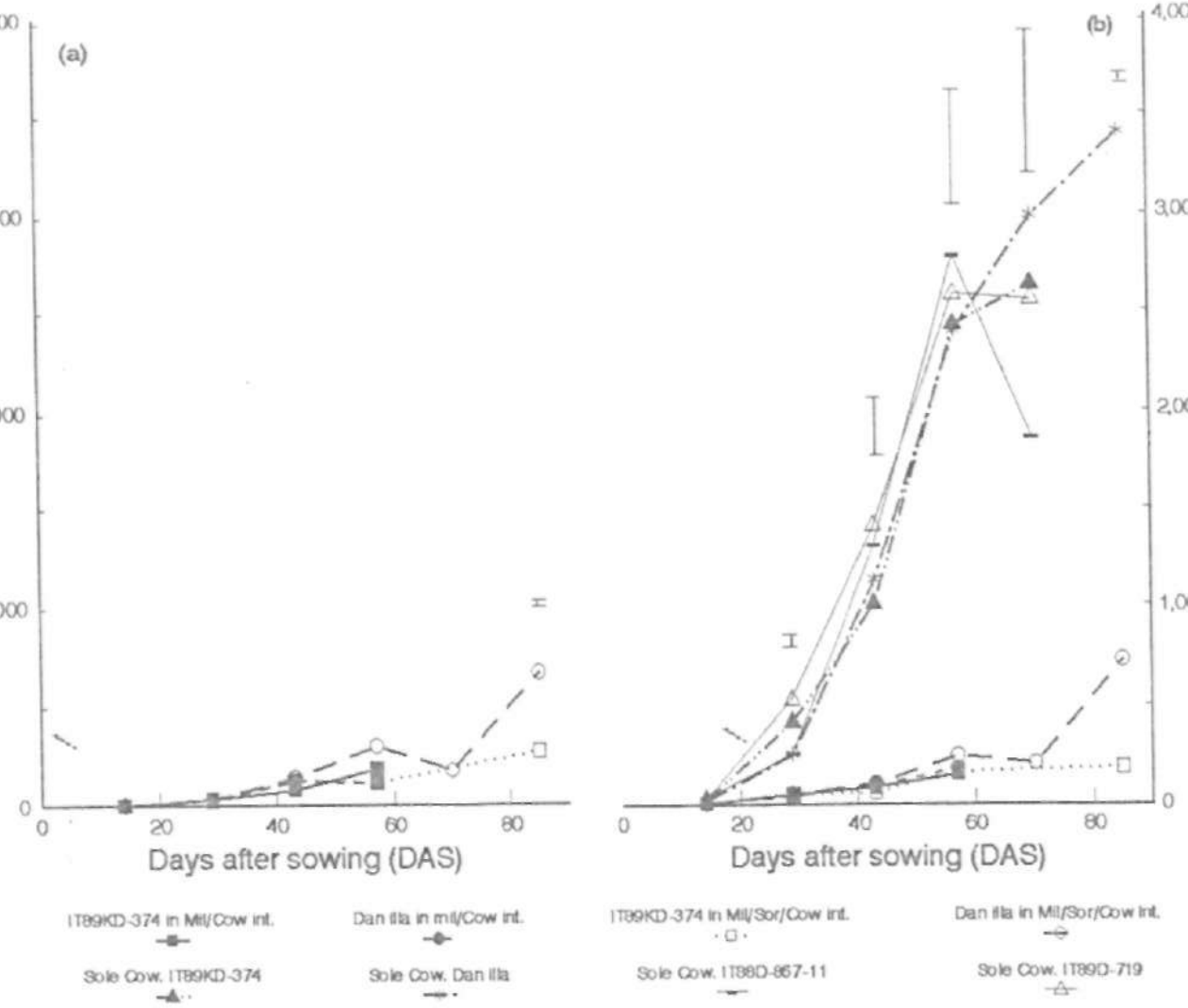


Fig. 4.26 The time course of total dry matter accumulation of cowpea as affected by cropping systems in (a) organic manure plus inorganic fertilizer application to cereal components and (b) organic manure application only during 1994 rainy season. Bars represent $LSD_{0.05}$.

by 61 and 66% than in the millet/cowpea and sole millet respectively.

Table 4.14: Total dry matter accumulation of millet based cropping systems as affected by cropping systems in 1995.

	Total dry matter production (kg ha^{-1})						
	Sole millet		millet/cowpea		millet/sorghum/cowpea		
DAS	OM+IF	OM	OM+IF	OM	OM+IF	OM	SE (df=6)
16	43	25.8	7.3	7.6	6.0	6.0	3.2
28	395	513	274	144	75	99	43.1
43	4933	2980	2573	2207	1956	1596	192.6
57	5444	5932	4101	4434	6468	4550	976
71	8055	14328	7111	4993	9360	9912	1534
84	7535	3686	6870	5875	19752	13049	1367.9

During the 3 years of the experiment, component crops LAI and combined TDM accumulation were dependent on cropping system. In the intercropping situations such as presented in this trial, the major effects of resource stress based on the amounts of resource use, is manifested on growth rate through the development and maintanance of the canopy and on the eventual translocation of assimilates to reproductive organs. The growth rate curvature at maximum TDM may also be a consequence of genetic variation when the response of a number of plants are combined. In sole cropping situations, total dry matter production was promoted during early stages of growth by the relatively higher plant density, and the difference in TDM was maintained to maturity. The difference in total dry matter were not statistically significant in the millet components of the millet based cropping systems.

This was a result of the high tillering ability of millet sown at low plant density and in essence, the low effects of intercropping on millet total dry matter production. The LAI observed for the local fodder cowpea-Dan-illa was always higher than for the improved semi-erect grain type when treatments were compared.

Total dry matter production of cowpea components were greatly affected by the associated cereal(s), C_4 plants, particularly the faster growing millet at the relatively higher density in the millet/cowpea intercrops. In the millet/cowpea intercrop, the growth duration of the cowpea components varied from 83 to 110 days, depending on the varietal photoperiod sensitivity, and was about 90 days for the millet (Ex-Borno). The onset of linear growth rate for the two crops is similar and the period of canopy overlap lasted for about 60 days, independent of the different cowpea cultivars growth duration. The time of cowpea planting relative to millet and sorghum (3 and 2 WAS respectively), allowed for greater growth and higher cereal canopy development that created competition problems for the low growing, less efficient dry matter accumulating cowpea components (C_3 plant).

4.4 Radiation (PAR) capture and use

4.4.1 *1994 cropping season*

The light interception measurement density within the cropping systems was high with only two replications within the time available for such measurements in a day. This limitation only allows for a limited use of statistical analysis on the light data collected, hence only means of two measurements were used to describe trends.

Light interception distribution between component crops as a function of time was related to the different cropping systems and soil fertility status. The rate of plant

canopy development determines part of the efficiency of radiation use, because light interception is a major function of leaf area index (LAI). An examination of the interception between and within rows of the different crop components in intercropping explains how intercepted radiation is partitioned between the component species differently to that expected on the basis of sole crops. Measured light interception trends, as shown in Figure 4.27, started at Day 206 which corresponds to 18 DAS cowpea, 28 DAS sorghum and 32 DAS millet. In the millet/sorghum/ cowpea cropping system (Figs. 4.27a and b), canopy light interception in the millet/sorghum, millet/cowpea fodder, millet/cowpea grain type (OM only) and fodder cowpea/fodder cowpea types components directions increased at a relatively faster rate than for the sorghum in combination with the two cowpea types and in the cowpea grain type/cowpea grain type components. The faster growth of the tillering millet and the prostrate and more vegetative growth of the fodder cowpea, Dan-illa, caused the combinations in which they occurred to intercept more light than combinations in which millet was not involved, or fodder cowpea not combined with millet or itself. This trend occurred on cropping system basis and for millet/sorghum, it was even more pronounced in the relatively higher soil fertility treatment. With the exception of millet/cowpea grain (OM+IF), it occurred for cases where millet was involved, because millet and cowpea fodder canopy development were more favoured.

The least fractional light interception recorded and maintained almost throughout the duration of crop growth was between sorghum and the grain type cowpea components. This was also in agreement with the lower LAI and TDM production observed in the intercropping systems (Fig. 4.27a and b). The peak periods of light interception in millet/sorghum of 62% and 76% in the OM and OM+IF

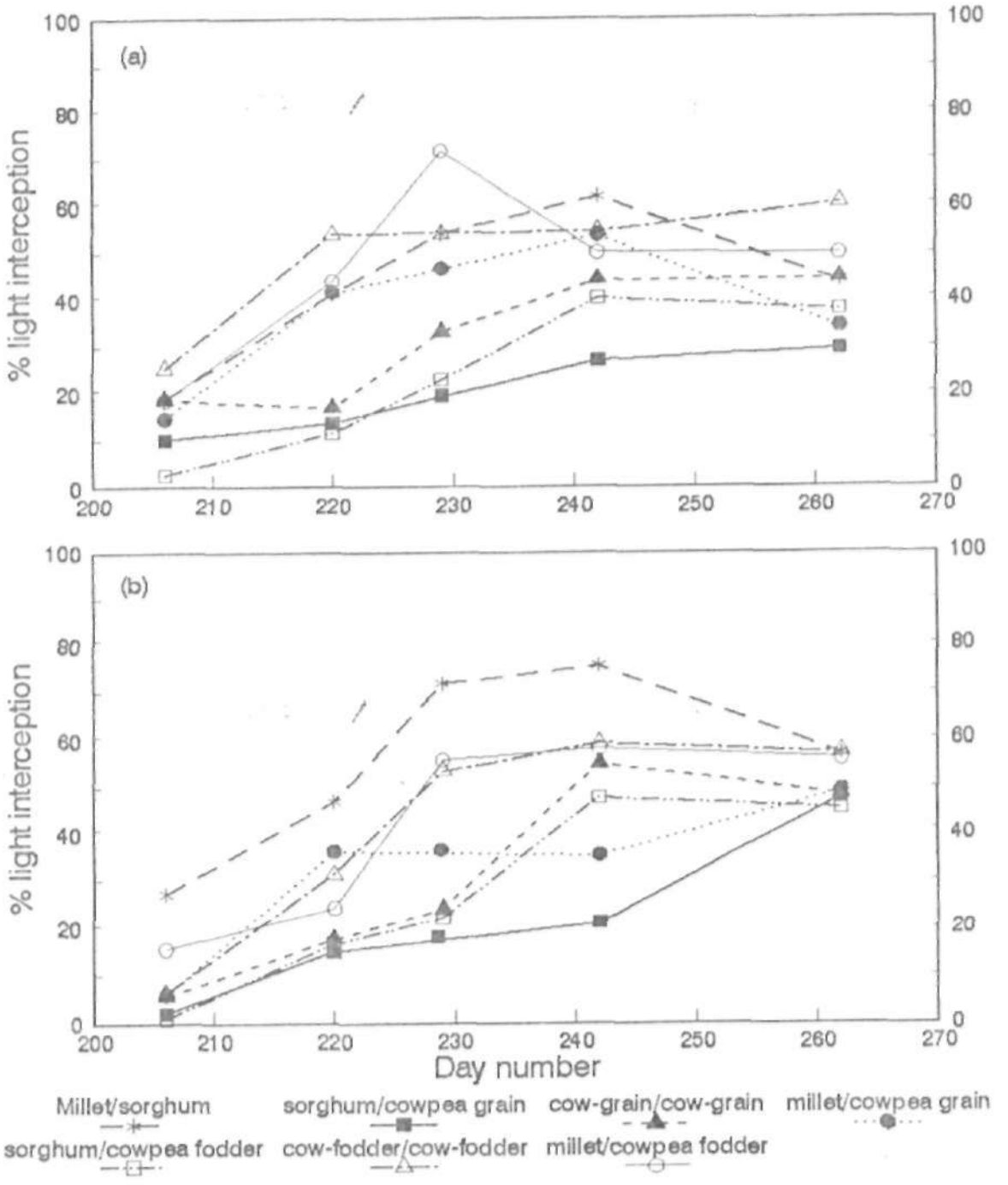


Fig. 4.27 Light interception patterns in relation to component crops distribution in space in the millet/sorghum/cowpea intercropping system with (a) pre-planting organic manure application alone and (b) organic manure plus inorganic fertilizer application during 1994 cropping season.

fertility treatments respectively, occurred at Day 242. This period coincided with the grain filling stage and canopy decrease of millet (78 DAS), while the sorghum experienced an increase in canopy development (≈ 60 DAS). Relatively high values of intercepted radiation were also recorded in the cowpea grain/cowpea grain, sorghum/fodder cowpea, fodder cowpea/fodder cowpea and millet/fodder cowpea directions about Day 242. The period after Day 242 until Day 262 showed an increase in light interception in the sorghum/cowpea grain type direction. This was the period of active vegetative growth in the intercropped sorghum, while the grain cowpea that already had a relatively poor growth and canopy development resulting from unfavourable weather conditions had reached a senescent maturity. The increase in light interception was more in sorghum/cowpea grain type with the relatively higher soil fertility sorghum treatment as expected than in the OM treatment (Fig. 4.27).

The partitioning of intercepted radiation in the millet/cowpea cropping system showed a higher canopy light interception between the millet components when compared with, trends observed in the millet/cowpea directions (Fig. 4.28a and b). At the peak of linear growth stages for millet and cowpea components, when their highest LAI were reached (Day 242), percent light interception in the millet/millet directions (82-86%) were 44% and 50% of the total system intercepted radiation in the millet/cowpea intercrops with pre-planting soil organic manure application alone and the fertility treatment with additional inorganic fertilizer application respectively. The millet/millet direction is a clearly higher intercepting combination while the trend of fractional radiation interception within the millet and the two cowpea cultivars was rather similar. Peak light interception in the millet/millet direction (Day 242) of the higher fertility plot (86%) was identical to what was recorded in the OM plot (82%).

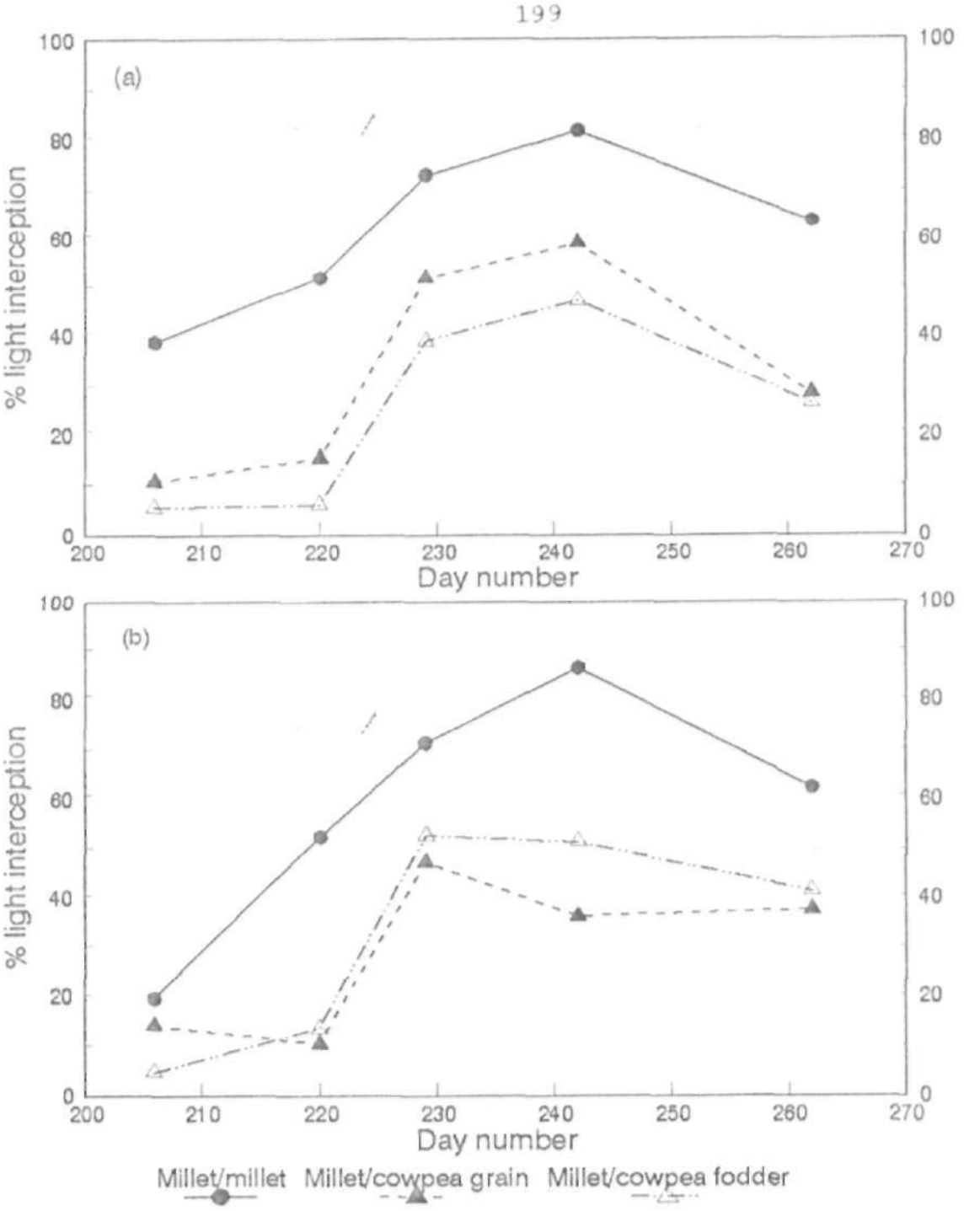


Fig. 4.28 Light interception pattern in relation to component crops distribution in space in the millet/cowpea intercropping system with (a) pre-planting organic manure application alone and (b) organic manure plus inorganic fertilizer application during 1994 cropping season.

The difference in soil fertility status among the treatments also did not affect much the cowpea light interception in the millet/cowpea intercrop.

Measured light interception among the sole cowpea treatments indicated similar trends (Fig. 4.29). The grain type cowpea cultivars IT89KD-374 and IT88D-867-11 have a determinate growth habit and mature faster than Dan-illa. Their initial rate of canopy development is expected to be faster than Dan-illa, but this was not well pronounced with IT89KD-374 during the 1994 season. Dan-illa recorded the maximum cowpea light interception (69%) at the end, in accordance with the highest LAI and TDM produced in the sole cowpea treatments (Fig. 4.29).

A comparison of the trend of cropping systems total radiation interception with the fastest growing cereal component shows that sole millet radiation interception was 15-65% higher than that of intercrops during vegetative period up through the commencement of grain filling at 68 DAS millet or Julian Date 242 (Fig. 4.30). During the 1994 cropping season, the maximum light interception that occurred in the sole millet was due to the higher plant density in the sole sown millet while the poor vegetative growth observed for all the cowpea cultivars was as a result of unfavourable weather condition that caused high insect population and foliage disease incidences. The higher light interception in the millet/cowpea intercrop is the reason for the greater TDM recorded in this canopy than in the millet/sorghum/cowpea. Although leaf area per millet stand was greater in some of the low density plots, the plant population was too sparse to intercept a similar percentage of radiation compared with the higher density sole cereal plots. The proportion of C_4 species in any of the crop mixtures, especially the tillering and faster growing millet component, however, had a dominant impact on the radiation interception profile and the amount intercepted

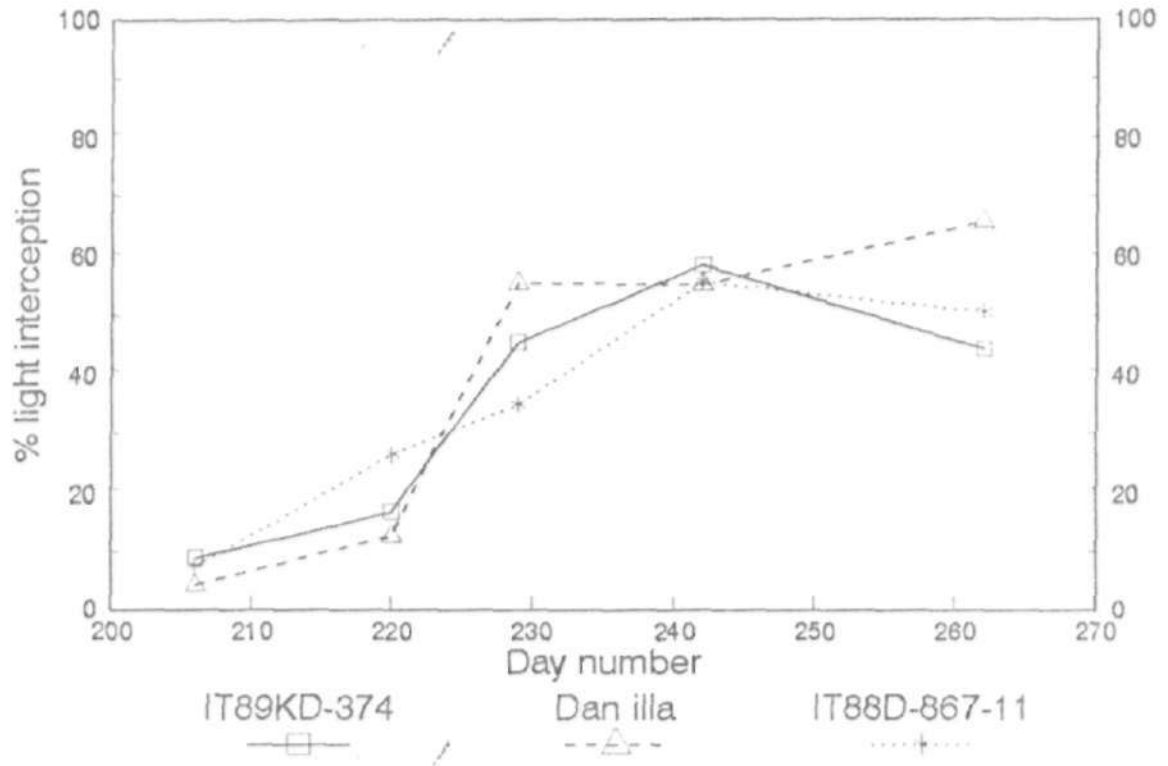


Fig. 4.29 Light interception pattern of sole cowpea cultivars during 1994 cropping season.

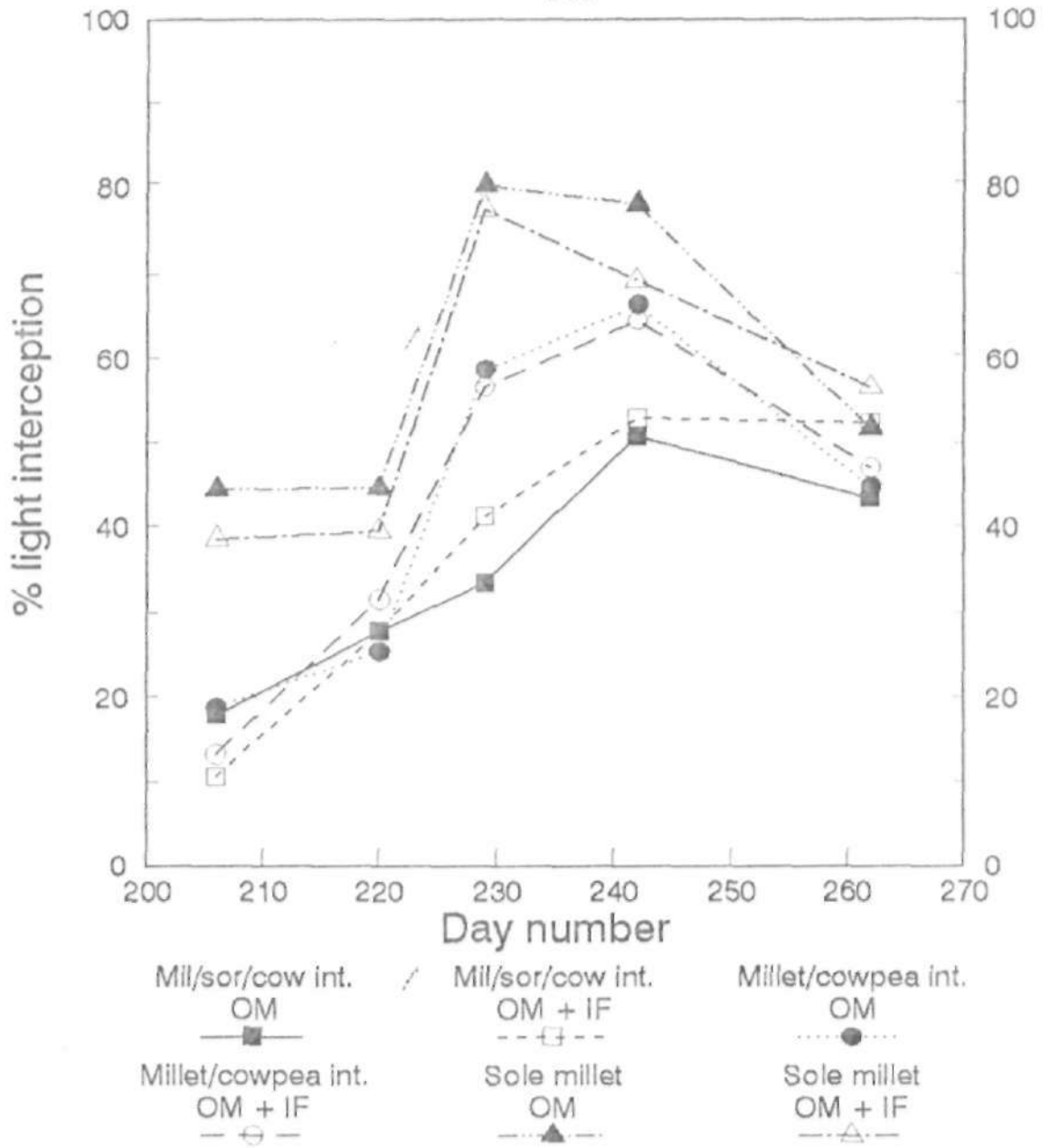


Fig. 4.30 Comparison of total light interception in sole millet with the millet based intercropping systems with preplanting organic manure application alone (OM) and organic manure plus inorganic fertilizer application (OM + IF) during 1994 cropping season.

by the mixture.

4.4.2 *1995 cropping season*

In the millet/sorghum/cowpea intercrops with pre-planting soil organic manure application alone, canopy light interception initially increased more rapidly in the direction of millet/sorghum, sorghum/fodder cowpea type and fodder cowpea/fodder cowpea types crop combinations than in the directions of sorghum and millet with the cowpea grain type and grain cowpea/grain cowpea type asociations, while after some time the grain cowpea/grain cowpea light interception behaviour did not differ much from that of the millet/fodder cowpea (Fig. 4.31a). For the OM+*IF* at Day 209 all interceptions were within 80 ± 10%. The maximum light interception within the intercrop of OM (93%) occurred in the millet/sorghum direction at millet maximum LAI and the period of rapid linear growth rate in sorghum (Day 222). The light measurements in the directions of the grain cowpea was terminated after crop senecence and harvest of the cowpea pods at about 75 DAS cowpea (≈ Day 248). The canopy development of the cowpea components was better in 1995 when compared with the 1994 season, hence the improved light interception and greater TDM recorded. The trend of light capture in the sorghum/grain cowpea direction was the least of all the crops in association; although, at the maturity of the grain cowpea, the remaining sorghum had appreciable canopy development. The sorghum component had an initial slow growth rate until about 65 DAS sorghum (≈ Day 233), while the grain type cowpea had a smaller vegetative structure than its corresponding sole crop and fodder cowpea sown sole and intercropped. The grain cowpea component was responsible for a substantial part of the initial radiation interception of its intercrops

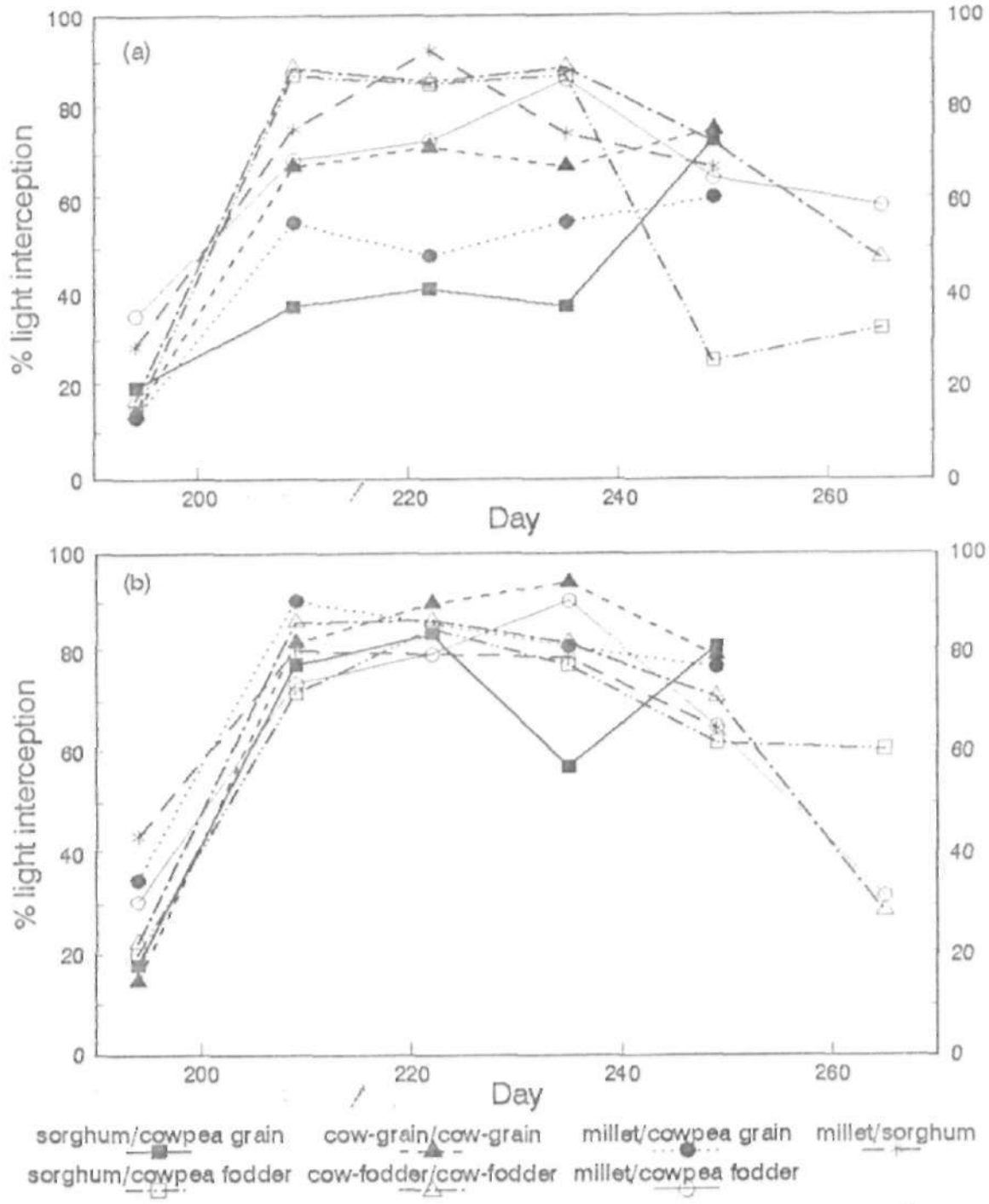


Fig. 4.31. Light interception patterns in relation to component crops position in the millet/sorghum/cowpea intercropping system with (a) pre-planting organic manure application alone and (b) organic manure plus inorganic fertilizer application during 1995 cropping season.

reached at about Day 210 (32 DAS, before cowpea flowering) and remained at this level, while sorghum increased in their intercrop. The periods of the decline in intercepted light in the millet in association with other crops, is explained by the decrease associated with millet canopy about panicle initiation Day 220, visible in the millet/sorghum direction and grain filling in the millet/cowpea fodder intercrop at Day 233 ($\approx$ 69 DAS) until maturity Day ($\approx$ 80 DAS) The period of increased radiation interception in the sorghum/cowpea grain interception started about 65 DAS sorghum ($\approx$ Day 233) and coincided with the stage of rapid linear growth rate of sorghum component and the maturity and leaf senescence of the grain cowpea type.

The higher TDM production in the higher fertility millet/sorghum/cowpea intercrop is reflected in the higher fractional radiation intercepted as a result of enhanced soil nutrient availability. The promotion of higher canopy development among all crops in association in the relatively higher soil fertility status plots of millet/sorghum/cowpea was also enhanced by the more rapid and greater intercepted radiation observed (Fig. 4.31b). The relatively higher light interceptions were in the cowpea grain and its association and also with itself. The decline in intercepted radiation and the subsequent rise thereafter in the sorghum/cowpea associations is in agreement with the joint growth characteristics of these components.

The similarity in the life cycle of millet and cowpea is shown in measured light intercepted as a function of time in the millet/cowpea intercrops (Fig. 4.32a and b). Although the initial radiation interception was much higher in the millet/millet direction, the maximum light interception among all other components in association was reached about the same period during the season. The highest light interception occurred along directions of millet in association with cowpea and the two cowpea

components. With the exception of the cowpea grain/cowpea grain, the plots with the higher soil fertility rates enhanced more continuous light interception after their maximum was reached. The decline observed in the intercepted radiation during grain filling did only exist in plots with pre-planting organic manure application alone, with the exception in OM+IF of the grain cowpea/grain cowpea association and for a short period, the millet/cowpea grain association (Fig. 4.32a and b). The smaller vegetative growth produced by the semi erect IT89KD-374 in the millet/cowpea intercrop was also the result of the lower radiation interception observed in its direction with millet. Also in association with another grain cowpea stand, its intercepted radiation was low later in the season for both fertility levels. During cowpea grain filling to crop maturity, there was a rapid defoliation in the grain type cowpea and hence the least light interceptor in association with other crop components at cropping system level.

An examination of the light interception by crop stands within and between rows in crops sown sole, explains how intercepted radiation is partitioned within the system in relation to canopy development and the expected assimilate that is accumulated (Table 4.15a). For sole cowpea plots, canopy development was more in the relatively wider space between rows as indicated by larger fraction of light intercepted than within crop rows. The trend of radiation interception as a function of time also varied with cowpea cultivar and their growth habits (Fig. 4.33).

Light interception at the initial stage of growth was greater in the erect and shorter duration, grain type cowpea cultivars (IT89D-719 and IT88D-867-11). With the exception of IT89D-719, the light interception of all the cowpea cultivars increased rapidly thereafter until maximum points between Day 221 and Day 235. The

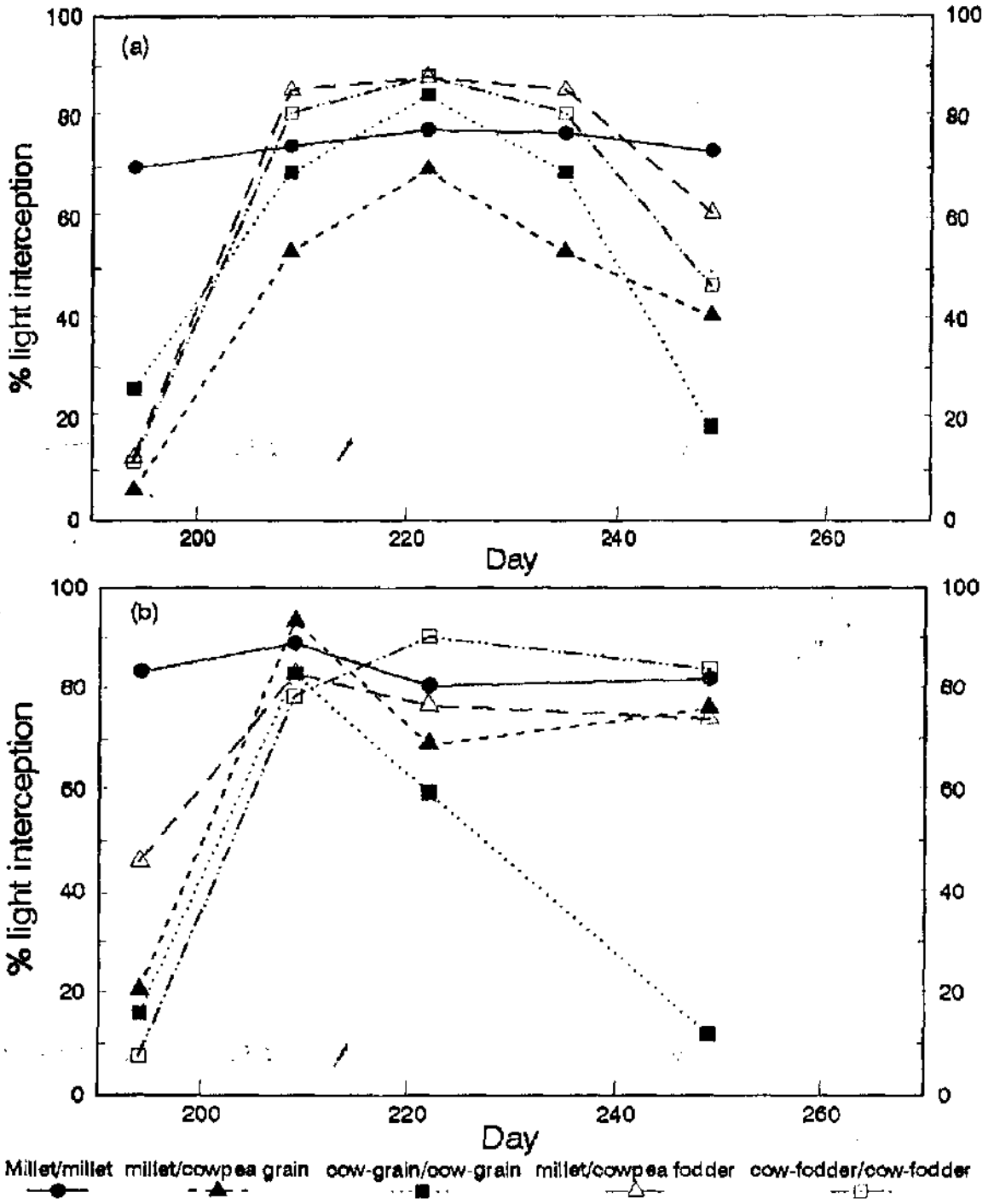


Fig. 4.32 Light interception patterns in relation to component crops position in the millet/cowpea intercropping system with (a) pre-planting organic manure application alone and (b) organic manure plus inorganic fertilizer application during 1995 cropping season.

light interception remained lowest in IT89D-719. During the cropping season, maximum light interception (90%) occured in the Dan-illa and IT88D-867-11 cultivars by Day 235 (58 DAS cowpea).

Table 4.15a Light interception profile between and within cowpea (IT89KD-374) sown sole, 1995

		% light interception	
		Within row	Between rows
DAS	Julian day	C/C/C	C/C
14	194	16	20
29	209	60	85
41	222	66	86
55	235	60	88
68	249	72	72
83	265	33	69

The two cowpea cultivars produced the greatest LAI and total dry matter at this period (around 58 DAS) of crop growth, but there was a rapid decline in the canopy of IT88D-867-11 during grain filling until maturity as a result of leaf senescence. Dan-illa, that maintained the higher level of radiation interception longer (Fig. 4.33) produced more dry matter than the other cowpea cultivars, while the poorest light interceptor (IT89D-719) produced the lowest canopy development and total dry matter as expected.

Among the sole cereal crops, light interception profile during the season varied with crop growth duration (Fig. 4.34). In the sole millet, canopy light interception was initially much higher due to its faster growth rate and canopy development than in the sole sorghum treatments. All the sole cereal treatments recorded earlier in the

season higher light interception between crop rows, where crop spacing was wider, while the highest maximum radiation interception was later in the season between plants along a row at the attainment of maximum LAI (Two examples in Table 4.15b).

Table 4.15b: Light interception profile by crop stands sown sole between and within crop rows, 1995

		% light interception				
		Sole millet (OM+IF)		Sole sorghum-Gaya Early (OM+IF)		
		Within row	Between rows		Within row	Between rows
DAS	Jday	M/M/M	M/M	DAS	S/S/S	S/S
16	194	64	50	25	37	17
28	209	59	79	40	64	76
43	222	89	79	52	77	73
57	235	76	58	66	95	76
71	249	34	48	79	66	62
84	265			125	48	62

At periods particularly after Day 222, sole sorghum variety-Gaya Early intercepted more radiation and produced greater canopy and TDM than ICSV 400. Light interception decreased in all the sole cereal plots from grain filling to a minimum at crop maturity, reflecting the decrease in LAI of the crops and the partitioning of assimilate more to the reproductive organs as against the vegetative parts.

Cropping systems total radiation interception compared over time with reference to the fastest growing sole millet sown at the recommended optimum density gives an insight into some of the advantages of intercropping at the farmers' level. Although the initial light interception in the sole millet sown at high density (53333

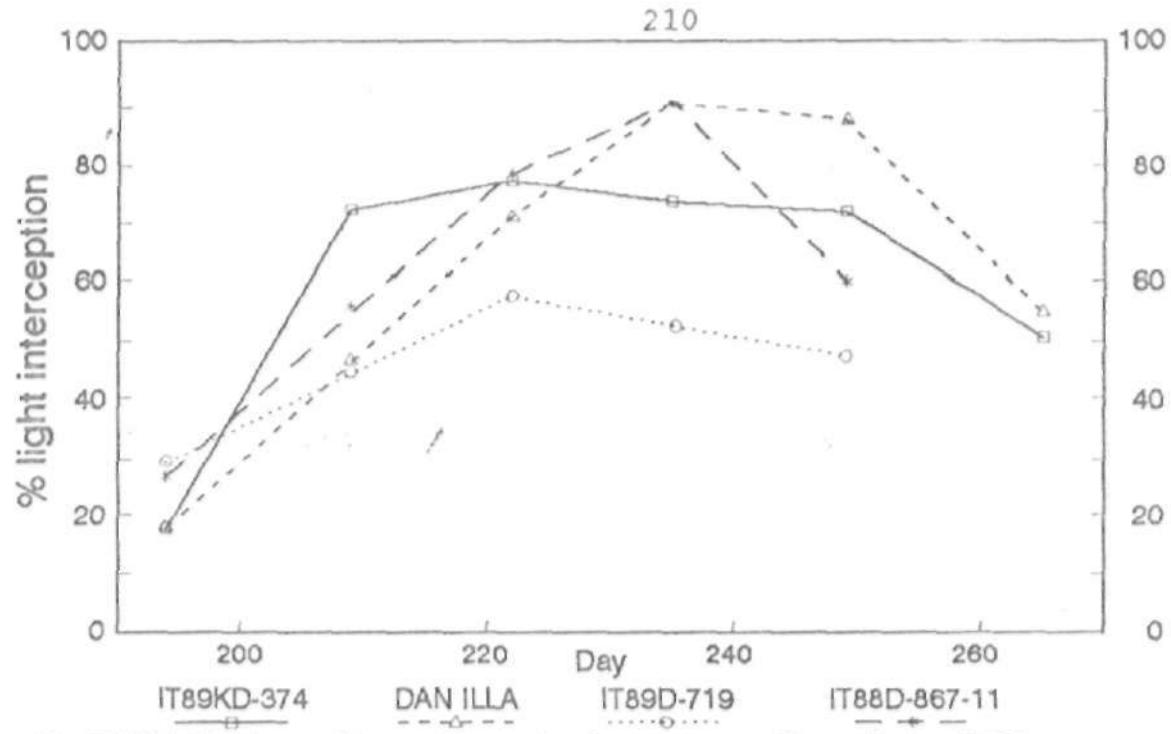


Fig.4.33 Light interception patterns of sole cowpea cultivars during 1995 cropping season.

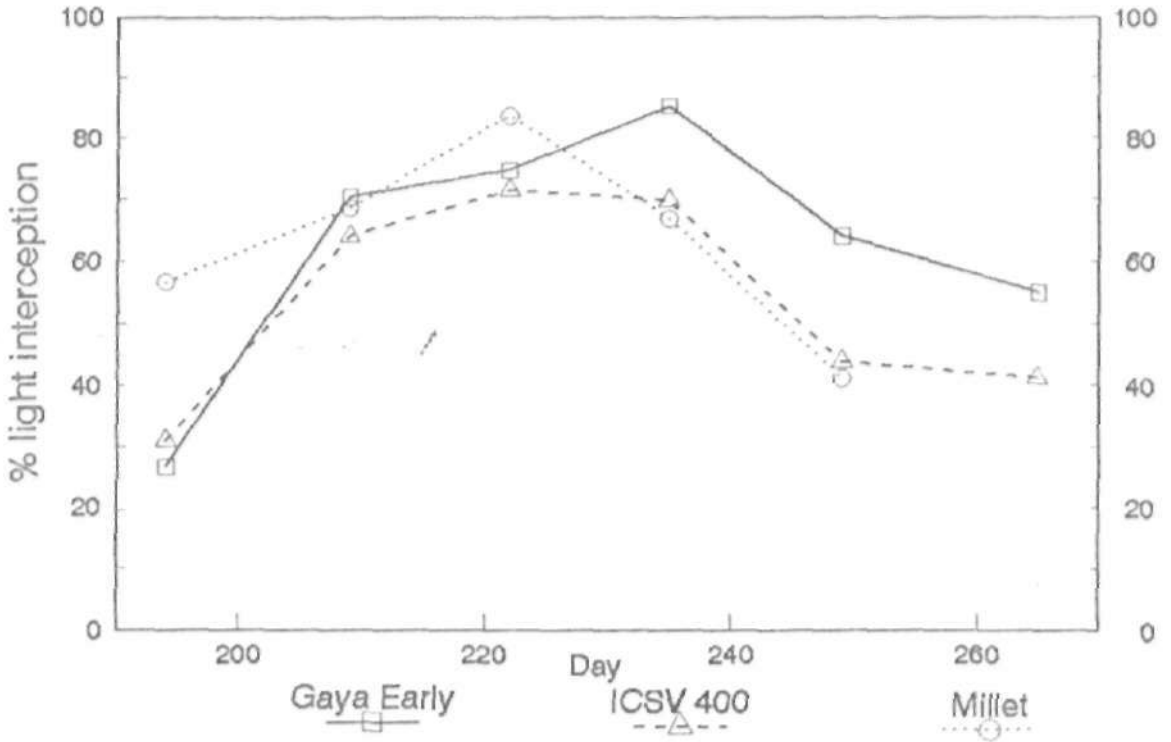


Fig. 4.34 Light interception patterns of sole cereal components (OM + IF) during 1995 cropping season.

plants ha^{-1}) was greater than the interception in the widely spaced intercrops (26667 plants ha^{-1}), the profile of light use increased rapidly and interception became greater by 5-22% (in absolute values) in the intercropping systems than in the sole millet at 45 DAS millet (Day 214) when maximum light interception occured in the higher fertility intercropping treatments (Fig. 4.35). At 50% panicle initiation of millet (≈ Day 222 i.e. 53 DAS), which coincided with cowpea pod filling stage, radiation interception started to decrease in the relatively higher soil fertility intercrops to reflect partitioning of assimilates from leaf to the reproductive organ. The trend of decrease in radiation interception of fully fertilised plots during grain filling until crop maturity was sole millet > millet/cowpea > millet/sorghum/cowpea intercrops (Fig. 4.35). The sorghum component of intercropping systems made light interception remain constant or decrease less, when its linear rapid growth commenced between the periods of millet and cowpea grain filling and maturity (≈ Day 233).

The influence of the weather in 1995 in terms of environmental resources distribution and availability favoured better crop growth, especially the cowpea components, than was observed in 1994. The relatively higher percentage light interception recorded among crop components in intercrops in 1995 also corresponded with the greater canopy developments and TDM production than was observed in 1994. The effect of the added fertility treatment in 1995 also improved crop productivity, especially of the sorghum components.

A major reason suggested for the greater cowpea components canopy development and TDM production is the lower canopies created by the millet components in the intercrops. These also allowed the greater penetration of radiation incident upon the cowpea components at low millet density in millet/sorghum/cowpea

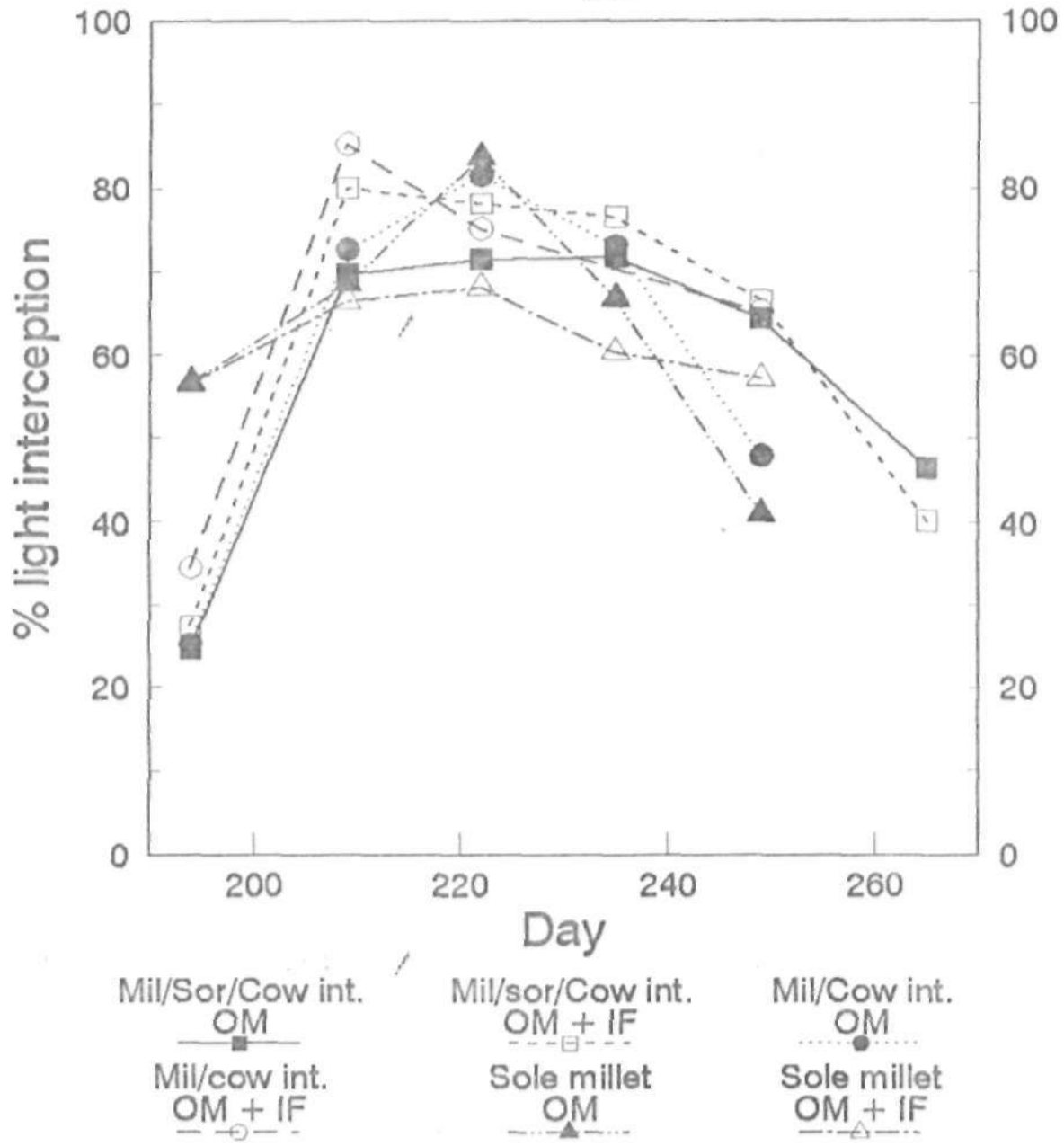


Fig. 4.35 Comparison of light interception in sole millet with the intercropping systems with pre-planting organic manure application alone (OM) and organic manure plus inorganic fertilizer application (OM + IF) during 1995 cropping season.

as compared to the millet/cowpea intercropping system.

4.5 Soil temperatures

4.5.1 *1994 cropping season*

The diurnal trend of soil temperature changes observed differ among the different crop combinations. Measured soil temperatures made only on cloudless days were selected for analysis of the cropping season. Periods of maximum LAI for millet and cowpea components in the sole and intercrops were respectively at Day 227 and Day 240. Day 240 also corresponded to the stage of rapid linear growth (LAI > 0.5) of sorghum sown sole and intercropped. These days, Day 257, which coincided with the period of millet senescent maturity and cowpea pod maturity, and Day 271, representative of the maximum LAI for sorghum, were used for comparing daily soil temperature trends among the cropping patterns considered (Figs. 4.36a and b; 4.37a and b).

The daily minimum soil temperature on these days occurred between 06.45 and 07.45 hr, while daily maxima were between 13.00 and 16.00 hr during the cropping season. Measured soil temperatures within the sole cereal plots at 10 cm depth were in excess of 30°C for more than 6 hr each day during the first 53 DAS millet (Day 227). All the intercropping systems involving millet and cowpea reached appreciable level of canopy development at Day 227, when ground cover by plants was high. The dense canopy cover of the vegetation protected the soil from strong irradiation and at night from strong net radiation loss, hence the low fluctuations of diurnal soil temperature values in the intercrops (Fig. 4.36a). Although soil temperature

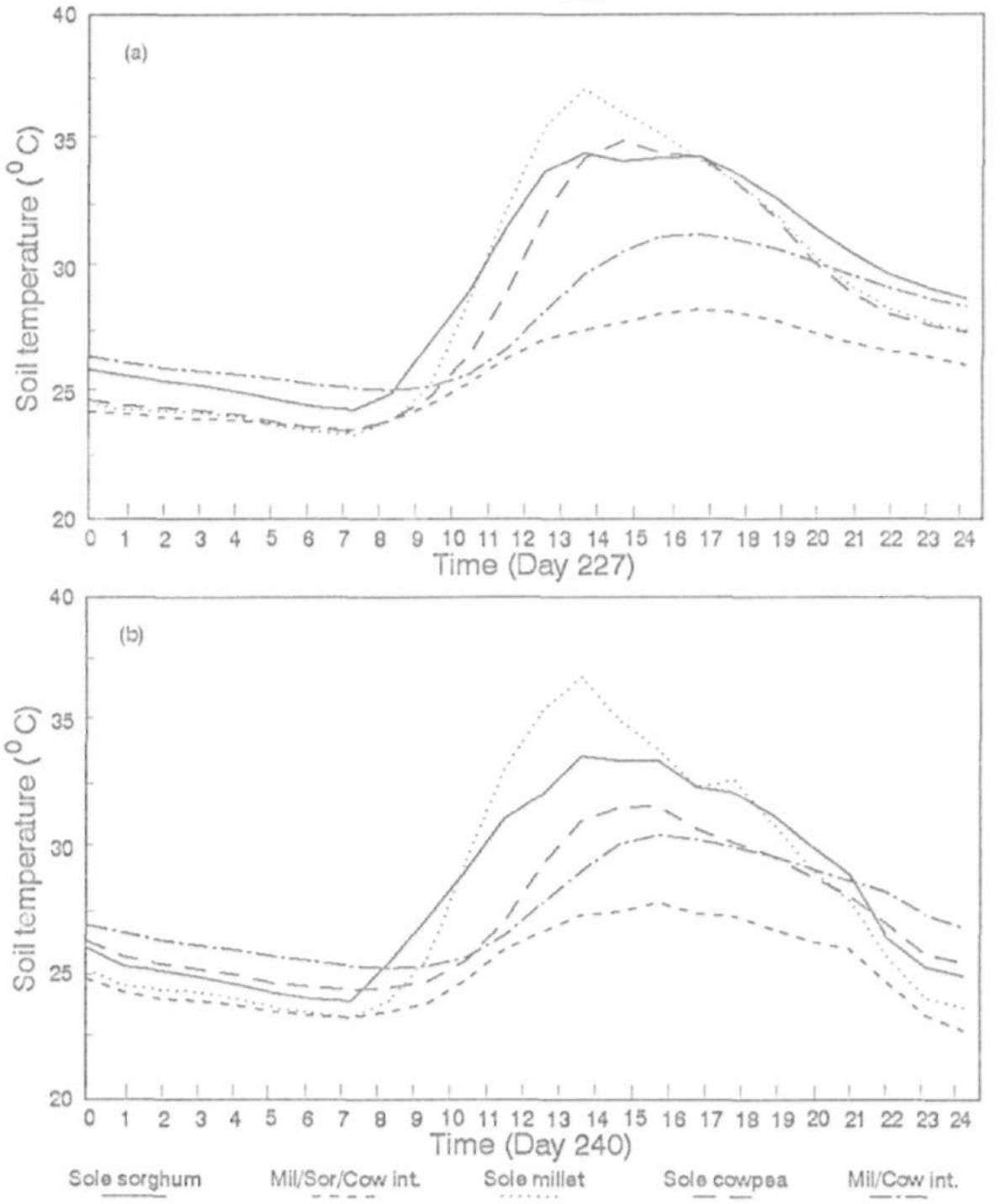


Fig. 4.36 Profile of soil temperature under crops at (a) millet components maximum LAI (Day 227) and (b) maximum LAI for cowpea components (Day 240) during 1994 cropping season.

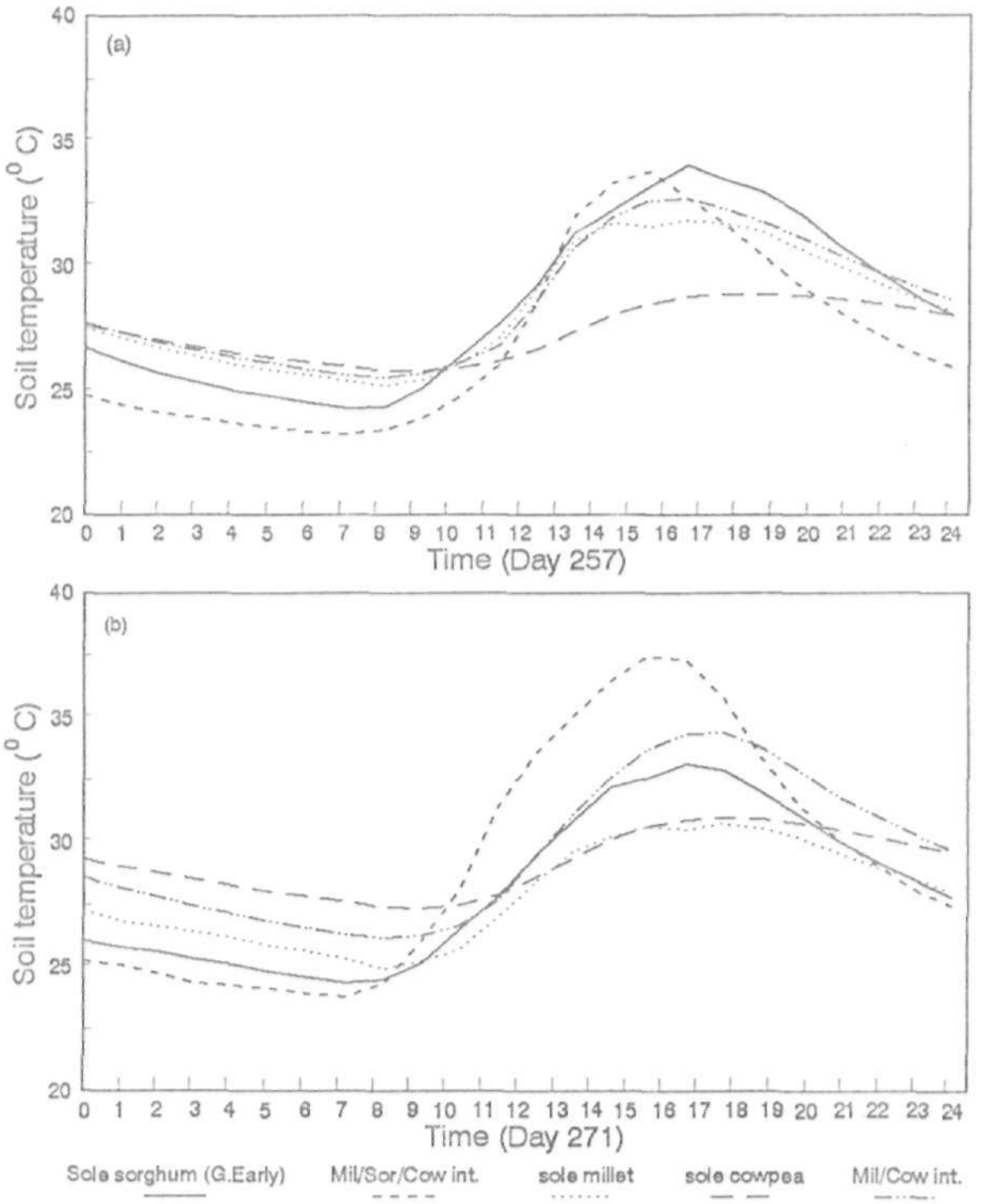


Fig. 4.37 Profile of soil temperature under crops at (a) millet senescent maturity and cowpea pod maturity (Day 257) and (b) maximum LAI for sorghum components (Day 271) during 1994 cropping season.

fluctuation can also be reduced by the somewhat higher soil moisture contents under crop canopy, owing to reduced evaporation and the cooling effects caused by the evaporation of soil water, it is more likely that the different amounts of shade cast by the sole and intercrops caused the differences in amplitude and phase shift at the same depth. The spreading canopies of the low growing cowpea components, already shaded by the taller cereal(s) in intercropping, seem to have created the lower diurnal temperature fluctuations in the intercrops relative to the sole crops. The millet/sorghum/cowpea and millet/cowpea intercrops with total plant population 26667 plants ha^{-1} per system gave consistently lower soil temperature range within the day, but also exhibited a clear phase shift of the temperature wave. The better growth and ground cover of low growing cowpea components, especially the prostrate and more vegetative Dan-illa in the millet/sorghum/cowpea intercrop, caused a more reduced amplitude of diurnal soil temperature changes (4.8°C) than in millet/cowpea intercrop (6.2°C), where cowpea growth was effected by the relatively higher density of the millet component.

The highest number of tillers produced (13 $\pm$ 2 tillers) by the millet components in the millet/sorghum/cowpea intercropping systems also created additional shade which reduced soil temperature and its fluctuation even more. All the sole crop plots recorded a higher diurnal soil temperature range than the intercrop plots. The intercropping systems of cereal and low growing legume, in essence offered a faster ground cover that protects the soil from the direct impact of solar radiation, causing reduced soil temperature and temperature fluctuation, and a better environment for plant growth and development at the earlier stages of crop growth, when competition for resource is more pronounced. For competing weeds however,

less radiation remains available for (re)growth under such situations, when weeds have to compete from a small plant situation onwards.

The period of maximum LAI in the cowpea components also coincided with relatively high millet LAI during grain filling on Day 240 (Fig. 4.36b). The amplitude of soil temperature fluctuation at this stage was lower in the intercrops than in sole crops. However, the diurnal temperature range in the sole cowpea plot was reduced, while daytime soil temperature was also lowered and nighttime soil temperature increased as a result of the greater canopy development (LAI> 1.5) and the better ground cover by the cowpea components (Fig. 4.36b). The soil temperature trend in the sole millet and sorghum plots were rather similar to that observed at millet maximum LAI on Day 227 (Fig. 4.36a).

Soil temperatures at cowpea pod maturity and start of millet senescence stage (Day 257) within the various cropping patterns are shown in Fig. 4.37a. The sole cowpea gave the lowest daytime temperature value. Millet/cowpea intercrop, sole millet and sole cowpea gave consistently higher nighttime temperature because of their now closer canopy structures that prevented the loss of radiation at that period of measurement. The tendency for the nighttime soil temperature reduction was highest in the millet/sorghum/cowpea intercrop and least in the sole cowpea. Diurnal soil temperature range was lowest in the sole cowpea system (3°C) and was highest in the millet/sorghum/cowpea intercrop (10.6°C), due to millet senescent maturity.

The soil temperature trend at millet maturity with all cropping patterns (Day 271) indicated a high difference in profile. Higher diurnal fluctuations in soil temperature values were recorded in the intercrops than in sole crop treatments (Fig. 4.37b). Daytime soil temperature was higher in intercrops than in sole crop situations.

Millet and grain cowpea senescence at crop maturity contributed to deteriorating canopy structure that affected soil cover (or plant foliage) and also affected the soil temperature profile. The relatively low density of millet in the millet/sorghum/cowpea intercrops and early cowpea maturity caused the exposure of more bare ground area to direct insolation and hence the highest daytime soil temperature (37.6°C) and diurnal temperature range (13.8°C) observed than in the other cropping systems. The trend of the diurnal soil temperature range was millet/sorghum/cowpea > millet/cowpea > sole sorghum > sole millet > sole cowpea (Fig. 4.37b). The slight reduction in soil temperature range in sole sorghum as compared to earlier stages of crop growth was due to the better ground cover resulting from the rapid linear growth (LAI> 0.6) recorded at this period. The result showed that because minima and maxima fall were all in daytime, the soil temperature fluctuations are greater during daytime than nighttime. They were smaller under dense canopies of sole plantings than in the sparse intercrops at crop maturity when the foliage of the grain cowpea and millet have become senescent.

4.5.2 *1995 cropping season*

The diurnal variation in soil temperatures among the various cropping systems during 1995 cropping season were analysed with regard to specific stages of crop development. The maximum period of canopy development of millet components in all the cropping systems (LAI> 2.5) at Day 212 also corresponded to periods of active vegetative growth of sorghum (LAI> 0.5). The period of rapid linear vegetative growth of cowpea components (LAI> 0.4) at Day 221 was also stage of high, but now decreasing canopy coverage by millet (LAI> 1.5) during grain filling

in all systems and sorghum active vegetative stage (LAI > 0.7). At cowpea maximum LAI (> 1.5) for all cowpea cultivars, millet LAI during grain filling decreased (LAI < 1.2), while sorghum canopy development improved (LAI > 1.4). The increase in canopy development of sorghum variety, Gaya Early (LAI > 1.6) by Day 248, was also the period of crop maturity and loss of foliage in the millet and cowpea components. However, the LAI of the prostrate and more vegetative cowpea component, Dan-illa, was greater than 1.5. Maximum canopy development for sorghum (Gaya Early) occurred at Day 263 when LAI was greater than 1.9.

The daily minimum soil temperature occurred between 07.00 and 08.15 on Day 221 (57 DAS millet), while daily maxima were between 14.00 and 17.00 hr. The rainfall period between 3.00 and 6.00 hr on Day 234 caused the depression of the nighttime temperatures. This was responsible for the lower minimum soil temperatures recorded between 03.30 and 07.30 hrs. The periods of maturity of millet and cowpea components (Day 248) recorded daily minimum soil temperatures between 06.30 and 07.30, while the maximum soil temperature was dependent on the component crop growth stage. Maximum daily soil temperature occurred in the actively growing cowpea (Dan-illa) in intercrop and sorghum (Gaya Early) components in sole and intercrop plots at 16.30 when crop canopies were well developed, while in the millet and Dan-illa in sole crops already at maturity stages and the control plot, soil maximum temperatures occurred between 17.00 and 17.30 hr.

The trend of diurnal soil temperature throughout the duration of crop growth in 1995 showed that maximum day and night time soil temperatures occurred in the control plot, where there was no vegetation cover (Figs. 4.38, 4.39 and 4.40). An exception was at sorghum maximum LAI (Day 263), when the maximum day time

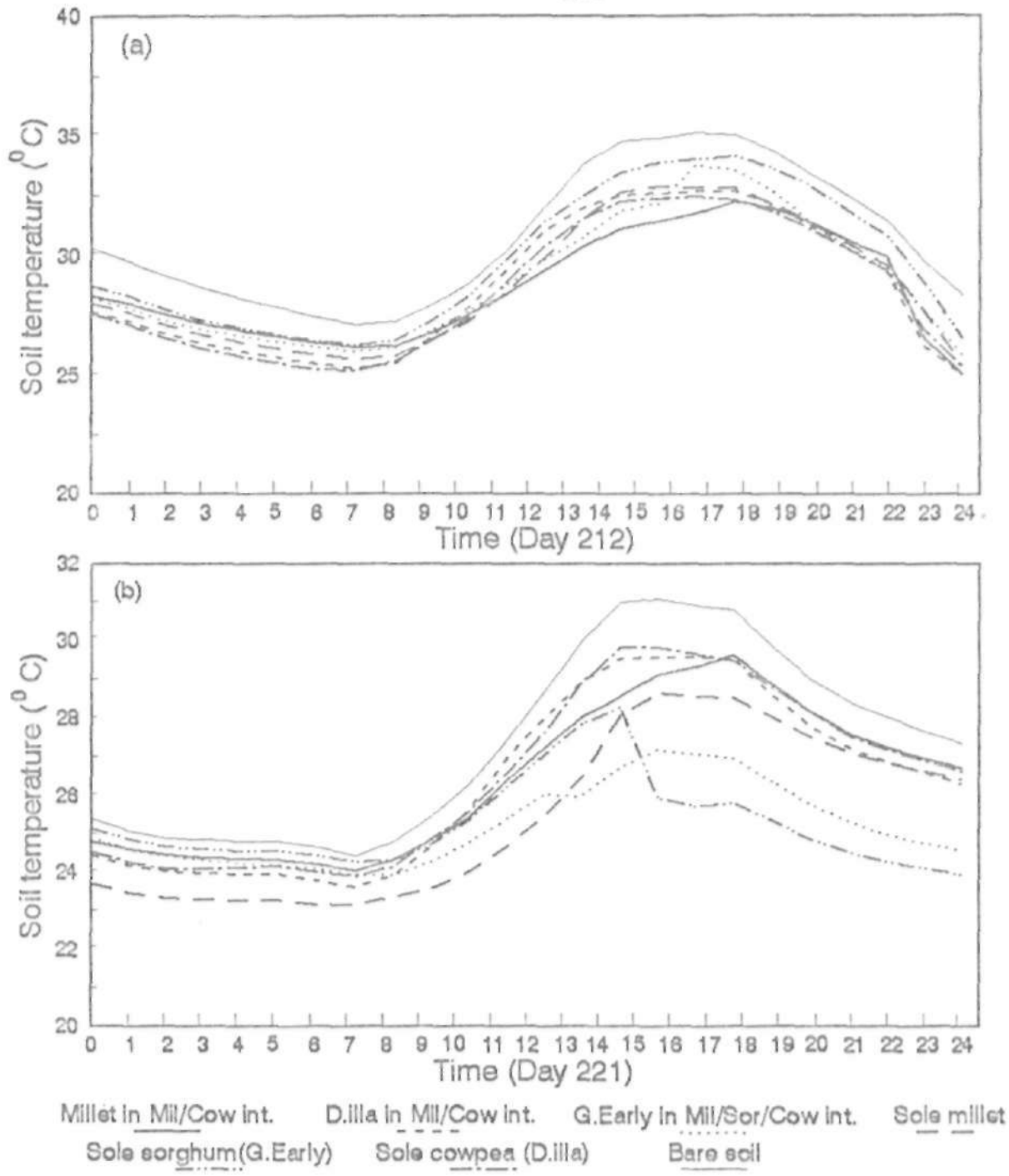


Fig. 4.38 Profile of soil temperature under crops at (a) maximum LAI of millet components and sorghum LAI> 0.5 (Day 212) and (b) high canopy development in all crop components (Day 221) during 1995 cropping season.

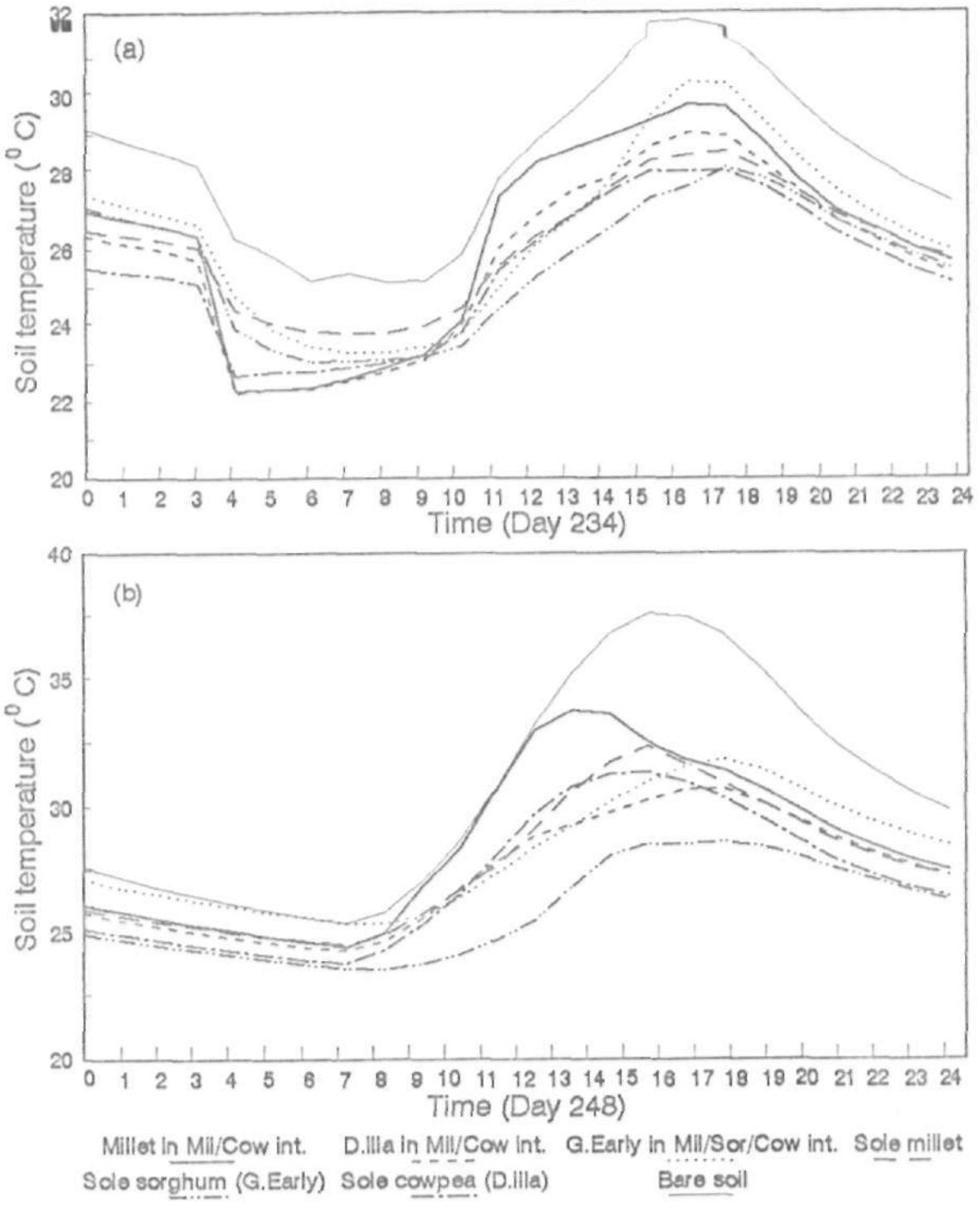


Fig. 4.39 Profile of soil temperature under crops at (a) LAI> 1.5 for cowpea components, millet grain filling and sorghum components LAI> 1.4 (Day 234) and (b) millet maturity, high LAI for Dan illa cowpea only and sorghum LAI>1.7 (Day 248) during 1995 cropping season.

soil temperature under millet shoot after harvest in intercropping system was slightly greater than the control. This higher midday soil temperature under the harvested millet shoot over the control site was due to the presence of bare soil, between the now relatively sparse crop stands, and the darker colour of the soil resulting from the greater organic matter content which was contributed by the senescent foliage of cowpea and millet components. An additional reason could be a relatively drier soil, resulting from crop root water extraction (transpiration) from the previously cropped land, compared to the bare soil.

The observed diurnal soil temperature trend on Day 212 (Fig. 4.38a), when the millet component reached its maximum canopy development and sorghum components had reached LAI of over 0.5, shows that the daily range of soil temperature was least in the intercropped millet stand (6.1°C) and greatest in the control (8.2°C) (Fig. 38a). Millet developed canopy quickly to shade the soil from direct solar radiation, and thus reducing soil temperature and fluctuation of soil temperature. Soil temperature fluctuation was sometimes lower in crop components within intercropping systems than in sole crops. For example, the diurnal soil temperature range of 6.1°C and 6.5°C under the intercropped millet, was lower than under the sole crop (7.3°C). The observed lower daytime soil temperatures in the millet than in the sorghum components was in agreement with the amounts of ground cover at this stage of crop development.

The amplitude of soil temperature under crops within cropping systems differ at the commencement of millet grain filling when the developed canopy was still great, sorghum LAI > 0.7 and cowpea LAI greater than 0.4 at Day 221. Sole millet at the begining of grain filling and canopy closure, but with decreasing foliage (LAI

> 1.5), recorded the lowest minimum night time soil temperature while the lowest minimum day time temperature (after 14.30 hr) occurred in the sole sorghum with increasing foliar development and canopy closure (Fig. 4.38b). The diurnal soil temperature range was lower in the sorghum components (3.3-4.1°C) than in millet (5.6°C) and cowpea (5.4-6.1°C) components of the different cropping systems.

At Day 234, millet LAI decreased but the cowpea and sorghum vegetation were already well developed at the peak of the rainy reason, when soils are wet. The amplitude of diurnal soil temperature fluctuations was greater in the intercropped crop components than in the sole crops as expected (Fig. 4.39a). The millet and grain cowpea components in intercrop and sole cropping systems had already matured by Day 248, with an appreciable decrease in crop canopy but with Dan-illa still retaining a high LAI, and hence, left soil patches that were bare and exposed to direct solar radiation. The higher daytime soil temperatures in the intercropped than in sole sorghum after midday was the resultant effect observed (Fig. 4.39b). The greater diurnal soil temperature range occurred in the millet components at their matured senescence (Day 248).

The maximum LAI for sorghum (> 1.9), sown sole and intercropped and sole cowpea, Dan-illa (> 1.5) were reached at Day 263. The dense canopy covers in the sole sorghum and cowpea plots created the low range of daily soil temperatures observed as against the matured sole millet, the intercropped cowpea and the sparse stands of sorghum in the intercropped plot, and particularly against the intercropped millet (Fig. 4.40).

The relative reduction in soil temperature fluctuation periods were observed to be earlier under the intercropping systems and sole cowpea than under sole cereals

situations. The net solar radiation received at the soil level is thus reduced earlier (or expressed differently, the shading becomes higher earlier) in these systems, with the resultant effect of lower water loss through evaporation, and hence a possibility for a better soil moisture conservation than in the sole cereal crops. The periods of relatively lower ranges of diurnal soil temperatures were also greater in the intercropping system than in sole crops. Such situations becomes important in the creation of more favourable environmental condition conducive to plant microclimate in terms of the biological, morphological and physical processes affecting crop growth and development. The relationship between surface soil temperature and shading suggests that the temperature that caused lower soil temperature conditions, also creates an environment less conducive to weed growth, once enough shade has been created.

4.6 Water balance studies

4.6.1 Soil infiltration capacity

The soil infiltration capacities in the different cropping systems during the 1995 season are shown in Figure 4.41. The steady state infiltration rates in all the cropping systems were reached within the cumulative time of 2½ hrs after ponding. The steady state infiltration rates of the different treatments was generally high and vary widely from 9.4 to 25 cm hr^{-1} with an overall mean of 17 cm hr^{-1}. The highest steady state infiltration rate was observed in the sole sorghum (25 cm hr^{-1}), while the least was from the sole cowpea plot (9.4 cm hr^{-1}).

The measured infiltration rate as a function of time under ponded water in the

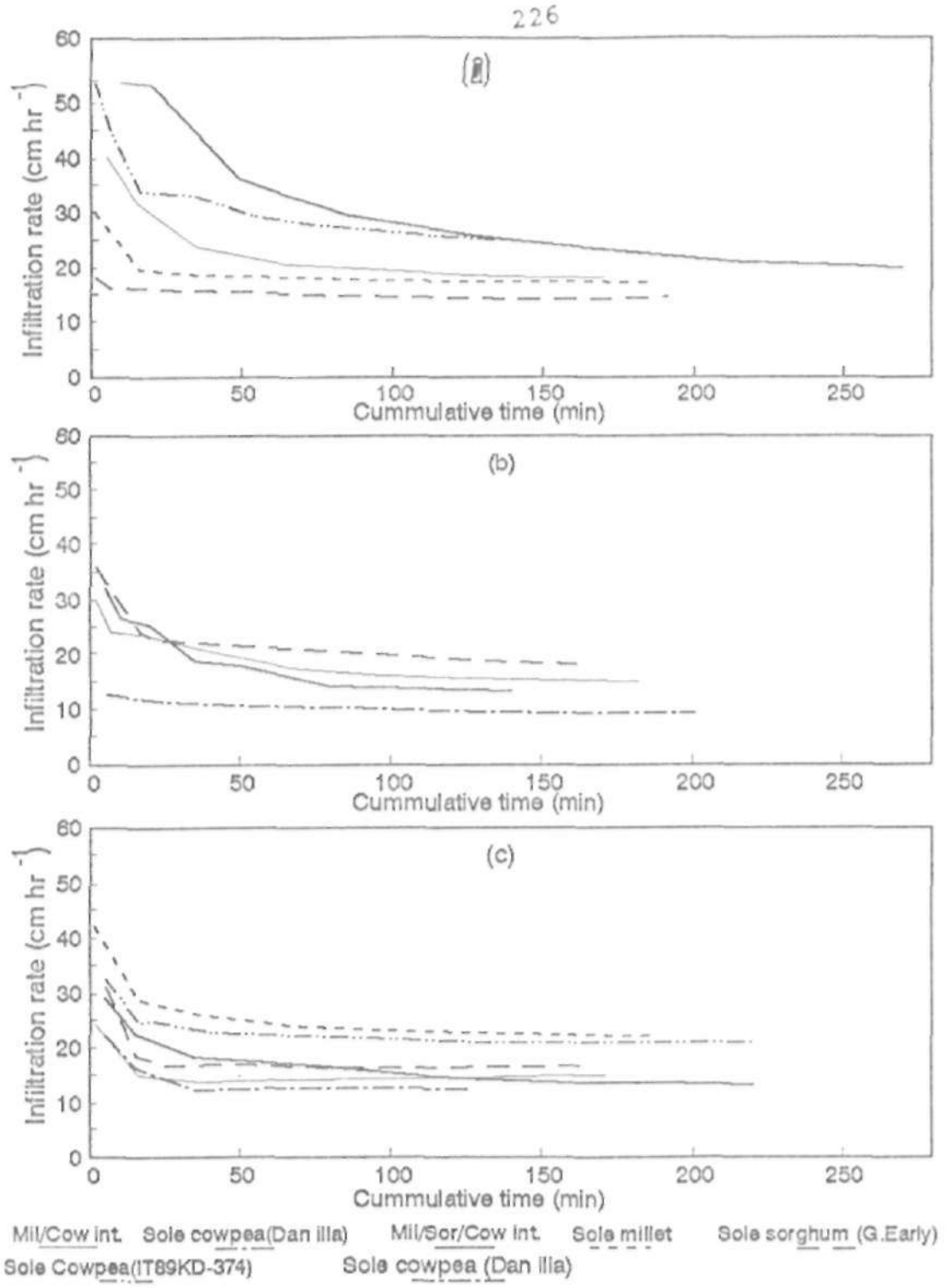


Fig.4.41 Infiltration rate as a time function under ponded water in different cropping systems at the end of 1995 rainy season. (a) Cylinder rings of 32 & 57cm diameters, (b) 30 & 55cm diameters and (c) 28 & 53cm diameters.

different cropping systems, using different pairs of the double cylinder rings also vary greatly and independently of cylinder ring size. A high degree of soil variability over distances of few meters within the plots is suggested as a reason for the wide differences observed. There was no clear difference in the trend of soil infiltrability among the sole and intercropped treatments in the three pairs of infiltrometer used. The high initial rate of infiltration in some sole and intercropping systems indicates the predominance of macropores and a high magnitude of the horizontal components of the hydraulic conductivity of the sandy soil under cultivated crops.

The highest rainfall intensities between 1993 and 1995 rainy seasons varied from 25 to 27 mm hr^{-1} and occurred at the peak of the seasons between mid-July and mid-September. The measured steady state infiltration capacity minimum of 9.4 cm hr^{-1} for the experimental area compared to the amounts and the intensity of rainfall received, indicates a very low chance of runoff or 'runin' occurrence in the relatively level field (slope $< 1\%$) during the rainy season.

4.6.2 Soil drainage (Deep percolation) losses

The drum lysimeter was used to determine the characteristics of drainage in the soils at Minjibir experimental farm in 1995. Using an assumption of 0.8 m as depth of rooting, the maximum root zone deep percolation losses in the grass grown lysimeter commenced after a high intensity storm (46.2 mm) on 9 August (57 DAS millet), at the peak of the rainy season and stopped on 29 September, 5 days after the last seasonal rain was recorded in the grassed lysimeter. However, drainage in the bare lysimeter lasted until 20 days after the last seasonal rainfall. The cumulative amount of rainfall to the period of the commencement of drainage was 327.6 mm,

which accounted for 58% of the total annual rainfall. The soil saturation point from field measurement under the various crop components varied from 0.14 to 0.20 cm^3 cm^{-3} by the first decade of September. The total drainage collected and measured over the period of June to October was 19 and 16 per cent of the rainfall that was lost through percolation in the bare (98.2 mm) and grassed (83.7 mm) lysimeters respectively. A substantial amount of water was therefore lost by drainage and most of this was from flowering to crop maturity stages of millet and cowpea components.

The soil moisture characteristics measured in the access tube installed at the centre of the draining drum lysimeter is presented in Figure 4.42. The moisture profile from 45 to 75 cm soil depth shows that the potential soil saturation point is attainable when soil moisture is 0.13 to 0.14 cm^3 cm^{-3}, while field capacity would occur at about 0.10 cm^3 cm^{-3}. The field observed saturation point and field capacity under crops from neutron probe measurements are greater than those determined through the drum lysimeter method. The saturation points under crops at the peak of the rainy season in August 1995 varied from 0.14-0.20 cm^3 cm^{-3}, while the field capacities were slightly higher than 0.10 cm^3 cm^{-3} ($\approx$0.11 cm^3 cm^{-3}). Under crops, higher amounts of moisture were observed between 30 and 40 cm soil depth in the soil profile than in soil layer below 50 cm. This means that the rooting zone, where larger root densities occurred, held larger amounts of soil water compared with the layer with relatively fewer roots lower in the soil profile (below 50 cm). A soil with many roots is more porous. Other sources of hydrogen and water in the soil are the roots themselves, which contain water of hydration as opposed to free water (and other hydrocarbons as 'apparent' moisture) water in the roots measured as free water

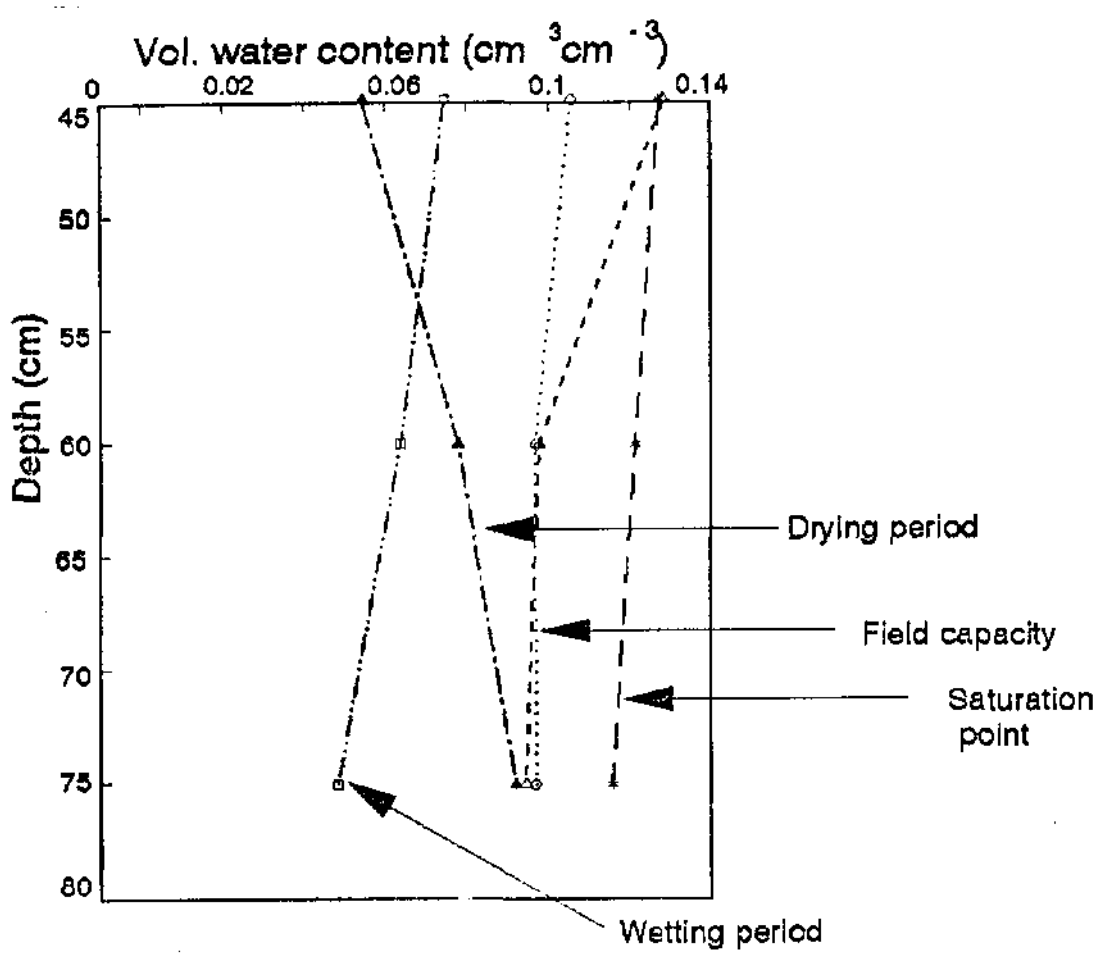


Fig. 4.42 Minjibir experimental site soil moisture characteristics as observed in the soil filled drum lysimeter.

by the neutron probe. This was not a measuring error but water indeed used by the crops. The negative water potential developed by the roots as a result of their internal conduction mechanism to the shoot, and daytime transpiration of the water to the atmosphere, also allow the dense root system to attract soil water, through the exertion of a higher osmotic pressure, to its surrounding than found in bare drying soil.

The assessment of wilting point for the soil of the experimental site could not be made as result of some technical and logistical problems experienced in the field. An inference drawn from the other works done in the arid and semi-arid West African zone on similar soil types have shown that the wilting point is attained when soil moisture content is at ≤ 0.05 cm^3 cm^{-3} i.e. ≤ 0.05m^3 m^{-3} (Agnew, 1982; Payne *et al.*, 1990; Grema and Hess, 1994). It was therefore assumed that no water movement occurred at about this moisture content.

4.6.3 Crop characteristics (rooting pattern) and soil water extraction

The moisture content profile measured by the neutron probe from access tubes placed 10, 20 and 30 cm from millet stands at a soil wetting phase and when the soil is wet are shown in Figures 4.43a, b and c. The trend of soil water extraction by millet roots, at 27 DAS (Fig.4.43a), shows the similarity in the measured soil water contents at the different access tubes distances from a plant until 60 cm soil depth. The access tube placed 10 cm from the plant was more sensitive to soil moisture extraction from 70 to 105 cm soil depth than the other access tube placements. At soil field capacity 65 DAS (Fig. 4.43b) i.e. the peak of rainfall, which coincided with the

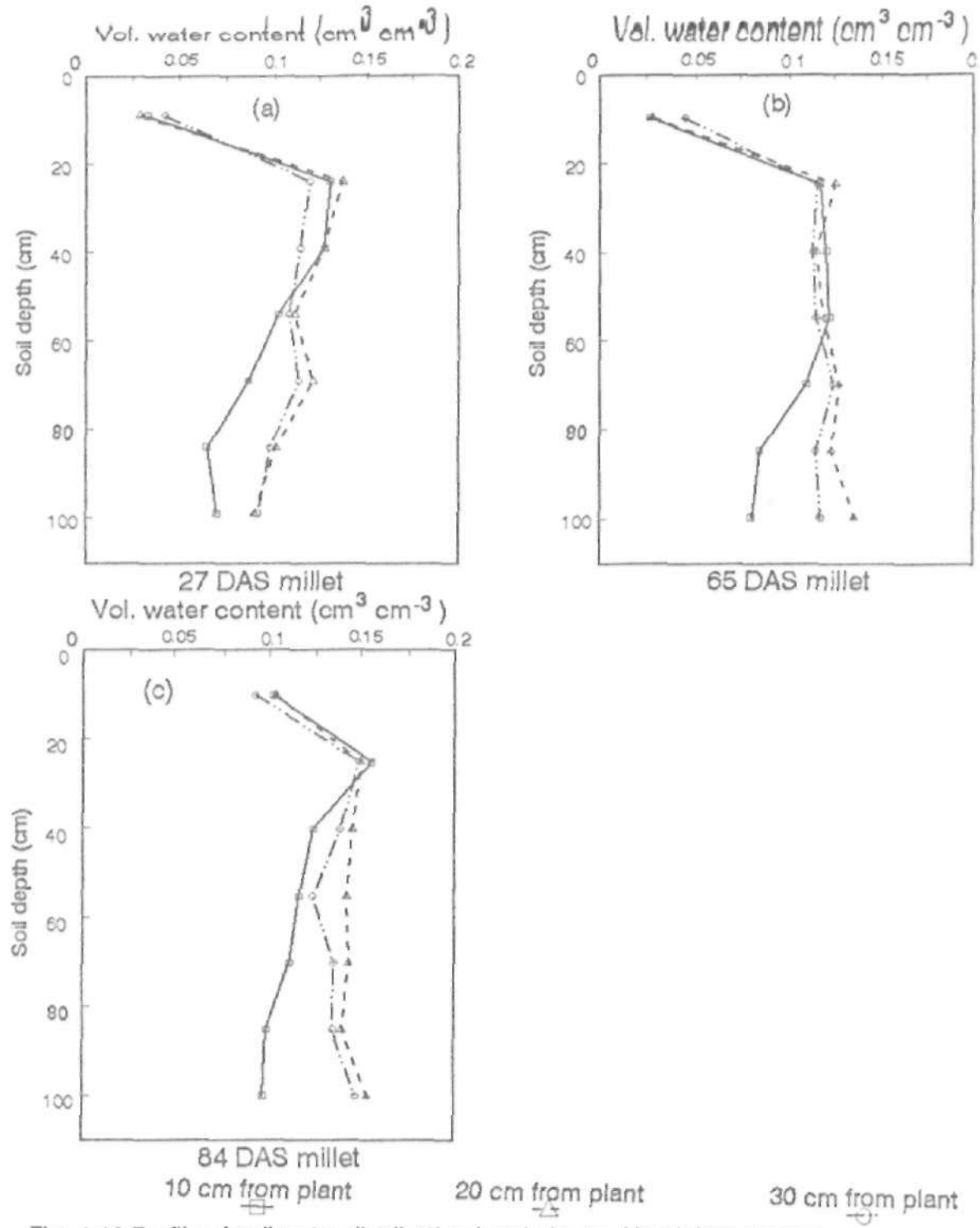


Fig. 4.43 Profile of soil water distribution in relation to Aluminium access tube placement from millet stands at (a) near planting (wetting phase), (b) reproductive stage (wet) and (c) millet maturity (wet), 1995.

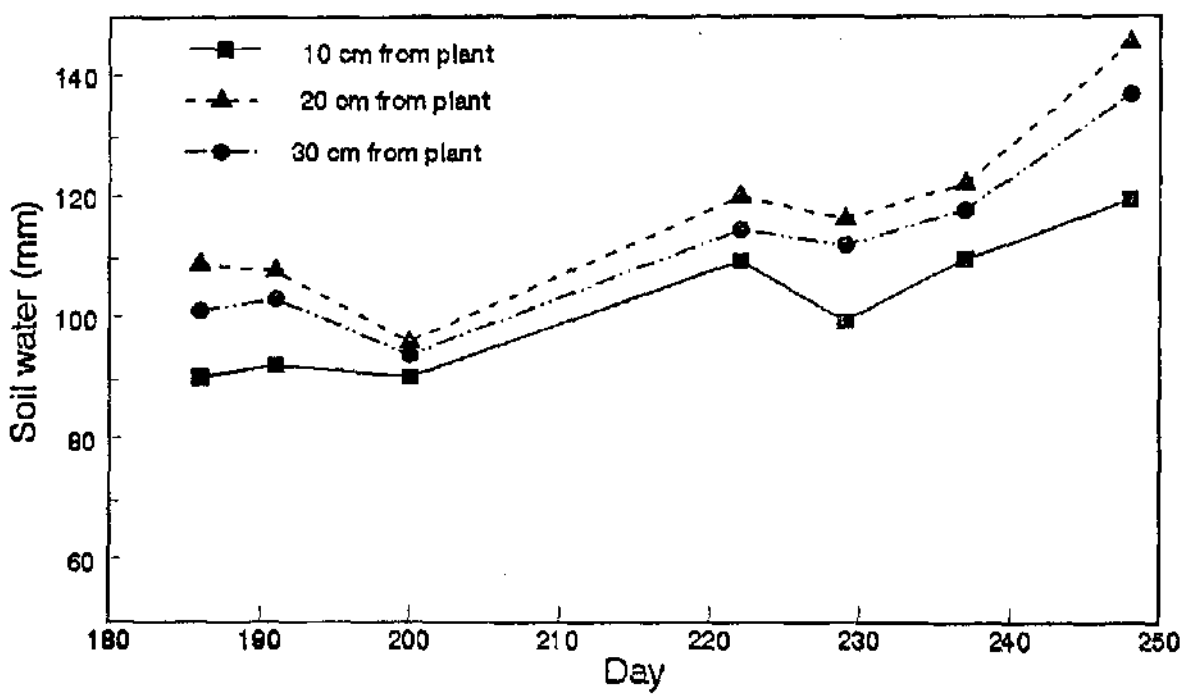


Fig. 4.44 Seasonal trend of measured total amounts of water in the soil to a depth of 110 cm, 1995.

reproductive stage of millet, root water extraction observed from neutron probe measurement was not effected by the three access tube placements differently until a soil depth of 70 cm inclusive which seems to represent the active root extraction zone. However, the 10 cm access tube placement shows greater sensitivity to root soil moisture extraction from 70 cm to lower soil depth of 105 cm. A similar trend, but already from 40cm depth downward, is observed at millet maturity, 84 DAS, which suggests the appropriateness of the 10 cm access tube placement away from the plant stand (Fig.4.43c). The trend of the total amount of water present in the soil to a depth of 105 cm can be seen in Figure 4.44. In combination with the results of Fig. 4.43, this result shows that 10 cm access tube placement from a millet stand recorded the least measured soil water, which implies from the distribution observed in Fig. 4.43 a better access tube placement among the placements tried, for detecting the sensitivity of the plant root water extraction of cereal for the deep, well drained sandy soils present on the experiment field.

4.6.4 Neutron probe calibration

The field calibrations of the CPN 503 Hydroprobe type neutron probe for every soil depth from 25 to 85 cm are presented in Figures 4.45, 4.46 and 4.47a. The regressions of the calibration equations show high statistical significance levels ($P < 0.001$), with a percentage variance accounted for $\geq 94\%$. The number of core samples obtained over the entire year of 1994, to provide a range of dry to wet soil conditions, also varied. Soil middle depths of 25, 40, 55, 70 and 85 cm, had core sample sizes of 24, 17, 17, 23 and 20 respectively. The number of samples used for

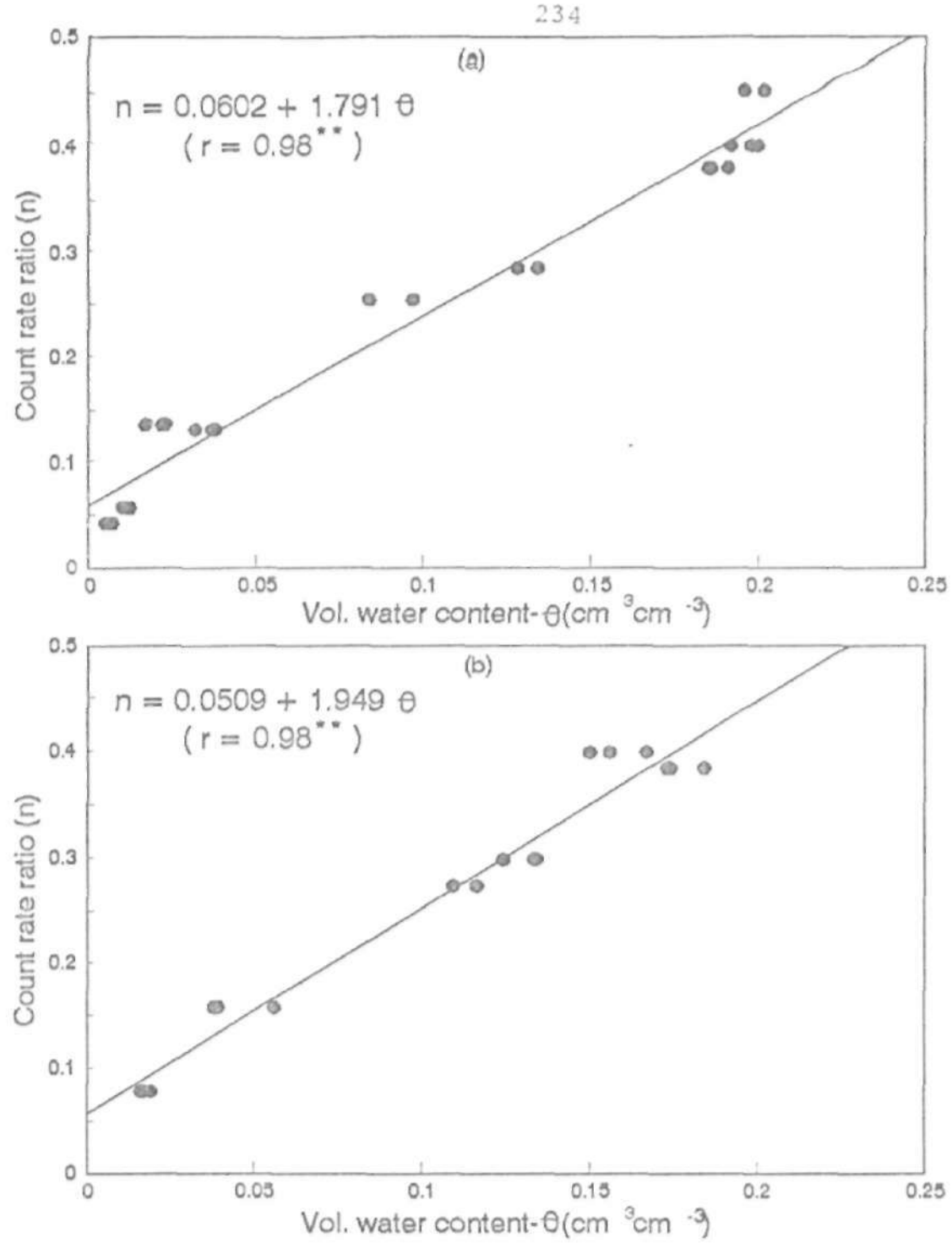


Fig. 4.45 Neutron probe calibration at (a) 25 cm and (b) 40 cm soil depths.

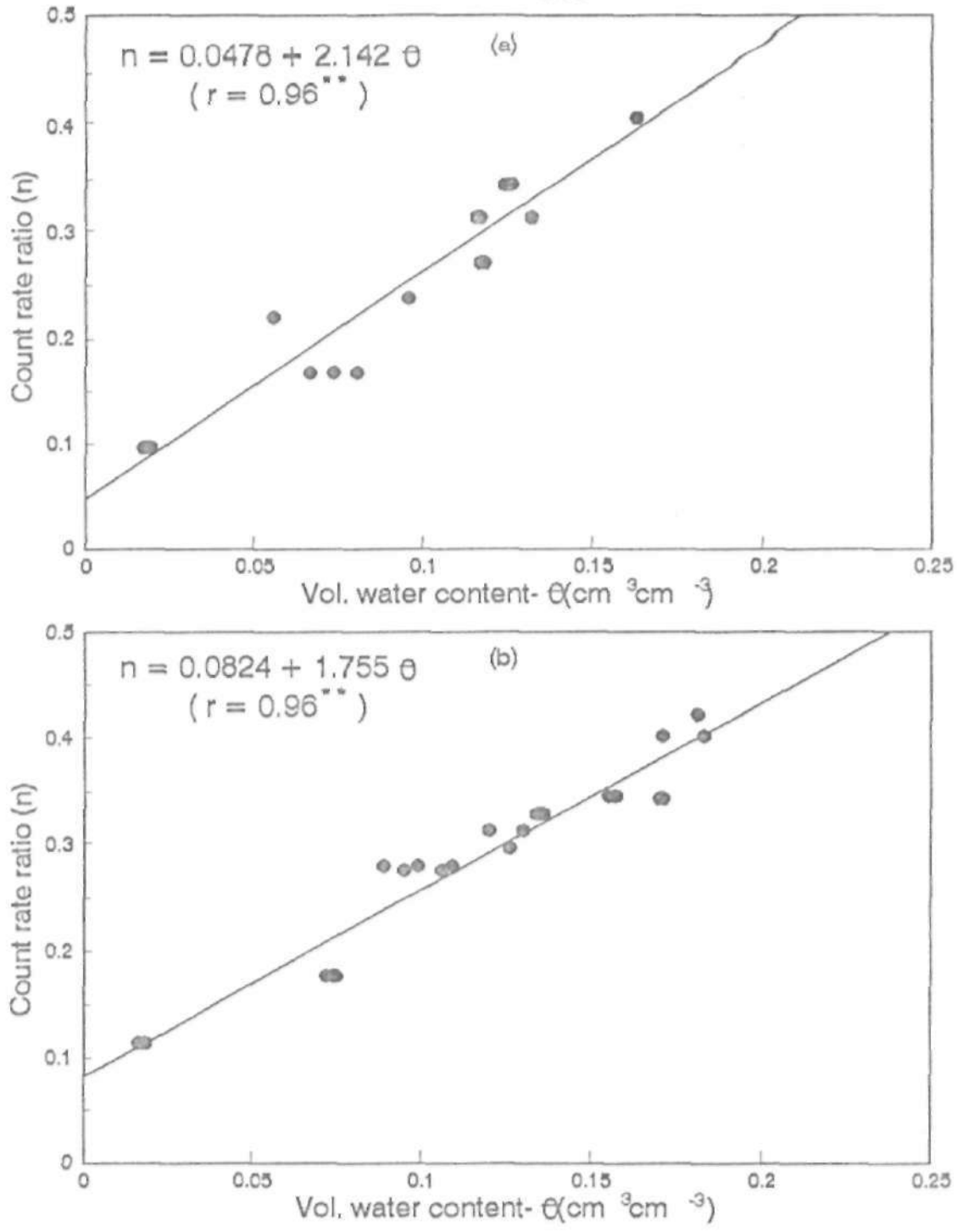
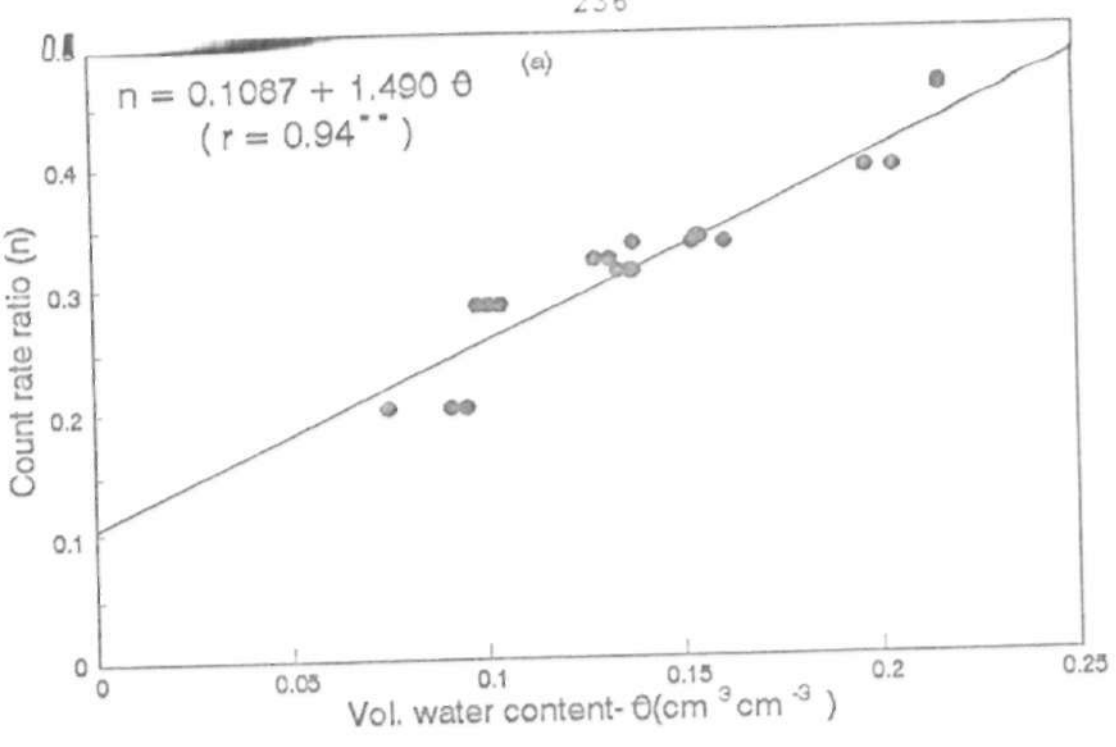


Fig. 4.46 Neutron probe calibration at (a) 55 cm and (b) 70 cm soil depths.



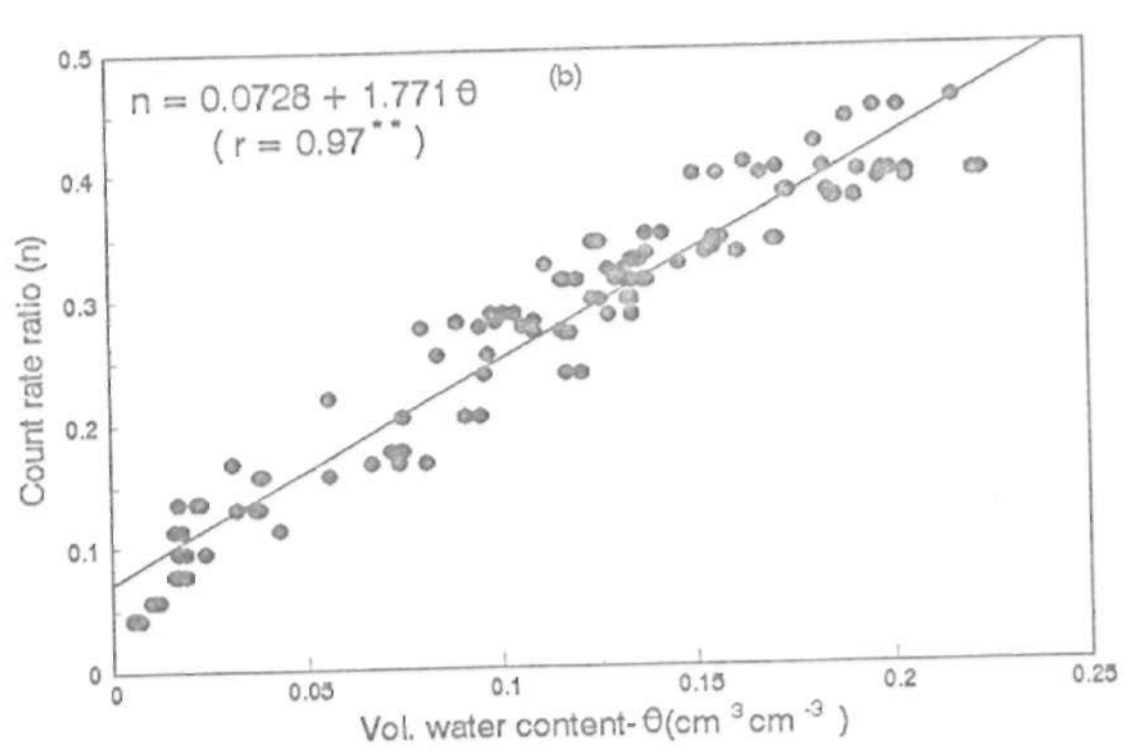


Fig. 4.47 Neutron probe calibration at (a) 85 cm and (b) 25-100 cm soil depths.

100 cm soil depth in the calibration curve is 8, and this was a result of the rejection of a lot of samples from the dry soil condition. The soil was very loose and friable during the dry season, and as such, getting core samples without compacting the soil became very difficult.

The mean soil bulk density for depths between 25 and 100 cm during the calibration of the neutron probe is 1.45 $\pm$ 0.06 g cm^{-3}, varying very little with depth. An exception occurred at about 25 cm depth, where it is 1.5 $\pm$ 0.064 g cm^{-3}.

A single calibration curve for our rather sandy soil, based on the low variability (CV $\approx$ 3.97%) in soil dry bulk density was derived using the pooled 122 core samples from 25 to 100 cm soil depths (Fig. 4.47b). The curve (r= 0.97) obtained for the calibration equation is highly significant statistically (P< 0.001), with an estimated observation standard error of 0.03, and quite sensitive and representative of the field conditions for the different soil depths.

The calibration equation derived from the pooled data for all depths was used for estimating Θ at soil profile depth measurements of 25 to 100 cm. The regression equation for the neutron probe calibration is used to derive the relationship below:

$$\Theta\ (cm^3\ cm^{-3}) = (n - 0.0728)/1.771 \qquad (r = 0.97) \qquad (4.1)$$

where Θ is the volumetric soil water content and n is the count rate ratio.

As indicated earlier, for the surface 0-15 cm soil depth, routine core samples were taken concurrently with the neutron probe measurements and soil moisture content were determined gravimetrically. The volumetric water content was derived by multiplying the gravimetric water content by the soil bulk density in this layer,

which was 1.47 ± 0.06 g cm^{-3}.

4.6.5 Soil water profiles

The patterns of wetting and drying of the soil profile are considered at the experimental site in relation to the crops root zone storage in the different cropping systems, and are also compared at the cropping system level for 2 years of experimentation. Profile water distribution was assessed at the wetting phase (near planting), wet phase (at millet and cowpea flowering) and drying phase (at sorghum maturity) to the depth of soil moisture measurement (105 cm).

4.6.5 (a) *1994 cropping season*

The pattern of soil profile water distribution in the millet based cropping systems is shown in Figure 4.48. Profile water distribution in the millet based systems near planting (26 DAS millet) indicates the wetting period of the soil and shows the level of water availability for plant use (Fig. 4.48a). Soil water in the top 0-15 cm indicates a higher soil moisture content in the bare ground (0.096 cm^3 cm^{-3}) than observed in the cropped land. The lower soil water content ($\approx$0.06-0.07 cm^3 cm^{-3}) in the millet based systems is attributed to the root water extraction activities of the crop, since the bulk of root development in terms of root length density is concentrated in the top layers of the soil during the early stages of crop growth. The combination of inadequate wetting of the soil, i.e. wetting front only just reaching the 40 cm, and the lower soil water content in the surface layers, where seedling roots were being established, coupled with the high evaporative demand from the atmosphere, are suggested as the factors responsible for the relative poor stand

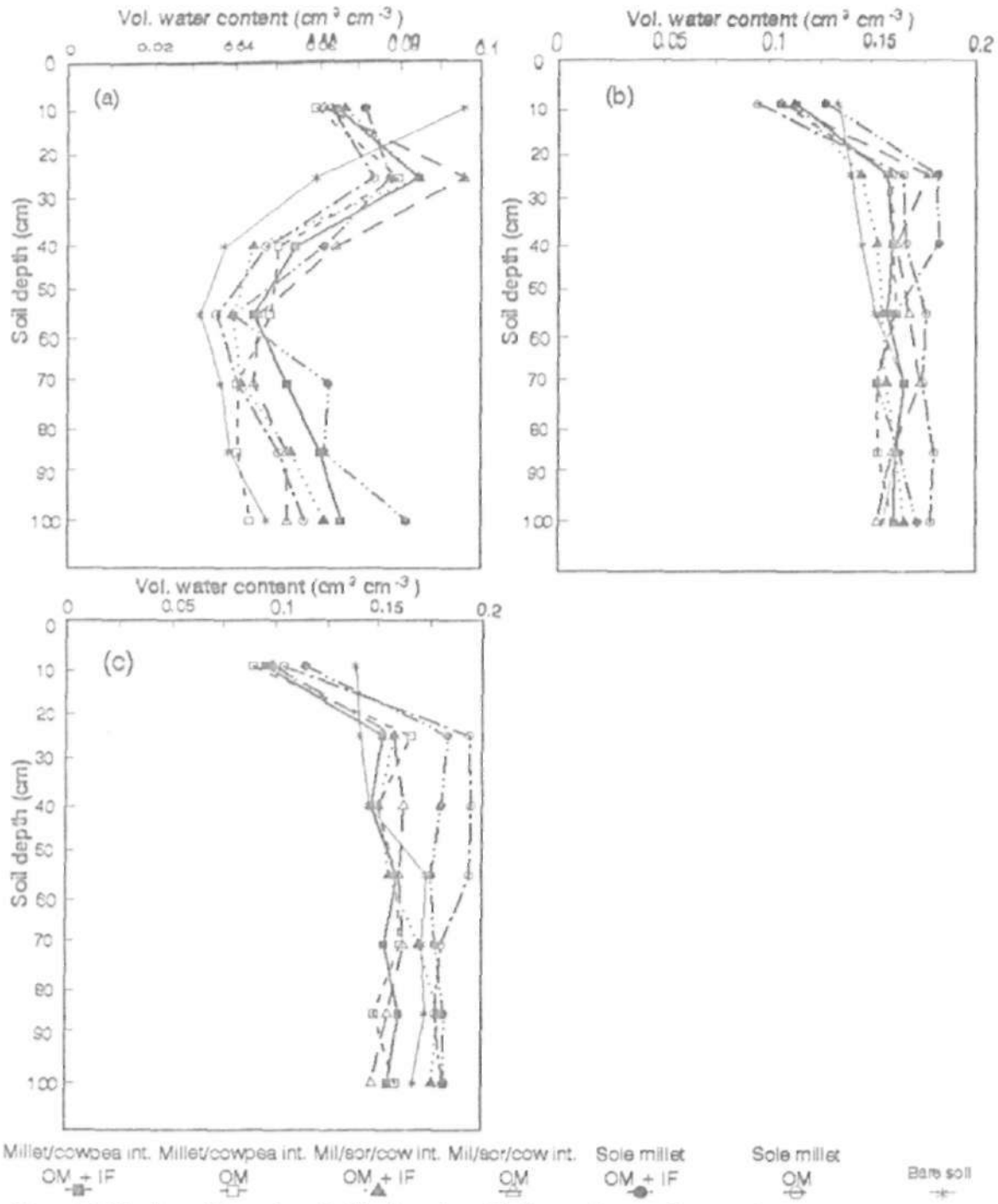


Fig. 4.48 Soil profile water distribution in millet based cropping systems compared with bare soil at (a) near planting (26 DAS millet), (b) millet head formation (53 DAS millet) and (c) at millet maturity (83 DAS millet). Water distribution points represent mean of three measurements.

establishment and repeated sowing of crops in 1994.

Soil water content, however was higher in the cropped land than in the bare ground for most of the soil depths below the surface layers. The difference in the top soil may have been assisted by thermally induced water vapour diffusion towards the bare surface at night. Soil water content below depth 25cm until 40 cm was significantly ($P < 0.05$) higher in millet based cropping intercropping systems (0.08-0.096 $cm^3\ cm^{-3}$) than in the bare plot (0.06 $cm^3\ cm^{-3}$) (S.E= 0.0084 $cm^3\ cm^{-3}$). From these data, it can be seen that if the measuring error is below 15%, then physically the errors do nt overlap. the actual measuring errors are certainly not that high and a value between 10% and 15% is more likely. Moreover, some of the errors do not apply to the moisture content differences, but only to absolute values in the same drection. Soil water content in the sole millet was also higher than in the bare ground, but this was not significant statistically. Sole millet sown at relatively higher plant density (53333 plants ha^{-1}) and also at a faster growth rate than sorghum and cowpea, produces a denser mass of roots to exert more negative water potential and extract more water than in the widely spaced intercrops with a total plant density of 26667 plants ha^{-1}. The decrease in total potential from the soil to leaf is very high in actively transpiring plants, while within the soil, the decrease varies with distance over which water moves to the roots and inversely with water content (Marshall and Holmes, 1992). The negative water potential developed by the root as a result of its internal conduction mechanism to the shoot, and daytime transpiration of the water to the atmosphere, allows the dense root system in the looser soil close to the surface to transfer and hold more soil water than bare soil, while the high porosity of the sandy soil ensures relatively free flow of water down the soil profile. During the night,

water drawn from the deep, moist soil horizons is conveyed to the shoots and also to the roots closer to the soil surface layer by internal conduction in the root system. The resultant lower water potential in the upper soil layers relative to the surface roots, induces a loss of water from the roots to the surrounding soil, causing higher surface soil moisture than under the bare soil (Larcher, 1995). Soil evaporation as a result of the higher thermal gradients in bare soil at night is another suggested factor responsible for this trend.

Water content at about 55 cm depth varied from 0.03 cm^3 cm^{-3} in the bare ground to 0.049 cm^3 cm^{-3} in the millet/cowpea (OM) intercrop, which was below the assumed wilting point of the soil and indicative of the soil wetting front during the season. Although the start of rainfall in 1994 was relatively earlier than in 1993 and 1995, the amount of rainfall between the time of sowing millet (23 June), and the first measurement of soil water (29 DAS), was not enough to extend deep into the soil profile, and was also used to meet the environmental high evaporative demand at that period. The relatively (somewhat) higher soil water contents below 70 cm soil depth downwards could be partly due to surface evaporation during the early season dry spell, but must have been strongly influenced by the earlier rains (168.6 mm) until millet sowing, that had percolated deep into the soil horizons (sandy) at the experimental site.

Soil water profile distribution at millet panicle initiation, as shown in Figure 4.48b, was also the period of maximum leaf area indices in most millets within the different cropping systems ($\approx$53 DAS), and $0.2 \leq LAI \geq 0.4$ of intercropped cowpea varieties ($\approx$ 32 DAS). This period occurred at the peak of the rainy season, by mid-August, when 67% of the annual rainfall had been recorded. Soil water profile

distribution indicates high water content in all treatments from 25 cm downwards. The observed soil water content varied from 0.14-0.18 cm^3 cm^{-3}, which values were within the measured soil saturation point and indicate that there was enough available water at millet panicle initiation.

Root extraction caused lower water contents in the cropped than the bare exposed surface soil (0-15 cm), but this did not show any statistically significant difference (S.E=0.012 cm^3 cm^{-3}, P= 0.49), suggesting that the bare soil evaporative loss was also high. This is also confirmed at lower depths. The physical error limits of $< 15\%$ but $\geq 10\%$ indicate the error limits indeed overlap. Around 25cm soil depth, soil water contents in the relatively higher fertility millet/cowpea (0.158 cm^3 cm^{-3}) and millet/sorghum/cowpea (0.145 cm^3 cm^{-3}) intercrops were significantly lower than in the sole millet at the higher fertility level and in the millet/sorghum/cowpea system at the relatively lower fertility level, i.e 0.182 and 0.177 cm^3 cm^{-3} respectively (S.E=0.009 cm^3 cm^{-3}, $P < 0.05$). That the significance level is rather low is confirmed by the physical error limits between the minimum and the maximum of these values that overlap at $\pm 12\%$. A similar trend in soil water content was observed around 40 cm soil depth with higher soil water contents in the high fertility sole millet treatment at field saturation than in the intercrops.

The observed trend indicates a somewhat better water use by the intercrops at these depths and the probable influence of component crops root distribution in relation to soil water extraction at this stage of crop growth. The canopy development of millet at panicle initiation was indicated by the LAI > 4.0 accounts for radiation interception of over 70%. The amounts of ground cover achieved at this stage of millet (sole) growth, particularly at the high fertility level, reduced soil evaporation

and hence higher soil water measured under the sole millet systems relative to the intercropping systems with lower ground cover and values of radiation intercepted. Below 40 cm soil depth, profile water distribution among the cropping systems and the uncropped ground remained not significantly different. The sole millet plots (OM) had more soil moisture than other cropping systems and the control. Extraction differences are more important here, although for bare soil evaporation remains of some importance.

The period of millet maturity, at 83 DAS, was also the period of pod filling in the fodder cowpea components ($\approx$ 60 DAS) and of about the maximum canopy development of the sorghum components ($\approx$ 75 DAS) of the intercropping systems. The rainfall amount in 1994 was 7% above the long term average and its distribution extended beyond the periods of millet and cowpea maturity into the third quarter of October. The profile water distribution (Fig. 4.48c) indicates that there was available water for the millet and cowpea components of the cropping systems at harvest. Soil water extraction by the dense crop roots of the millet based cropping systems at the near surface soil layers (0-15 cm) resulted in significantly lower soil moisture than in the bare ground surface soil. Near surface soil water varied from 0.09 to 0.11 cm^3 cm^{-3} in the cropped plots as against the bare ground with 0.14 cm^3 cm^{-3} (S.E=0.009 cm^3 cm^{-3}, $P < 0.001$). Between around 25 cm until around 55 cm depths, soil profile water contents were relatively slightly lower in the higher soil fertility treatment, but the effects of additional fertilizer application did not show any statistical significance at the same cropping system level.

A comparison among the cropping systems at millet maturity indicate that the available soil water in the sole millets of the two fertility levels were appreciably

higher than in the intercropping systems at soil depths from about 25 cm until near 55 cm. Soil available water was 0.195 and 0.185 $cm^3\ cm^{-3}$ in OM and OM+IF sole millet, which show significant difference statistically from Millet/cowpea values (OM= 0.16 $cm^3\ cm^{-3}$ and OM+IF= 0.15 $cm^3\ cm^{-3}$) and millet/sorghum/cowpea values (OM= 0.16 $cm^3\ cm^{-3}$ and OM+IF= 0.16 $cm^3\ cm^{-3}$) at about 25 cm depth (S.E=0.01, P= 0.019). The sole millet (OM only) values differ by 14-23% from the intercrop values for an error limit of ±10%, only the highest and lowest values do not overlap. The same trend was observed until around 55 cm soil depth and this indicates a better use of soil moisture in the intercrops than in the sole millet and/or remaining influence of soil evaporation differences at soil layers above 55 cm depth. Soil water extraction by the intercrops were consistently higher below 55 cm depth than in the sole millet, as shown by the higher available soil moisture measured in the sole millet plots (Fig. 4.48c). The sorghum component, now in its active vegetative growth stage, along with the podding cowpea fodder type in the millet/sorghum/ cowpea and millet/cowpea intercrops were responsible for this higher water extraction in the intercrops, that could have otherwise remained unused.

The soil profile water distribution in the sorghum based cropping systems (Millet/sorghum/cowpea, sole Gaya Early and sole ICSV 400) are shown in Figure 4.49. Soil water profile distribution at 19 DAS sorghum on 19 July, 1994 (Fig. 4.49a), indicates the same trend as observed in the millet based systems in the surface soil layers (0-15 cm depth). Surface soil water was higher in the bare surface (0.096 $cm^3\ cm^{-3}$) than in the cropped surfaces (0.053-0.070 $cm^3\ cm^{-3}$) as a result of plant root water uptake, perhaps assissted by thermally induced water diffusion upwards at night in bare soil. Sole Gaya Early (OM+IF) extracted more water from the soil than the

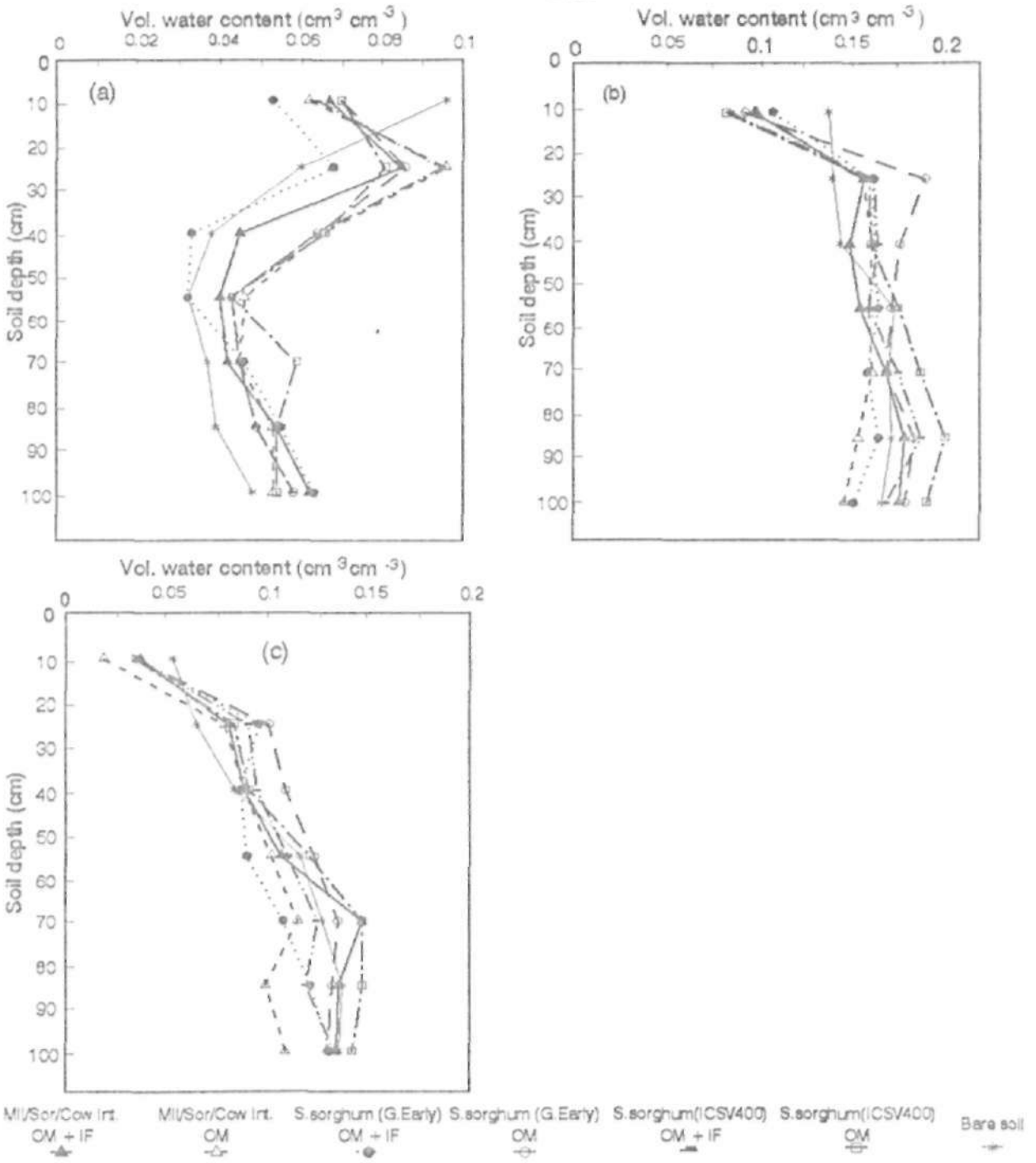


Fig. 4.49 Soil profile water distribution in sorghum based cropping systems compared with bare soil at (a) near planting (19 DAS sorghum), (b) sorghum head initiation (76 DAS sorghum) and (c) at sorghum maturity (114 DAS sorghum) in 1994. Water distribution points represent mean of three measurements.

other cropping systems.

The soil available water around 25 cm depth indicates a higher water content in the intercrops, sole ICSV 400 and sole Gaya Early (OM) than in the sole Gaya Early (OM+IF) and bare ground. Soil available water in the bare ground and sole Gaya Early (OM+IF) were similar and lower than measured in the other systems below the wetting front (about 40 cm depth). Soil available water profile from around 55 cm and below was higher in all cropped plots than in the bare ground, showing the involvement of soil evaporation in surface soil water status.

Soil profile water distribution at sorghum head formation (76 DAS) indicates still a significant ($P < 0.01$) higher surface available water in the bare surface soil (0.14 $cm^3\ cm^{-3}$) than in cropped plots (0.08-0.11 $cm^3\ cm^{-3}$), due to active plant roots water uptake, which was additional to smaller soil evaporative loss to the atmosphere (S.E=0.009 $cm^3\ cm^{-3}$) (Fig. 4.49b). However, soil profile water distribution around 25 until 40 cm depth indicates higher soil available water, sometimes with very little difference, in the sole sorghum plots than in the intercropping systems. This period coincided with grain maturity in the millet and cowpea components of the intercropping systems, but the measured soil water (0.157 $cm^3\ cm^{-3}$ for both OM+IF and OM) are not significantly different from sole Gaya Early with OM+IF treatment (0.162 $cm^3\ cm^{-3}$) and sole ICSV 400 at both OM (0.16 $cm^3\ cm^{-3}$) and OM+IF (0.162 $cm^3\ cm^{-3}$) around 25 cm depth. Sole Gaya Early (OM), however, kept significantly higher moisture (0.19 $cm^3\ cm^{-3}$) than in all the other systems and bare ground at around 25 cm depth (S.E=0.01 $cm^3\ cm^{-3}$, $P<0.02$), showing less extraction with respect to the high fertility sorghum and a combination of that with lower soil evaporation with respect to the other treatments. Around 40 cm depth, for the same

reasons, soil available water also indicated higher amounts in the sole sorghum treatments than in millet/sorghum/cowpea intercrops and bare ground, but only appreciably different from the millet/sorghum/cowpea intercrop (OM+IF) and bare ground. The higher soil water values in the sole sorghum plots (0.161-0.176 cm^3 cm^{-3}) were significantly higher than the values observed in the high fertility millet/ sorghum/cowpea intercrop (0.149 cm^3 cm^{-3}) and bare ground (0.144 cm^3 cm^{-3}) (S.E= 0.0078 cm^3 cm^{-3}, P= 0.006).

The trend of soil available water between 25-40 cm depth, with most differences very small, was sole G.Early (OM) > sole ICSV 400 (OM+IF) > Sole G.Early (OM+IF) > sole ICSV 400 (OM) > millet/sorghum/cowpea (OM) > millet/sorghum/cowpea (OM+IF) > bare ground. The soil depths of 0-40 cm indicate that a somewhat better use of soil available water is achievable at about field saturation point in the millet/sorghum/cowpea intercropping system, and especially at a high soil nutrient level for the sorghum component than in the sole planted (Gaya Early OM only) sorghum. The differential rooting of crops in intercropping systems compared with their sole crops may be a major reason, but low soil evaporation of sole crops may contribute as well. This could be directly through evaporation or indirectly through a better water holding of soil with denser roots. Around and below 55 cm soil depth, the cropping system with G.Early sorghum variety shows more water extraction than in the sole ICSV 400 (Fig. 4.49b). Soil available water at 70 cm depth was affected by soil fertility level. Sole ICSV 400 (OM) root zone water storage (0.187 cm^3 cm^{-3}) was significantly more than observed in the ICSV 400 (OM+IF) plots (0.175 cm^3 cm^{-3}), while ICSV 400 at system level, significantly stored more water in the root zone than G.Early sown sole and millet/sorghum/cowpea

intercrop with G.Early as a component (S.E= 0.0006 cm^3 cm^{-3}, P< 0.05). The available water in the soil profile below 55 cm depth showed that G.Early sorghum variety at cropping systems level produced greater dry matter than ICSV 400, and extracted more water at greater soil depth than ICSV 400. This is also indicative of a deeper rooting system in the G.Early component than in ICSV 400.

The profile of soil available water distribution at sorghum maturity (114 DAS), after the rains had ceased in 1994, indicates a rapid decrease in surface soil (0-15 cm) available water (Fig. 4.49c). Soil water under the bare surface (0.053 cm^3 cm^{-3}), which was at the assumed wilting point, was significantly higher statistically than in cropped plots (0.019-0.037 cm^3 cm^{-3})(S.E= 0.0033 cm^3 cm^{-3}, P= 0.016). The period of sorghum maturity, which is the final soil drying phase, indicates a gradual increase in soil available water down the profile. Soil profile water distribution shows that there was enough available water ($\geq$ 0.08 cm^3 cm^{-3}), at sorghum maturity, from around 25 cm downward. Soil available water from 55-100 cm depth was still around field capacity. Root zone water extraction of ICSV 400 was still less than observed in systems with G.Early at around 25 cm and below at sorghum maturity.

The pattern of soil profile water distribution in the sole cowpea treatments to the maximum depth of measurement (around 105 cm) gives an indication of varietal differences in relation to water extraction in the rooting zone (Fig. 4.50). Surface soil (0-15 cm) available water at 11 DAS cowpea indicates that soil water extraction by cowpea roots in the surface layer was also clearly higher than the water loss in the bare ground surface soil (0.096 cm^3 cm^{-3}) (Fig. 4.50a). For the local prostrate and vegetative cowpea variety, Dan-illa, soil available water was the least (0.054 cm^3 cm^{-3}), but this was not significantly different from IT89KD-374 (0.065 cm^3 cm^{-3}) and

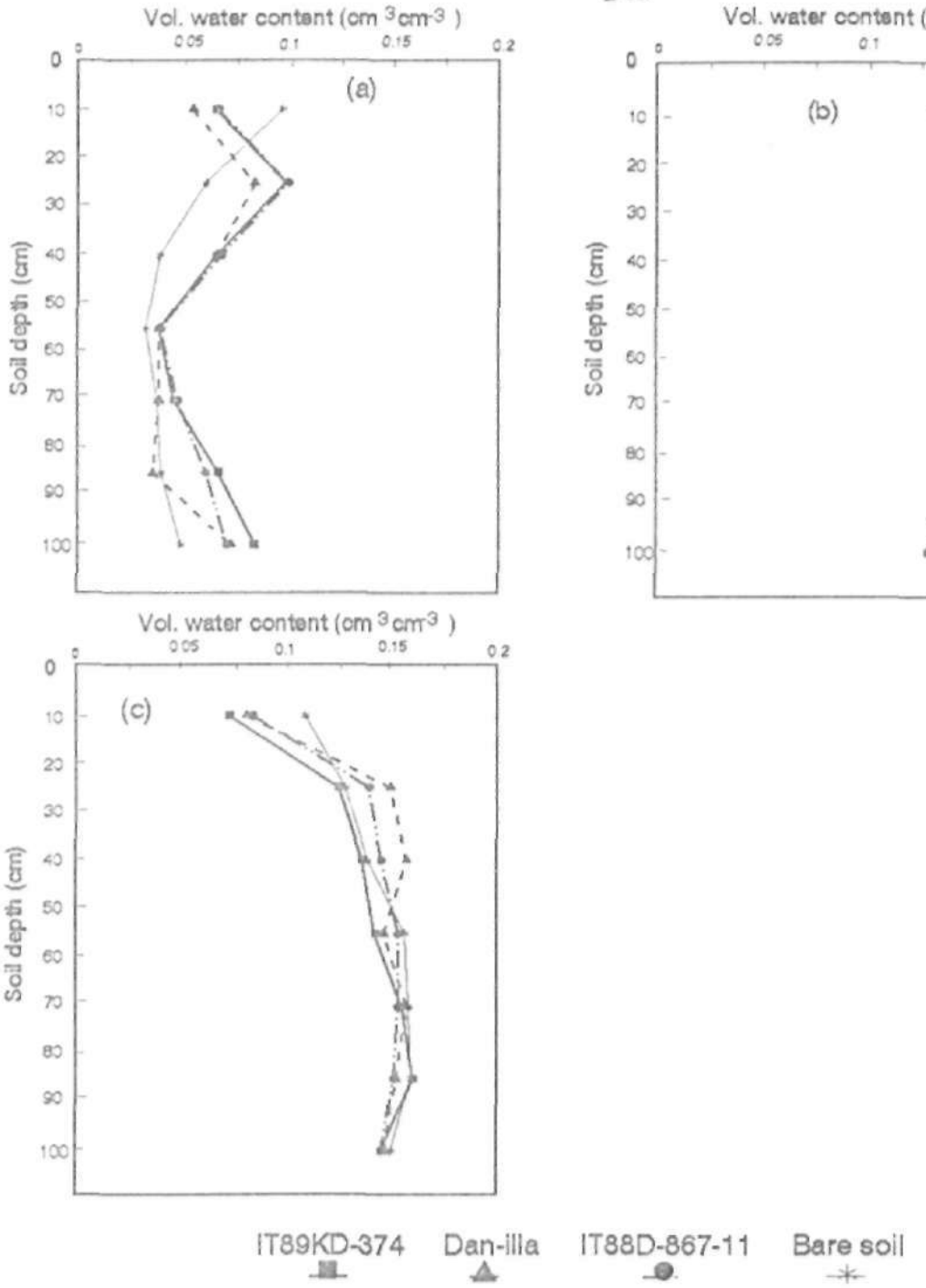


Fig.4.50 Soil profile water distribution in sole cowpea varieties compared with bare soil at (a) near planting (11 DAS cowpea), (b) flowering (46 DAS cowpea) and (c) at IT89KD-374 and IT88D-867-11 maturity (76 DAS cowpea) in 1994. Water distribution points represent mean of three measurements.

IT88D-867-11 (0.066 cm^3 cm^{-3}) [S.E= 0.008, P= 0.22]. Dan-illa was still a better soil water extractor around 25 cm depth than the two less vegetative grain cowpea varieties in the sole cowpea plots, while the bare ground to the same depth held the least amount of soil water (0.060 cm^3 cm^{-3}). Soil water availability in the sole cowpea varieties was similar from around 40 cm depth until the zone of an earlier wetting below a depth of 55 cm. Soil available water thereafter, was greater in the IT88D-867-11 and IT89KD-374 than in Dan-illa until at 100 cm depth, when it became similar to that of IT88D-867-11, but less than in IT89KD-374 for reasons that must be realted to the cropping patterns and therefore soil differences of an earlier season (Fig. 4.50a).

The soil profile water distribution of sole cowpea plots at about flowering (46 DAS) is shown in Figure 4.50b. The period was the peak of the rainy season, and close to the peak of leaf area development as well as the accumulation of substantial amounts of dry matter in the sole cowpea treatments. Soil available water was within field saturation point for most depths of measurement, hence indicating the availability of water at flowering. However, surface soil available water contents (0-15 cm) below the sole cowpea stands were similar, and more than observed in the bare ground, but this did not show any statistically significant differences. Cowpea canopies, growing close to the soil surface, may conserve somewhat more soil moisture and so reduce the water loss to the atmosphere compared with a bare ground situation, but this somehow remains speculative in this case. Soil available water around 25 cm was Dan-illa > IT88D-867-11 > IT89KD-374 > bare ground. The differences have only marginal meanings. At 46 DAS, Dan-illa cowpea cultivar had rooted deeper and was more active in water extraction at lower levels than the other sole cowpea systems.

different crops.

4.6.5 (b) *1995 cropping season*

The better distribution of rainfall after the sowing of crops in 1995 (Fig. 4.2c), ensured a good soil hydraulic conductivity that became high enough to permit the transmission of drainage water to deeper layers as shown by the wetting front, that must have occurred below the depths of measurement, in the millet based cropping systems at 29 DAS (Fig. 4.51a). Crop root water extraction from the surface soil layers (0-15 cm depth), caused lower soil available water (0.035-0.050 cm^3 cm^{-3}) than the loss to evaporation only, under the bare ground surface soil (0.070 cm^3 cm^{-3}). They were different significantly at $P<0.01$ (S.E= 0.0041 cm^3 cm^{-3}). The profile soil water distribution further down indicates physically meaningful higher ($P< 0.01$) values of soil available water in the cropped plots than in the bare ground until around 85 cm soil depth. Next to soil water extraction nearer the surface, differences in soil cover must have also played a major role at this stage. Although the millet/sorghum/ cowpea intercrop (OM) soil available water was greater than that for the other cropping systems from around 55 cm to around 105 cm soil depth, these differences did not show any statistical significance. At these larger depths, roots must have been scanty or absent.

The soil profile water distribution at millet maximum canopy development, when the initiation of panicle formation commenced in most of the cropping systems (55 DAS), reflects the effects of cropping system and soil fertility level on soil available water content (Fig. 4.51b). Surface soil (0-15 cm) water content in the relatively high fertility (OM+IF) millet based cropping systems and bare ground were

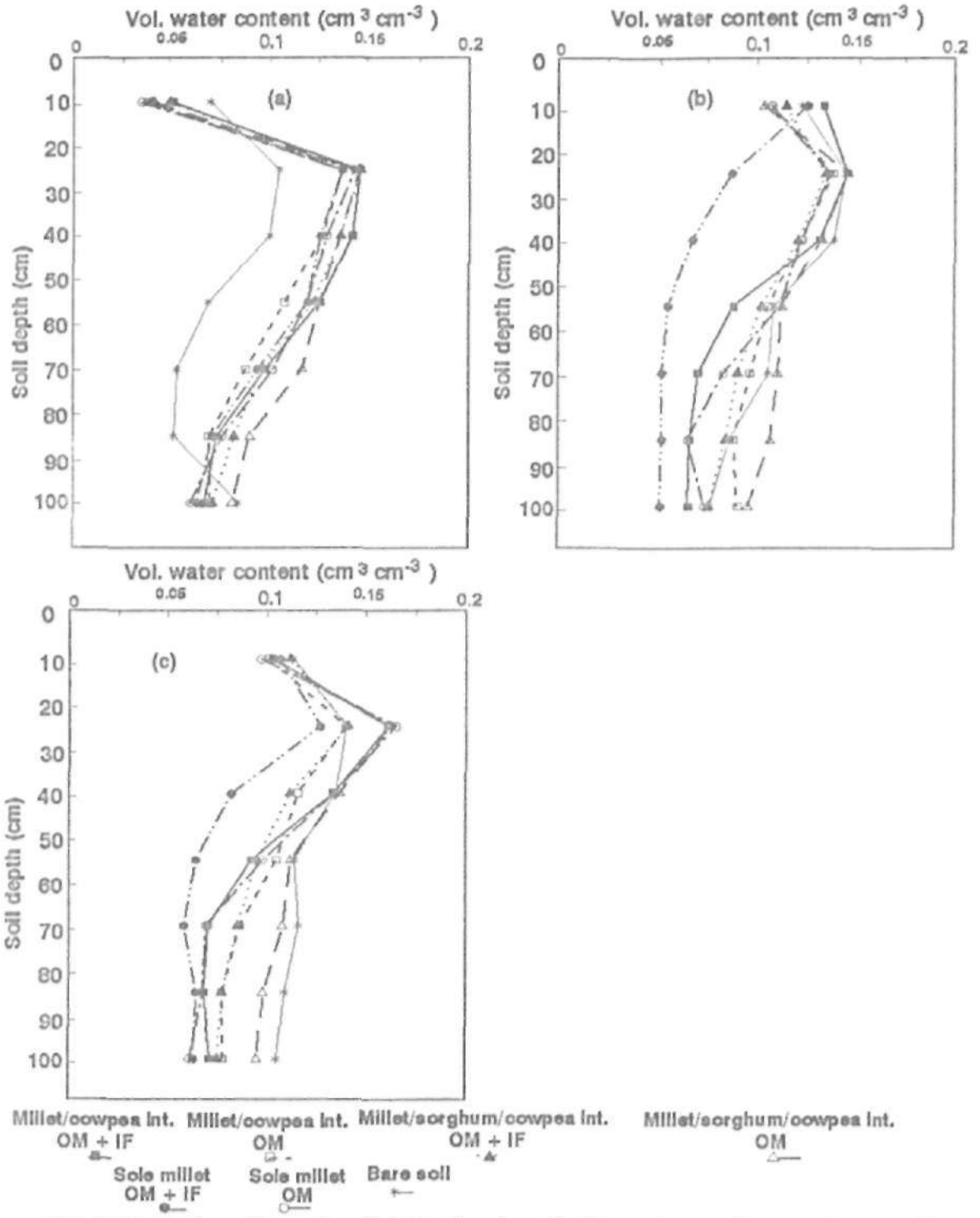


Fig. 4.51 Soil profile water distribution in millet based cropping systems and bare ground at (a) near crop establishment (29 DAS), (b) millet panicle initiation (55 DAS) and (C) millet maturity (83 DAS) in 1995. Water distribution points represent mean of three measurements.

higher than in the low fertility (OM) systems, but only statistically significant when the millet/cowpea (OM+IF) is compared with millet/cowpea (OM), millet/sorghum/ cowpea (OM) and sole millet (OM) at $P<0.05$. The higher soil surface protection by better developed canopies counteracting the differences in extraction from these layers at this stage of crop development is suggested for these differences.

The relatively lower amounts of rainfall in 1995 than in 1994 caused the relatively higher fertility sole millet, planted at a high density (53333 plants ha^{-1}), to show a significantly higher water extraction below the surface soil layer from around 25 cm until around 70 cm depth ($P< 0.01$). Except for the higher fertility sole millet, soil available water below the soil surface layers until around 55 cm depth was similar for all the cropping systems and bare ground, although the other high fertility treatments started to show higher extraction around 55 cm. Thereafter, until the maximum depth of profile measurement (105 cm), the relatively higher fertility treatment (OM+IF), at the cropping system level, significantly affected soil available water ($P< 0.05$).

The root water extractions in the high fertility cropping systems were clearly higher than in the treatments with pre-planting organic manure application alone, due to the more vigorous root development enhanced by the increased soil fertility (Fig. 4.51b). Soil water root extraction trend at the cropping system level was sole millet > millet/cowpea > millet/sorghum/cowpea. Plant population density, and to a lesser extent, the millet density in the intercropping systems, played a major role in the systems root zone water extraction. Except for the sole millet (OM+IF), soil available water was relatively close to field capacity for most depths of measurement. This indicates that there was sufficient available water at millet panicle initiation. However,

in the high fertility sole millet, soil available water around and 55 cm depth was coming close to the assumed wilting point. This suggests that water supply may have been a limiting factor in the sole millet plot during the reproductive stage. This was also reflected in the dry matter production at harvest, which was higher in the high fertility sole millet, but statistically not significantly different from the sole millet with pre-planting application of organic manure alone (see section 4.3.2 c).

Soil profile water distribution at millet maturity (83 DAS) in the millet based cropping is shown in Figure 4.51c. The distribution of rainfall in 1995 extended until the third decade in September and ensured improved soil water storage, i.e. about field capacity, to millet at grain maturation. Surface soil layer (0-15 cm) available water indicates a slightly higher value in the bare ground, but this was statistically not different from the surface values under cropped plots. This meant that the factors of extraction and surface evaporation must have been roughly in balance.

Soil profile water distribution below the surface layers until around 55 cm depth shows that soil available water extraction in the sole millet (OM+IF) remained significantly higher, down the profile, than was measured in most of the other cropping systems. This difference was statistically significant around 40 cm and around 55 cm depth at $P < 0.05$. Only at 55 cm did fertility effect appears to apply to all crops, but only hysically meaningful for sole millet. At the cropping system level, soil profile water distribution around 55 cm until around 105 cm depth, indicates the trend: Bare ground > millet/sorghum/cowpea > millet/cowpea > sole millet, with a fertility effect superimposed at around 70 cm. Crop root water extraction to the final depth of measurement, was more in the high density sole millet than in the intercrops (Fig. 4.51c). The relatively higher soil fertility treatment in the

different cropping systems generally increased soil water extraction in the rooting zone compared to what was observed in the relatively low fertility plots, but this was only significantly ($P < 0.05$) different in the millet/sorghum/cowpea intercrops, from around 70 cm until around 105 cm.

The soil profile water distributions in the sorghum based cropping systems during the 1995 rainy season are shown in Figure 4.52. Soil profile water distribution near crop establishment (24 DAS), indicates the activities of plant roots in the extraction of water from the surface soil (0-15 cm) [Fig. 4.52a]. Measured soil available water under cropped ground in the different sorghum based systems were statistically similar (0.039-0.05 $cm^3\ cm^{-3}$), but significantly lower at $P < 0.05$, than in the surface layers under the bare ground (0.07 $cm^3\ cm^{-3}$). The soil available water from 25 cm until around 70 cm depth, was similar in all the sorghum based cropping systems, but significantly higher than in the profile below the bare ground ($P < 0.01$), evaporation effects apparently being more important than extraction effects. This argument is strenghtened by a fertility effect in sole ICSV 400 and the millet/sorghum/cowpea intercrop at 70 cm. At around 85 cm depth, soil available water in the bare ground and sole Gaya Early (OM) were similar and significantly lower than in the other cropping systems. The soil water content at the maximum depth of measurement (around 100 cm), indicates physically meaningful lower available water in the sole G.Early at the two fertility levels than in the sole ICSV 400 and Millet/sorghum/cowpea intercrops at the two fertility levels, and the bare ground.

In the period of peak canopy development of sorghum components (81 DAS), of the different cropping systems in 1995 season, soil available water was sufficiently near field capacity in the bare ground profile. Cropping system, sorghum variety and

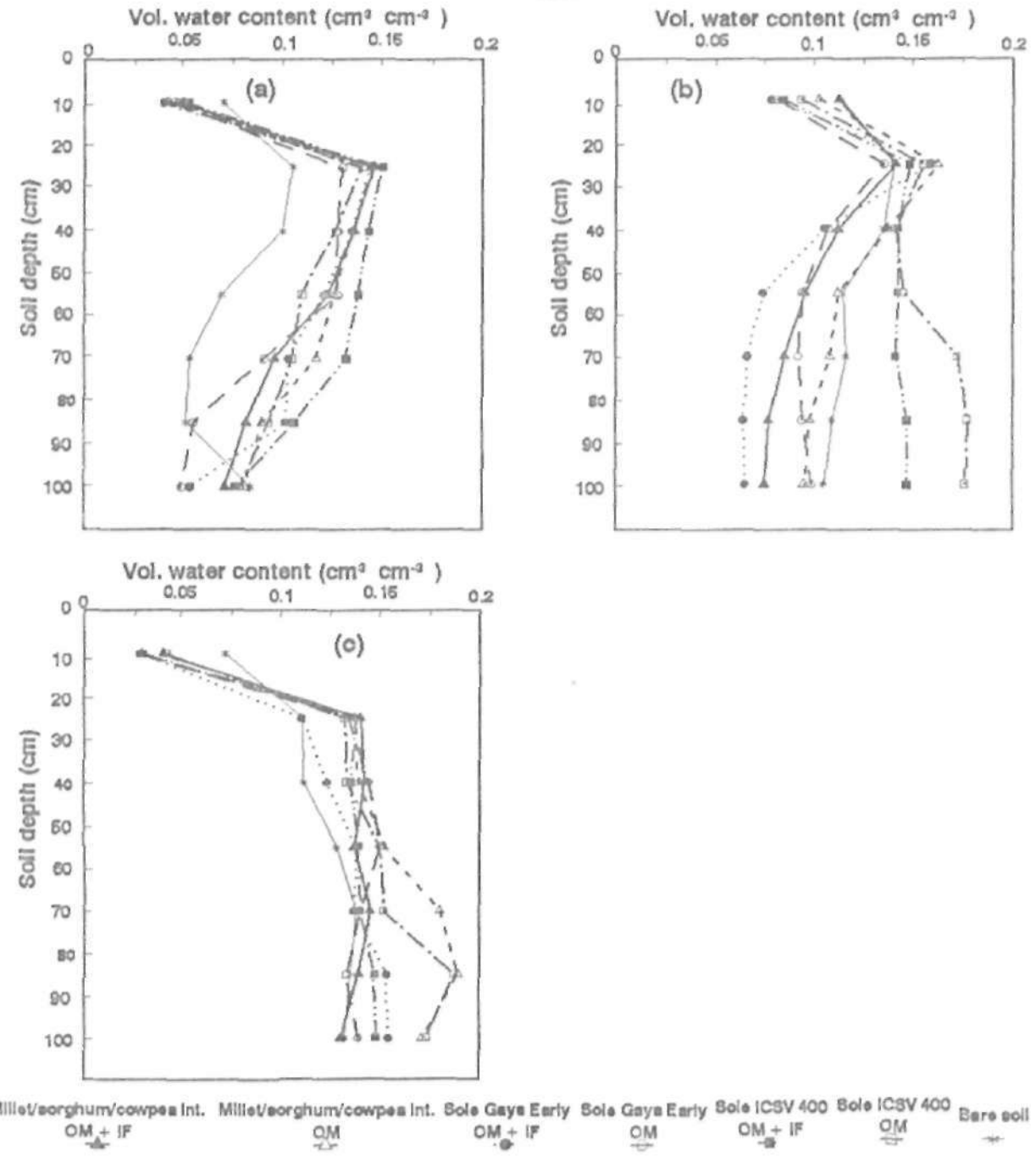


Fig. 4.52 Soil profile water distribution in sorghum based cropping systems and bare ground at (a) near crop establishment (24 DAS), (b) sorghum head formation (81 DAS) and (c) sorghum maturity (110 DAS) in 1995. Water distribution points *represent mean of three measurements.*

soil fertility, had great influences on soil profile water distribution (Fig. 4.52b). Surface soil water around 25 cm depth was similar for all treatments. The bare ground and the millet/sorghum/cowpea (OM+IF) intercrop have slightly higher soil water content in the surface layer (0-15 cm) than the other systems (Fig. 4.52b). However, below around 25 cm soil depth, the effects of cropping systems and soil fertility levels on soil available water became prominent. At the cropping system level, the trend of root zone soil water extraction was sole Gaya Early > millet/sorghum/cowpea > sole ICSV 400, with fertility effects increasing with depth. The sorghum variety within the intercrop is the farmers' variety i.e. Gaya Early. Gaya Early is more vegetative and accumulates more dry matter than the improved ICSV 400, which is of shorter height and matures earlier. The Gaya Early in sole and intercrops tends to realize more root zone soil water extraction than ICSV 400, due to the higher root densities it produces compared to ICSV 400. The measurement points below a profile depth of around 55 cm in Fig. 4.52b indicate that water extraction, within the rooting zone, to the maximum depth of measurement, was significantly ($P < 0.05$) more enhanced in the relatively high soil fertility treatments (OM+IF) than in those with organic manure application alone (OM), within the same cropping system. These differences became physically meaningful beyond a depth of 55 cm. Sole ICSV was the least effective root zone soil water extractor at the two fertility levels and also produced the least dry matter per unit land area, when compared with the sole G.Early and the millet/sorghum/cowpea intercrops, the higher plant population than the intercrops notwithstanding (see section 4.3.2 c).

The soil profile water distribution at sorghum maturity (110 DAS) on 4 October, about two weeks after the last rain in 1995, indicates that soil available water

below the surface layer (0-15 cm) was within the field capacity range, hence suggesting that the sorghum based systems had access to sufficient available water at maturity (Fig. 4.52c). The soil available water in the surface layer (0-15 cm) was significantly ($P < 0.01$) higher in the bare ground (0.07 $cm^3\ cm^{-3}$) than in the cropped surface soils (0.03-0.04 $cm^3\ cm^{-3}$), which, due to extraction cum evaporation, were already below the assumed wilting point (S.E= 0.0051 $cm^3\ cm^{-3}$). Measured soil profile water below the surface layers until around 55 cm depth shows statistical similarities in soil available water among the different cropping systems, except for the high density sole Gaya Early in the relatively higher soil fertility treatment and bare ground, which had lower soil profile water contents. The soil available water below around 55 cm depth in the relatively low fertility sole ICSV 400 and millet/sorghum/ cowpea intercrop were higher than in the sole Gaya Early at the two fertility levels, the high fertility (OM+IF) sole ICSV 400 and millet/sorghum/cowpea intercrop, and the bare ground plots to the maximum depth of measurement at 100 cm. While only the low fertility millet/sorghum/cowpea intercrop had significantly ($P < 0.05$) higher soil available water than in the other cropping systems around 70 cm depth, the same treatment and the sole ICSV 400 were significantly ($P < 0.05$) higher in soil water than the rest of the treatments, below this 70 cm until the highest depth of measurement. These were due to the differences in soil water extraction by roots in the various systems.

In the sole cowpea treatments, soil profile water distribution at various stages of crop growth and development are shown in Fig. 4.53. The surface soil (0-15 cm depth) available water at near planting (13 DAS), indicates the prominence of combined (somewhat reduced) soil evaporation and crop roots water extraction over

only evaporation from the bare ground surface (Fig. 4.53a). Soil available water was significantly ($P < 0.05$) higher in the bare ground surface layer than in layers under the sole cowpea plots. The profile of water distribution below the surface layers, among the various treatments, shows varietal differences in sole cowpea soil water extraction. Immediately below the surface layer, at around 25 cm depth, the more vegetative of the cowpea varieties sown sole, Dan-illa and IT89KD-374, showed the least extracted available water. They had physically meaningful differences with IT88D-867-11 and bare soil (Fig. 4.53a). Sole IT86D-719 and the bare ground profile also recorded significantly ($P < 0.01$) higher soil available water than was observed in IT88D-867-11. Below around 25 cm soil profile depth until around 85 cm depth, the bare ground soil available water level was significantly lower ($P < 0.01$) than in the cropped land. This must be due to differences in evaporation and water holding capacity while extraction by roots at these layers is still low or non existent.

The trend of soil available water among the sole cowpea was IT89KD-374 > Dan-illa > IT88D-867-11 > IT86D-719. IT86D-719 which accumulated dry matter fastest at the early stages of growth extracted overall more water than the other sole cowpea varieties. The determinate, and early maturing sole grain cowpea varieties, IT86D-719 and IT88D-867-11, sown at a relatively higher plant density (53333 plants ha^{-1}), show higher water extraction, not sufficiently compensated by higher soil cover, than the more vegetative IT89KD-374 and Dan-illa (35556 plants ha^{-1}). Only the highest among these differences is physically meaningful at the $\pm 10\%$ level. The soil water content at the end of profile depth measurement (100 cm) was similar for all the treatments.

The soil profile water distribution at cowpea flowering (44 DAS), over the full

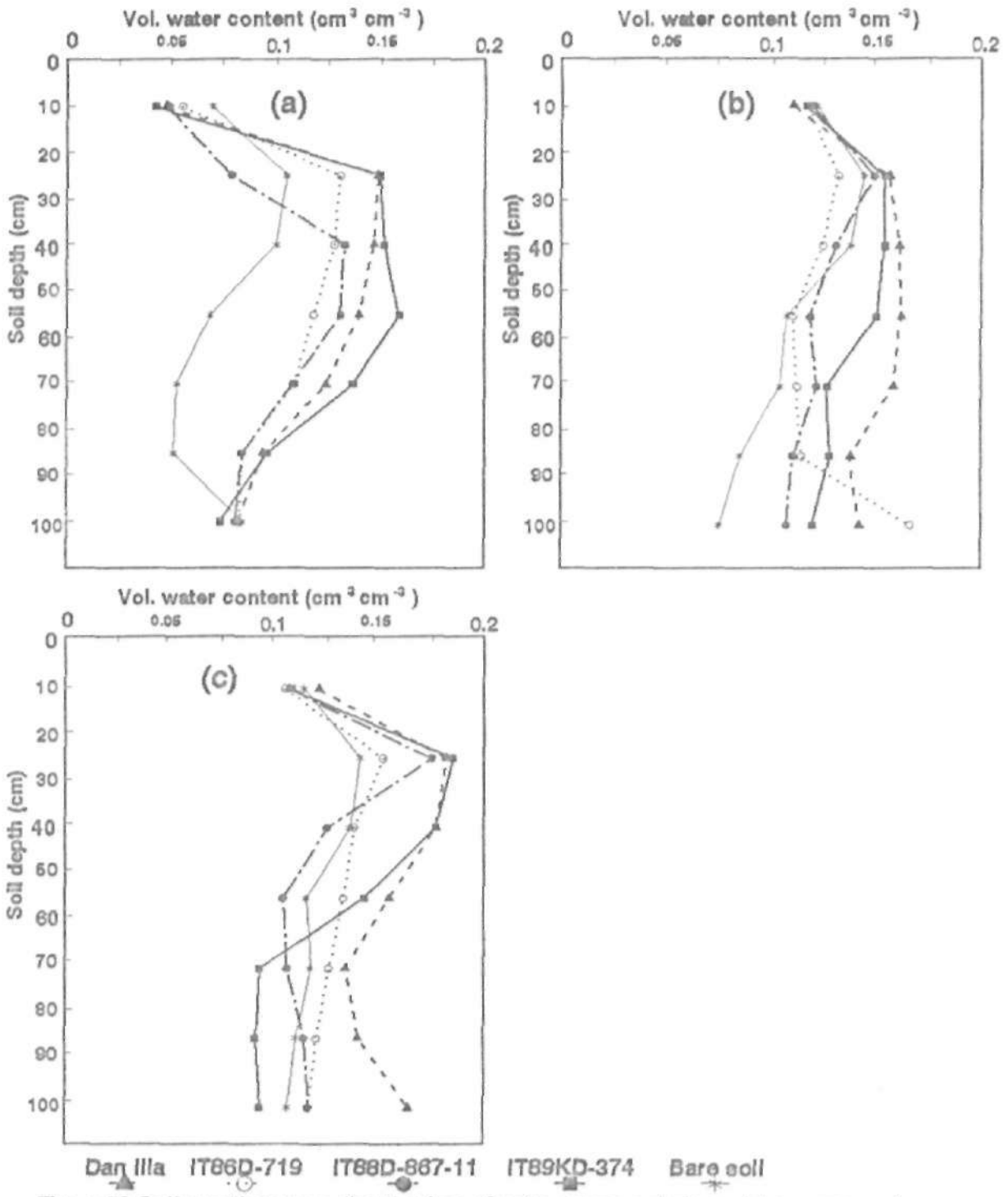


Fig. 4.53 Soil profile water distribution of sole cowpea plots and bare ground at (a) *near cowpea establishment* (13 DAS), (b) *cowpea flowering* (44 DAS) and (c) at IT86D-719 senescent maturity and IT89KD-374 and IT88D-867-11 pod maturity (83 DAS) in 1995. Water distribution points represent mean of three measurements

depth of measurement (0-100 cm), indicates soil available water near the estimated field capacity (> 0.10 cm^3 cm^{-3}) and hence there was enough available water at flowering for all the cowpea varieties (Fig. 4.53b). While surface soil (0-15 cm) available water was similar for all treatments, plant population density and cowpea variety influenced soil available water below these surface layers until 100 cm depth. Soil root zone extraction from the relatively higher density, grain type, earlier maturing IT86D-719 and IT88D-867-11 was more than in the lower density, later maturing and more vegetative IT89KD-374 and Dan-illa. The better dry matter accumulator of the grain type cowpea varieties (IT88D-867-11) and of the more vegetative varieties, Dan-illa (see Figure 4.53c), showed lower root zone extraction than IT86D-719 and IT89KD-374 respectively (Fig. 4.53b). As the bare soil water content is only little, different soil evaporation may also have played a role in the upper layers of the profiles. Expressed differently, the earliest maturing of the four cowpea varieties, IT86D-719, indicates the highest root zone extraction until around 85 cm depth, while the latest in maturing, and most vegetative variety, Dan-illa, shows the least water extraction. These differences are physically meaningful. Soil available water below around 25 cm until around 70 cm depths was also significantly ($P < 0.01$) higher in the Dan-illa than in the IT86D-719 plots, confirming more water extracted by the latter.

The amount of available water in the soil profile of sole IT86D-719 and IT88D-867-11 cowpea plots at senescent maturity and pod maturity stages in the IT89KD-374 (83 DAS), showed there was sufficient available water until these cowpea varieties were harvested (Fig. 4.53c). IT86D-719 is earlier maturing than IT88D-867-11.

Soil available water in the surface layers (0-15 cm) was higher in the most vegetative, but latest maturing Dan-illa plots, but this was not significantly different from the other treatments, which were physically similar. Soil water below the surface layer, at around 25 cm depth indicates significantly ($P < 0.05$) less water use under IT89KD-374, Dan-illa and IT88D-867-11 than in the earliest maturing IT86D-719 and bare ground. The trend of soil profile water extraction of the senescent IT86D-719, below the surface layer until 100 cm depth, was similar, but slightly higher than in the bare ground. Soil water in the IT88D-867-11 plots, from around 40 cm until around 70 cm depth, was lower but statistically similar to the bare ground profile. Dan-illa, still with most of its canopy and in pod development stage, indicates the least water extraction below 40 cm until 100 cm depth compared to the other cowpea varieties. These differenes, apart from the smallest at 55 cm and 70 cm, were all physically meaningful. The decrease in soil available water between around 55 cm and around 85 cm depth measurements are indicative of the active root extraction zones and the lower soil evaporation rates resulting from a greater ground cover of IT89KD-374 and Dan-illa than IT88D-867-11 and IT86D-719.

A comparison of the sole cowpea varieties shows that the farmer's variety (Dan-illa), which is of a later maturity and more vegetative, with the improved, less vegetative, grain cowpea varieties (IT89KD-374, IT88D-867-11 and IT86D-719), is the least extractor of soil water and also reduces soil evaporative losses most. The amount of soil water the stand of a cowpea genotype can extract depends mainly on its physiological attributes. This implies a relatively lower water requirement of Dan-illa as compared to the other cowpea varieties, and a better adaptation to the environment of the study, especially in the competitive cereal based intercropping

situation, during low rainfall seasons. Later on in the discussion section, water use efficiency will learn other aspects to this picture.

4.6.6 *Soil moisture storage*

4.6.6 (a) *1994 cropping season*

The soil moisture storage term being reported in this section was that occurring within 0-100 cm profile depth measurements(referred to as 'root zone water storage') and it was assumed that the maximum rooting zones of the crops were within these depths.

Such soil moisture storage trends in relation to the seasonal rainfall distribution in the millet and sorghum based cropping systems, and the sole cowpea systems are shown in Figs. 4.54 and 4.55, and for all the cropping systems in Table 4.16. Although 1994 rainfall amount (769.8 mm) was 7 percent above the long term average and extended until the third decade in October, its distribution in the early part of the growing season, in June, did not supply enough soil water for a good seedlings establishment. The root zone water storage at 26 DAS millet, 19 DAS sorghum and 11 DAS cowpea (Day 200, 19 July), varied from 51 to 70 mm in all the cropping systems compared to the bare ground of 46 mm. These were equivalent to the approximate average values that varied between 0.049 and 0.067 $cm^3\ cm^{-3}$, and higher in the cropped than in the bare ground (0.044 $cm^3\ cm^{-3}$) profiles. These storage values were close to the assumed wilting points for the soil in the experimental site, and especially low in the upper layers of the soil, and hence the initial poor seedlings establishment observed earlier in the season between mid June and mid July. The increase in rainfall distribution in time and space after mid July increased root zone

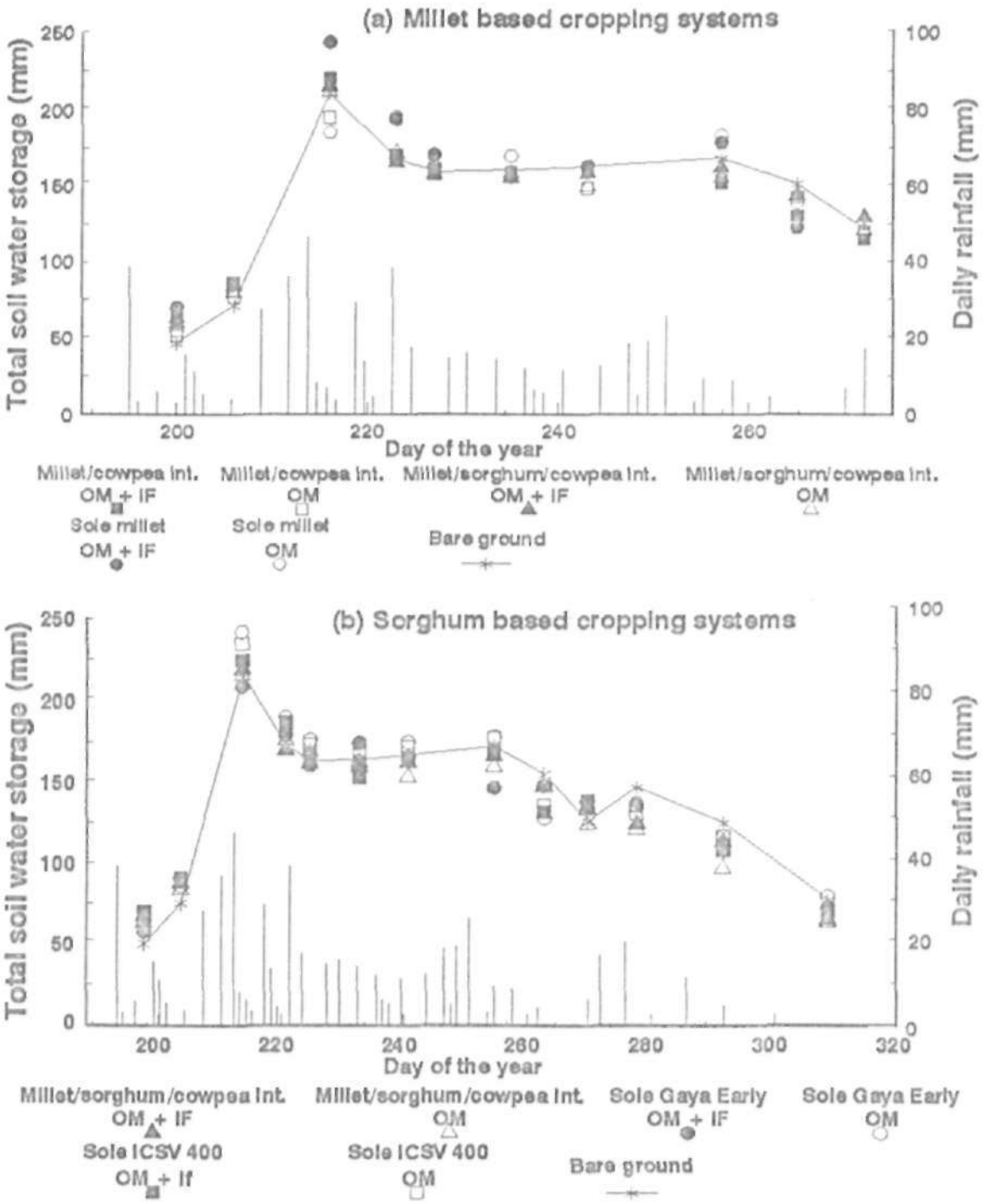


Fig. 4.54 Root zone (<1.0 m) soil water storage in (a) millet based cropping systems and (b) sorghum based cropping systems in relation to seasonal rainfall distribution during the 1994 cropping season.

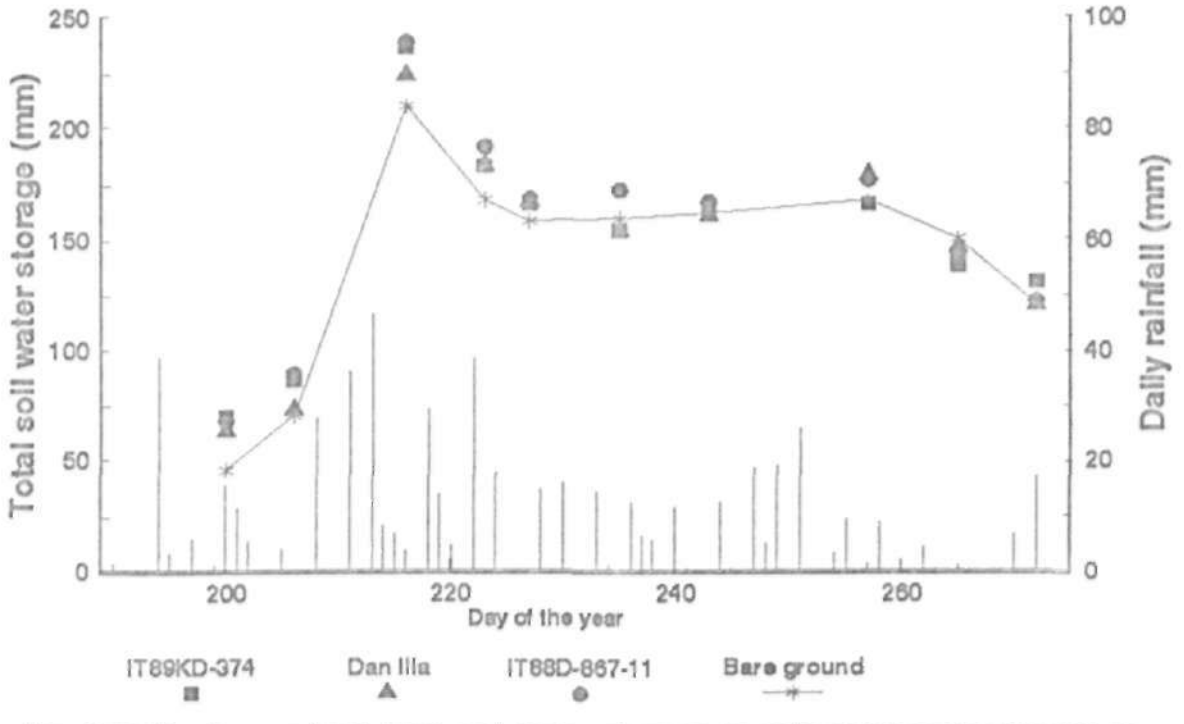


Fig. 4.55 Root zone (< 1.0 m) soil water storage in sole cowpea treatments in relation to the seasonal rainfall distribution during the 1994 cropping season.

Table 4.16 Total water content (0-105 soil depth) during 1994 cropping season. Total volumetric water content value (mm H_2O) is the average of three replications.

TREAT	FERT	DAYS OF THE YEAR (JULIAN DAY)											
		200	206	216	223	227	235	243	257	265	272	280	311
MIL/COW	OM + IF	64.4abcd	56.0ab	220.3abcd	170.5cd	161.4a	159.3cd	160.3abcd	152.3ghi	129.8cd	114.9c		
	OM	51.1de	51.4abc	194.9ef	169.4cd	158.0a	158.6cde	148.4d	153.8ghi	142.4ab	119.8bc		
MIL/SOR/ COW	OM + IF	59.3abcde	53.9abc	215.1cd	166.0d	157.4a	155.4cde	158.3bcd	162.2efg	145.2ab	129.1ab	120.2a	61.0de
	OM	63.1abcd	79.7abc	211.7cde	171.8cd	166.8a	158.2cde	169.7cd	155.7fgh	144.2ab	120.2bc	116.4a	59.2e
SOLE MILLET	OM + IF	70.0a	85.9ab	243.5a	194.0a	170.6a	156.1cde	163.1ab	178.3abc	122.3d			
	OM	54.6bcde	76.2abc	185.5f	195.3a	170.1a	169.7ab	163.1ab	183.0a	138.6abc			
S. SOR (G.EARLY)	OM + IF	53.7cde	87.0ab	204.8de	175.1bcd	156.6a	170.3a	161.8ab	162.6i	144.1ab	129.4ab	131.7a	68.2bc
	OM	63.1abcd	82.1abc	238.2ab	185.9abc	172.5a	159.2cd	170.9a	174.0abcde	124.2d	134.2a	132.9a	75.1a
S. SOR. (-400)	OM + IF	66.2abc	85.5ab	220.7bcd	182.2abcd	164.1a	149.0e	162.1ab	165.1de	127.6cd	134.6a	131.0a	67.0cd
	OM	60.1abcde	87.5a	230.6abc	183.1abcd	169.1a	164.7ab	167.8ab	173.3abcde	131.9bcd	132.1ab	126.5a	60.3e
S.COW (C-576)	OM	70.2a	87.2ab	236.7ab	183.5abcd	166.4a	154.7de	165.2ab	166.5cdef	138.8abc	131.6ab		
S.COW D.YLLA)	OM	63.7abcd	73.6bc	224.5abcd	183.9abcd	167.8a	154.5de	161.4abc	179.7ab	146.9a	121.bc		
S.COW (-867-11)	OM	68.3ab	89.7a	239.1ab	192.2ab	168.6a	172.6a	167.4ab	177.3abc	143.9ab	123.0abc		
BLANK (CONTROL)		46.4e	71.1c	210.5cde	168.4cd	158.9a	159.9bcd	162.4ab	168.0bcd	150.9a	121.6bc	142.3a	72.8ab
STANDARD ERROR (df-16, when all the treatments are considered)		5.8	5.72	8.41	7.45	6.25	4.04	4.66	5.16	5.05	5.13	12.6	2.34

abcdefghi - Alphabetic notation ascribed to means. In a column, means followed by a common letter are not significantly different at the 5% level using DMRT for comparing all possible pairs of treatment means.

storage to reach maximum values varying from 185 to 243 mm, within the first week in August (Day 216). These root zone water storages were higher than 0.17 $cm^3\ cm^{-3}$, and above the estimated field capacity, thus ensuring sufficient available water. The water content at this stage also inferred the commencement and occurrence of deep percolation drainage below the rooting zone.

The soil water storage within the root zone in the millet based cropping systems remained above field determined field capacity (116 mm i.e $\approx 0.12\ cm^3\ cm^{-3}$) and varies visibly from 115 to 129 mm at about Day 272 (30 September). However, there was no large differences in soil water storage at cropping system level, as soil fertility treatments did only significantly affect storage close to and at millet maturity (Fig. 4.54a). At millet grain filling and maturity (Days 257 and 265), root zone water storage in the relatively lower fertility (OM) treatments are generally higher than in the higher fertility (OM+IF) ones, but were only significantly ($P < 0.05$) different in the millet/cowpea intercrops and sole millet systems at maturity on Day 265 (Table 4.16).

Soil water storage in the sorghum based cropping systems after field saturation on Day 216, was similar in the sole and intercropping systems until the start of active growth in the sorghum component (LAI ≈ 0.5) about 54 DAS (Day 235) when there were some significant differences (Table 4.16). Stored water in the millet/sorghum/ cowpea (OM) was slightly higher than in the higher fertility (OM+IF) system, but not statistically significant, while under the sole Gaya Early systems, root zone stored water was significantly ($P < 0.05$) higher in the OM+IF plots (170 mm) than in the OM plots (159 mm). However, under the earlier maturing sole ICSV 400 systems, the higher fertility treatment caused again a significant reduction in soil water storage

when compared with the relative low fertility plots (Table 4.16). Gaya Early sorghum seem better able to extract more water under low fertility conditions while ICSV 400 is able to do the same under high soil fertility treatment, which lies more in the line of expectation because of the better growth and root development of G.Early compared to ICSV 400. Soil fertility treatment during sorghum head formation (after Day 272) until maturity (Day 311) did not influence soil water storage in the millet/sorghum/cowpea intercrops (Table 4.16). At the maturity of the sole sorghum varieties, the differences had again reversed with respect to Day 235. The root zone water storage under the low fertility Gaya Early (75 mm), was now significantly ($P < 0.05$) higher than under the high fertility Gaya Early (68 mm), while in the ICSV 400 systems, now at senescent maturity, soil water storage was significantly ($P < 0.05$) higher under the OM+IF (67 mm) treatment than under the low fertility ICSV 400 (60 mm). For sorghum Gaya Early, the higher fertility treatment had enhanced water use. Soil root zone water storage at sorghum maturity was generally lower in the intercropping systems, and varied from 59 mm in the millet/sorghum/cowpea intercrop (OM) to 75 mm in the sole Gaya Early (OM). These storage values were still above the assumed wilting point, but below the field capacity, to indicate that there was sufficient available water at sorghum harvest.

The trends of soil water storage in relation to rainfall distribution under the sole cowpea systems are shown in Fig. 4.55. The root zone water storage under the sole cowpea treatments was after establishment (> 28 DAS, Day 216) slightly higher in the IT88D-867-11 than in IT89KD-374 and Dan-illa until about flowering at about 47 DAS (Day 235). At flowering, soil storage under the grain and earliest maturing of the three cowpea varieties, IT88D-867-11, became significantly ($P < 0.05$) higher

than in Dan-illa and IT89K-374 (Table 4.16). The soil water storage at harvest (Day 272) varied, without statistically significant differences from 121 mm, under Dan-illa to 132 mm, under IT89KD-374, indicating soil moisture conditions still near field capacity and hence sufficient available soil water.

From the above root zone storage analysis, it follows that the amount of rainfall in 1994, and in essence, soil available water in the crop rooting zone, was not a limitation to crop growth. The abundance of soil available water after the initial deficits at establishment, throughout the growing season, caused little variations among the treatments in soil water storage. The relatively higher plant population densities in the sole crop treatments than in the intercrops did also not have significant effects on soil water storage during the 1994 season.

4.6.6 (b) *1995 cropping season*

The trends of the different cropping systems root zone (0-105cm depth) water storage in relation to rainfall amounts and distributions during the 1995 cropping season are shown in Figs. 4.56 and 4.57. The total annual rainfall in 1995 was about 564 mm, 22% less than the long term average for Kano. However, the rainfall distribution after crop sowing (Day 186) ensured soil water storage greater than 88 mm (i.e. ≈ 0.08 cm^3 cm^{-3}) not too far from field capacity, and hence its availability during crop seedlings establishment (Table 4.17). Another feature of the 1995 rainfall pattern was that the monthly totals throughout the season never exceeded the estimated potential evapotranspiration, even so at the expected peak of the rainy season in August/early September (Fig. 4.5). The implications of the expected soil moisture deficit are expressed by the observed stored water in the rooting zone in relation to

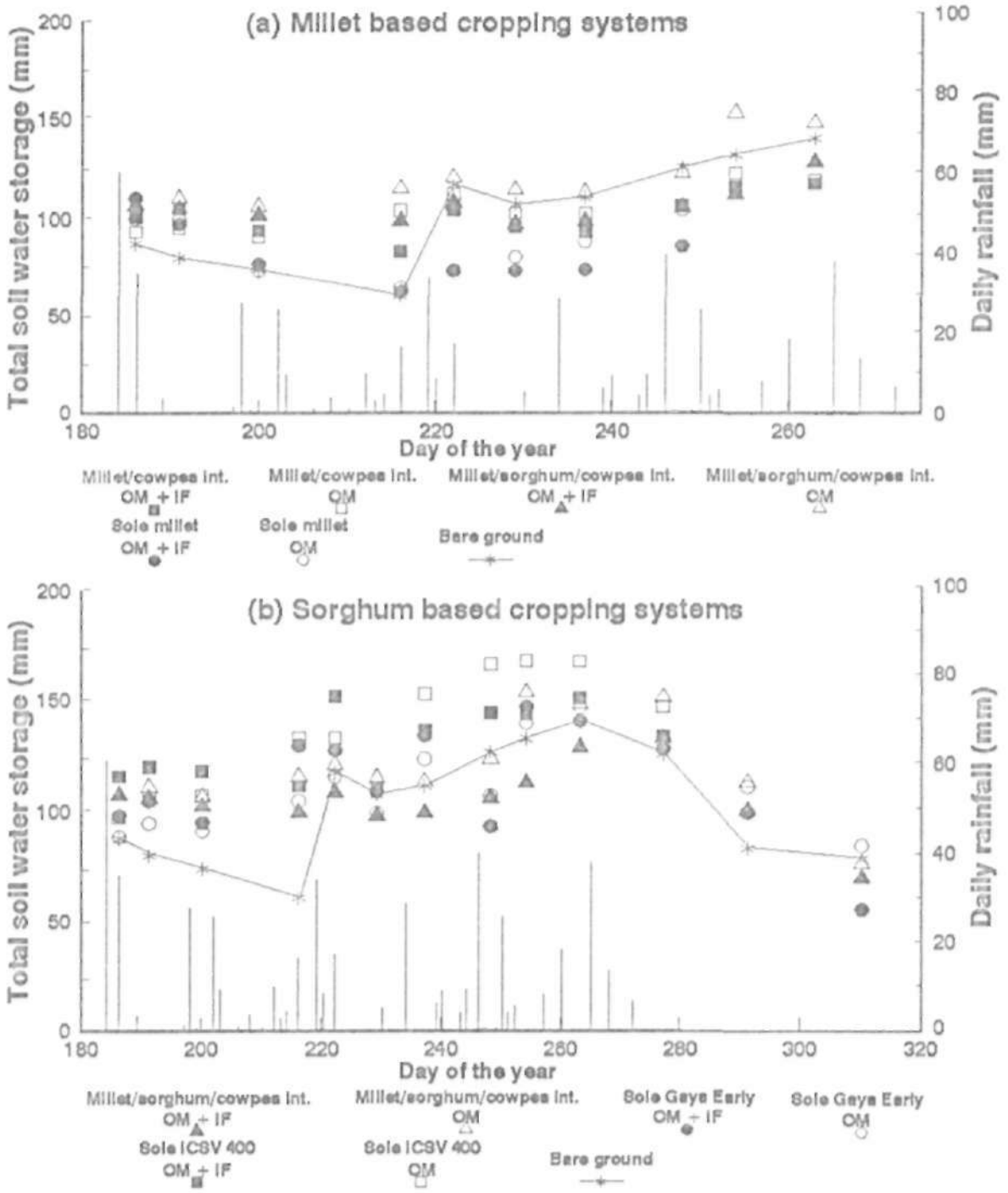


Fig. 4.56 Root zone (< 1.0 m) soil water storage in (a) millet based cropping systems and (b) sorghum based cropping systems in relation to seasonal rainfall distribution during the 1995 cropping season.

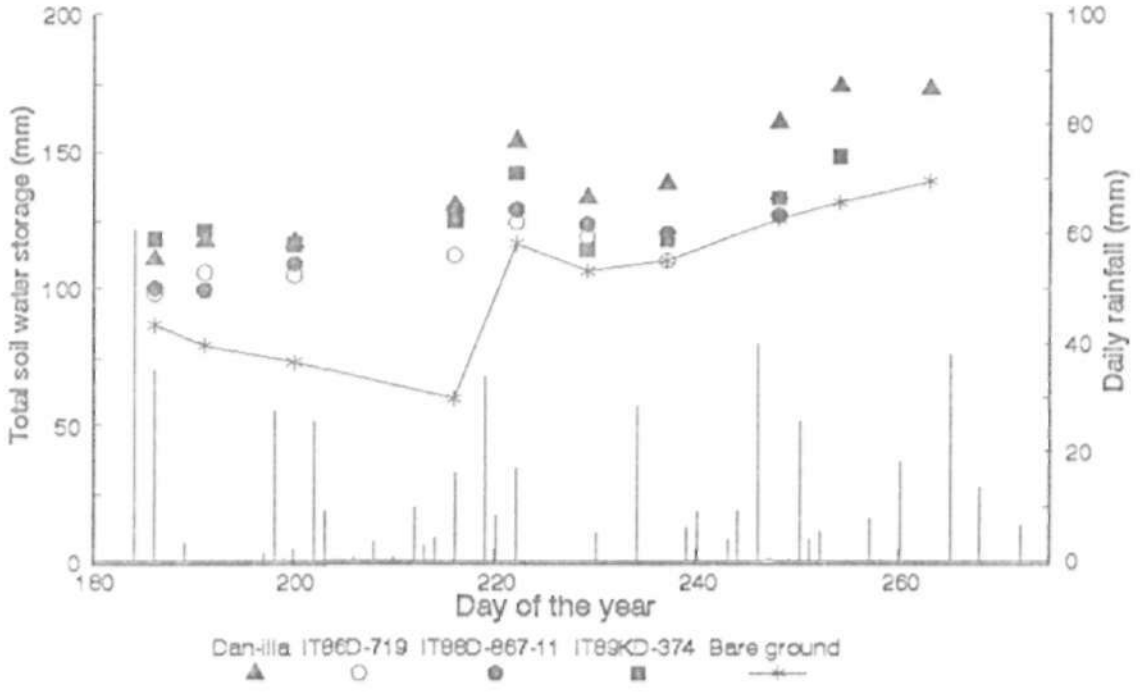


Fig. 4.57 Root zone (<1.0 m) soil water storage in sole cowpea treatments in relation to the seasonal rainfall distribution during the 1995 cropping season.

cropping systems and soil fertility levels.

In the millet based cropping systems, root zone water storage was similar at 27 DAS millet (Day 191), before the application of additional fertilizer to high fertility treatments in all the cropping systems. Soil water storage about millet panicle initiation at 52 DAS (Day 216), 10 days after complete fertilizer application to high fertility treatments, was significantly affected by cropping systems and soil fertility levels. The higher fertility millet/cowpea and millet/sorghum/cowpea intercrops held significantly ($P < 0.05$) lower water contents compared to their OM treatments, due to higher water use, while in the sole millet, soil water storage was only slightly higher under the OM than in OM+IF plots (Fig. 4.56a). However, at cropping system level, the general trend of the root zone water storage was millet/sorghum/cowpea > millet/cowpea > sole millet, reflecting the plant densities (Fig. 4.56a). In the three millet based cropping systems, the least seasonal root zone water storage (62 mm) was recorded at about panicle initiation (52 DAS, Day 216) in the high fertility sole millet. The relatively higher plant population density in the sole millet plots (53333 plants/ha^{-1}) compared total with intercrops density (26667 plants/ha^{-1} i.e. 1333 millet plus 6667 for each of the two cowpea cultivars in millet/cowpea or same with 6667 millet, sorghum and each cowpea cultivar in millet/sorghum/cowpea) and density of the more vigorous millet plants now at the peak of canopy development caused this wide variation in soil water storage (Fig 4.56a).

The root zone soil water storage during millet and cowpea grain filling (Day 222), had still significantly ($P < 0.05$) lower water content in the high fertility sole millet (73 mm) than under the other millet based systems (105-120 mm) [Table 4.17]. The water stored under the high fertility sole millet through grain filling seems held

Table 4.17 Total water content (0-105 soil depth) during 1995 cropping season. Total volumetric water content value (mm H_2O) is the average of three replications.

TREAT	FERT	DAYS OF THE YEAR (JULIAN DAY)											
		191	200	216	222	229	237	248	256	263	277	291	310
MIL/COW	OM + IF	105.2ab	94.1b	83.2f	104.6e	95.8abc	93.0fgh	106.1cd	116.0ef	117.2f			
	OM	95.6b	90.9bc	104.0de	111.9cde	102.6abc	102.2defg	106.4cd	122.9def	118.5ef			
MIL/SOR/ COW	OM + IF	105.3ab	101.6ab	98.8e	107.9de	97.3abc	98.7efg	105.6cd	112.2f	128.0def	131.9a	99.6a	69.1a
	OM	110.5ab	106.2ab	115.1bc	120.6bcde	114.4abc	112.8cde	123.1bc	153.1abc	147.7bc	150.6a	112.3a	75.8a
SOLE MILLET	OM + IF	97.6b	76.3cd	62.3g	73.3f	73.3c	73.5h	85.9d					
	OM	99.8b	73.3d	64.0g	104.6e	80.2bc	88.2gh	104.6cd					
S. SOR (G.EARLY)	OM + IF	104.4ab	94.4b	129.1a	127.1bc	108.3abc	133.6abc	92.6d	146.6abc	140.0cde	127.5a	98.8a	54.7a
	OM	94.1c	90.8bc	104.0de	115.1cde	98.5abc	123.0bcd	106.4cd	139.0cdef	145.8bc	131.2a	110.2a	83.8a
S. SOR. (-400)	OM + IF	119.6a	117.6a	110.9cd	151.5a	110.1abc	135.7ab	143.7ab	143.1bcde	150.3bc	132.5a		
	OM	105.2ab	106.5ab	132.0a	132.1ab	109.3abc	152.4a	165.8a	167.4ab	167.1ab	146.1a		
S.COW (C-374)	OM	121.5a	116.5a	124.8ab	142.6ab	114.4abc	118.4bcd	133.4b	149.0abc	154.4abc			
S.COW (D.ILLA)	OM	117.5a	117.3a	130.7a	154.2a	133.2a	138.7ab	161.3a	174.5a	173.4a			
S.COW (-867-11)	OM	99.8b	109.4a	128.1a	129.1b	123.9ab	120.3bcde	127.1bc	151.8cdef				
S.COW (C-719)	OM	106.3ab	105.1ab	112.3cd	124.6bcd	119.0abc	110.7bdf	133.6b	140.6bcd				
BLANK (CONTROL)		79.8c	73.6d	60.4g	116.8cde	106.9abc	110.6def	125.8bc	132.0cdef	139.8cde	124.8a	82.8b	77.4a
STANDARD ERROR (df=18, when all the treatments are considered)		7.25	6.96	3.1	9.09	13.85	9.30	10.53	11.60	9.17	6.75	6.47	6.47

at a high negative soil moisture, such that crop water requirements were not adequately met till harvest. This must be the reason for the overall similar dry matter production of the sole millets with the two fertility treatments. In the millet/sorghum/ cowpea intercrops, the higher soil fertility plots stored lower root zone water than the relatively lower fertility plots during millet grain maturity (Day 229-237), but they did not show any statistically significant difference. In the millet/cowpea intercrops, soil water storage at the two fertility levels were also not significantly different through grain filling until millet harvest (Day 254). During the cropping season, root zone water storage of the millet based systems reached a maximum (153 mm) at millet and cowpea grain type maturity, under the lower fertility millet/sorghum/cowpea intercrop by about mid September (Day 254), equivalent to an average water content of about 0.15 cm^3 cm^{-3}.

In the sorghum based cropping systems, root zone water storage after seedling establishment at 19 DAS (Day 186) through 33 DAS (Day 200), was generally influenced by cropping system. The trend of the root zone water storage was sole ICSV 400 > millet/sorghum/cowpea > sole Gaya Early. However, after the additional fertilizer application to sorghum components of the high fertility treatments 10 WAS sorghum, soil water storage under the sorghum based systems became somewhat affected by soil fertility levels after Day 248 (Table 4.17). The root zone water storage under the relatively low fertility sorghum based systems was higher than in the high soil fertility treatments, but the differences were not statistically significant at the cropping system level at sorghum high canopy development (LAI at maximum for ICSV 400 and > 1.3 for Gaya Early). The root zone storage reached a maximum of approximately 167 mm (Day 254) during the season under the sole ICSV 400

(OM), while the minimum of about 55 mm occurred under the late maturing higher fertility sole Gaya Early plots (Fig. 4.56b). The root zone soil water storage from crop establishment until sorghum maturity was between the estimated field capacity and wilting points, reflecting the availability of near sufficient soil moisture in the sorghum based systems until sorghum maturity.

In the sole cowpea systems, the periods after cowpea establishment begining from 8 DAS (Day 186) until 22 DAS (Day 200), before rapid cowpea canopy development (LAI $<$ 0.3), the root zone water storage under the early maturing, and more determinate, grain cowpea types (IT86D-719 and IT88D-867-11) were lower than under the later maturing semi erect IT89KD-374 and the prostrate and most vegetative Dan-illa cowpea varieties (Fig. 4.57). In the sole cowpea systems, root zone storage reached a maximum of about 175mm (0.17 cm^3 cm^{-3}) under Dan-illa during pod maturity at Day 254 (76 DAS), while the seasonal minimum storage (99 mm) was found under IT86D-719 near planting (8 DAS) [Table 4.17]. The range of soil water storage indicates there was available water throughout the duration of growth of the different cowpea varieties. Water supply was, therefore not a limiting constraint to cowpea production in this area. However, under the sole cowpea treatments, from 22 DAS (Day 200) until maturity, there was greater root zone water under the Dan-illa cowpea than the other sole cowpea cultivars sometimes significantly different and sometimes not (Table 4.17). This reflects the lowest water use rate of the most vegetative and highest dry matter accumulating Dan-illa cultivar as compared to the other improved, but less vegetative cowpea varieties. The trend of the root zone water storage under sole cowpea treatments IT86D-719 and IT88D-867-11 at maturity was Dan-illa $>$ IT89KD-374 $>$ IT86D-719 $>$ IT88D-867-11. The farmer's choice

of Dan-illa in their cereal based intercropping systems is thus understood in the adaptation of this cowpea cultivar to the arid and semi-arid zone as evident in its relatively lower water use rate and the probable effects of its prostrate nature and strong vegetative growth on soil microclimate improvement. The strong vegetative growth of Dan-illa is also of great importance for its fodder production which sustains the strong livestock component of the zone's farming systems.

4.6.7 *Crop water use*

4.6.7 (a) *1994 season*

The drainage term of the seasonal water balance calculation (see equation 3.11) of crop water use during the 1994 cropping season was not used. This was due to a defect in the design of the draining drum lysimeter used for this purpose. The estimate of crop water use hence assumed there was no deep drainage in 1994. However, this is not true of the actual field situation since 1994 rainfall was more than the long term average for Kano by 7%, and its distribution extended until the third decade of October. The observed root zone water storage under the different cropping systems indicated the availability of soil water, after crops establishment until crops maturity. Soil water was well above the estimated field capacity (> 0.11 cm^3 cm^{-3}). At the observed water contents, water is being held at such low suction that drainage would occur freely. The calculated crop water is relative and thus used to compare treatments at the end of the 1994 cropping season. A calculated example of crop water use during the 1994 cropping season is shown in appendix 4.3.

A summary of the seasonal crop water use of the different crop components

in the intercrops and the cropping system averages are shown in Table 4.18. The seasonal water use by the sole cowpea treatments varied from 386 to 400 mm. The difference in seasonal water use of 3.5%, within the measuring accuracy, suggests very little varietal effects during above average annual rainfall years as recorded in 1994. In the sole millet systems, the higher fertility treatment used approximately 8% more water than the sole millet, where pre-planting organic manure alone was applied. The seasonal crop water use of sole sorghum treatments varied from 488 to 506 mm. The improved early maturity ICSV 400 used slightly more water (501-506 mm) than the local, late maturing Gaya Early (488-490 mm). In summary, the varietal differences in water use are too little under the 1994 weather conditions to make meaningful conclusions. The water use of the various components in the intercrops at the two fertility levels were also rather similar to their corresponding types sown sole (Table 4.18). This similarity does also apply to the unfertilized cowpea compared to cowpea in the millet/sorghum/cowpea and millet/cowpea intercrops at the two fertility levels. The sorghum components of this system reached maturity over 25 days after the harvest of millet and cowpea in the association, thus accounting for the extra water use at system level over the sole millet and cowpea systems.

A comparison of the seasonal cropping system water use shows a much higher water use of the millet/sorghum/cowpea intercrop than of the millet/cowpea system. It indicates a slightly higher value (7% more) in the high fertility millet/cowpea (377 mm) than in relatively lower fertility millet/cowpea intercrop (351 mm). A smaller effect of soil fertility treatment on system water use was observed in the millet/ sorghum/cowpea intercrops. The high fertility millet/sorghum/cowpea (503 mm) used 2% more water than the low fertility millet/sorghum/cowpea (493 mm) intercrop.

Table 4.18: Seasonal crop water use (mm) during 1994 cropping season.

TREAT	COWPEA			MILLET	SORGHUM		SYSTEM MEAN WATER USE
	IT89KD-374	IT88D-867-11	DAN-ILLA	EX-BORNU	GAYA EARLY	ICSV 400	
SOLE COWPEA	389	400	386				*
SOLE MILLET OM+IF				388			*
SOLE MILLET (OM)				357			*
SOLE SORG. OM+IF					488	501	*
SOLE SORG. (OM)					490	506	*
M/C OM+IF	400		400	377			377
M/C (OM)	381		389	355			351
M/S/C OM+IF	386		376	360	499		503
M/S/C (OM)	384		390	352	507		493

Note: OM=Organic manure application only (pre-planting), 4t/ha

OM+IF=Pre-planting organic manure application plus top dress application of N.P.K fertilizer to cereal components.

* - Sole crops seasonal water use are shown below the columns under the name of crop variety.
M/C - Millet/cowpea intercrop
M/S/C- Millet/sorghum/cowpea intercrop.

4.6.7 (b) *1995 season*

The drainage term used in the calculation of crop water use was that occurring below the grassed draining lysimeter, reported in section 4.6.2 of this chapter.

However, the root zone is expected to extend beyond the soil profile depth measurements to at least 100 cm. The assumed drainage loss estimates, to below the rooting zone are based on the duration of crop growth during the 1995 season. They were about 80mm, 84mm, 80mm and 81mm for millet, sorghum, cowpea grain types (IT89KD-374 and IT88D-867-11) and cowpea cultivar, Dan-illa respectively (see Appendix 4.4 for the calculation). The fact that the observed soil water storage in the high fertility sole millet was much lower than in the other cropping systems, indicates that the water was held at high tension and hence the possibility for soil drainage loss is drastically reduced. The drainage term in the crop water use of the high fertility sole millet has thus been assumed to be zero. Table 4.19 shows the seasonal crop water use of components within cropping systems and the pooled averages at cropping systems levels.

The seasonal crop water use of the sole cowpea treatments varied from 188 mm in Dan-illa to 204 mm in IT88D-867-11. The trend of sole cowpea seasonal water use was IT88D-867-11 > IT89KD-374 > Dan-illa. IT88D-867-11 used 8% more water than Dan-illa. The storage terms under the sole cowpea systems were high throughout the season and are considered to be available water. However, in the sole millet treatments, soil fertility had an influence on water use. The high fertility sole millet seasonal water use (258 mm) was approximately 17% more than that in the relatively low fertility sole millet (215 mm).

In the sole sorghum treatments, the high soil fertility treatments also had some effects on crop water use. Sole Gaya Early (OM+IF) used 341 mm, 11% higher than in the Gaya Early with OM treatment (303 mm), while in the sole ICSV 400, the high fertility treatment used 284 mm, 12% more water than where pre-planting organic

Table 4.19: Seasonal crop water use (mm) during the 1995 cropping season.

TREAT	COWPEA			MILLET	SORGHUM		SYSTEM MEAN WATER USE
	IT89KD-374	IT88D-867-11	DAN-ILLA	EX-BORNU	GAYA EARLY	ICSV 400	
SOLE COWPEA	191	204	188				*
SOLE MILLET OM+IF				258			*
SOLE MILLET (OM)				215			*
SOLE SORG. OM+IF					341	284	*
SOLE SORG. (OM)					303	251	*
M/C OM+IF	205		224	208			211
M/C (OM)	206		212	188			196
M/S/C OM+IF	224		229	215	345		339
M/S/C (OM)	186		214	197	332		332

Note: OM= Organic manure application only (pre-planting) 6t/ha

OM+IF= Pre-planting organic manure application plus top dress application of N.P.K fertilizer to cereal components.

* - Sole crops seasonal water use are shown below the columns under the name of crop variety.
M/C- Millet/cowpea intercrop
M/S/C- Millet/sorghum/cowpea intercrop.

manure alone was applied(251 mm). The late maturing sole Gaya Early at the two fertility levels also used 20% (OM+IF) and 21% (OM) more water than the early maturing improved ICSV 400 from planting to maturity.

The seasonal crop water use of millet in the intercropping systems varies slightly in relation to cropping systems and soil fertility levels (Table 4.19), but the former must be considered to be within the measuring accuracies. The seasonal water use of millet in the millet/sorghum/cowpea (OM+IF) was 215 mm, only 3.5% more than in the millet/cowpea intercrop. At the low fertility level (OM), seasonal water use was only 5% more in the millet in millet/sorghum/cowpea than the one in millet/cowpea. However, the fertility level influence are respectively 9% and 10.5% higher water use values at higher fertility level in millet/cowpea and millet/sorghum/cowpea systems respectively than their low fertility treatments. This would mean that millet in the millet/sorghum/cowpea intercrops had slightly more access to available soil water as a result of the lower density of the faster dry matter accumulating millet than in the millet/cowpea intercrops with double the millet density in millet/sorghum/cowpea intercrops. The sole millet (OM+IF), however, used 37% and 31% more water than the low fertility millet/cowpea and millet/sorghum/cowpea intercrops respectively, and also 24% and 20% more water than the high fertility millet/cowpea and millet/ sorghum/cowpea intercrops.

The Dan-illa cowpea water use at cropping system level was similar in the millet/sorghum/cowpea and the millet/cowpea intercrops within the measuring accuracies. The high soil fertility treatments also increased Dan-illa's water use by about 6% in the millet/cowpea intercrops, while the increase was about 7% in the millet/sorghum/cowpea intercrop. When compared with the sole Dan-illa, the water use in the intercropping situation was greater due to a combination of effects from plant density differences. It varies from 11% more in the lower fertility Dan-illa in millet/cowpea intercrop to 18% in the Dan-illa component of millet/sorghum/cowpea

(OM+IF). The differences between these values must be due to the side effect of the additional fertilizer application to the millet and sorghum components, the last difference being higher. The water use of cowpea grain type, IT89KD-374, in the two fertility levels of millet/cowpea intercrops was similar, and they were respectively 8% and 7% higher than in sole IT89KD-374, due to the combination of the efffects of plant density differences and additional fertilizer side effect. However, in the millet/sorghum/cowpea intercrops, the high fertility millet/sorghum/cowpea plots caused an increase in IT89KD-374 water use (224 mm) of 17% compared to the millet/sorghum/cowpea OM treatment (186 mm). The sorghum in the millet/sorghum/cowpea intercrops also experienced slightly higher water use ($\approx$ 4%) in the relatively high fertility treatment than in the OM treatments. However, this has to be viewed within the scope of the measuring accuracies.

While water use of millet sown sole at the two fertility levels was higher than in their corresponding fertility levels in the intercrops, as a result of the higher planting densities, the reverse was the case with the Dan-illa cultivar in sole and intercrop situation, where fertility levels and soil evaporation may have been involved respectively. The IT89KD-374, with the exception of the situation in the low fertility millet/sorghum/cowpea, used more water in the intercrops than when sown sole. The generally somewhat higher water use of the Dan-illa than the IT89KD-374 in intercropping indicates its better competitive ability for soil moisture and hence a better adaptation in cereal based intercropping systems.

A comparison of seasonal water use at the intercropping system level (Table 4.19, last column) shows that the millet/sorghum/cowpea used much more water than the millet/cowpea system. This was due to the later maturity of the sorghum

component in the millet/sorghum/cowpea system, hence more use of stored soil water, strengthened by the use of Gaya Early in the intercrop. Within the same cropping system, the high fertility millet/cowpea water use was 211 mm; 7% more than in the millet/cowpea intercrop with OM treatment (196 mm) (Table 4.19). However, in the millet/sorghum/cowpea intercrops, high soil fertility did not increase system water use over the relatively lower fertility treatment. While the effects of higher soil fertility on water use were not negligible (11-17%) in the sole cereal treatments, the effects in intercropping were lower and varied from only 2 to 7%. This suggests these intercropping systems at the farmers' level creates less demand and a better soil water use than in the sole crop situation.

4.8 Crop Root studies

4.8.1 *Image analyzer (Delta-T Root Length Measurement System) calibration*

The calibration of the automatic image analyzer using a cotton thread of accumulated lengths from zero to 120 cm yielded a curve that showed high statistical significance ($P < 0.001$) and accounted for about 96% of percentage variance. The calibration equation is

$$\text{Root length (cm)} = \text{Average count}/77.9 \qquad (4.2)$$

The calibration expression in equation 4.2 overestimates actual length measurements of 20, 40, 60, 80, 100 and 120 cm by about 37, 35, 24, 15, 8 and 2% respectively. A greater sensitivity to root length measurements was obtained by separating the

counts and actual length measurements into two; one comprising of the relationship between average counts and thread lengths from zero to 40 cm and the second of 60 to 120 cm thread lengths. The percentage of variance accounted for, in both cases improved considerably, to 99.9%. The relationship between the average counts from the image analyzer and actual thread length from 0-40 cm is represented by:

$$\text{Root length (cm)} = \text{Average count}/119.3 \qquad (4.3)$$

The equation slightly overestimate the actual length at 20 cm, by 3%, and is exact at 40 cm length. The relationship from 60-120 cm length is represented by :

$$\text{Root length (cm)} = \frac{(\text{Average count} - 2808.5)}{56.75} \qquad (4.4)$$

The difference between the measured and actual thread lengths from the relationship in equation 4.4 is less than 1%. Hence the two equations (4.3 and 4.4) were used based on the average counts recorded in the two directions of measurement, for the conversion of the average counts per root sample to actual root lengths during the three years of field experiments. For average counts less than 4770, equation 4.3 applied, while equation 4.4 was used for count values above 4770.

The root length density (RLD) in cm root per cm^3 soil was calculated for separate soil cores by Eq. 3.13. The treatment average of two replications was used for analyzing the root length densities and rooting depths at the different stages of crop growth considered in this section for the three years of data collection.

The root systems of millet, sorghum and cowpea sown sole and in the different intercropping systems, were compared at 4 WAS in 1993 and 1994, while in 1995 it was at 6 WAS, and in periods between the commencement of their reproductive stages, when crops had achieved their maximum LAIs and highest root development potentials and grain filling.

4.8.2 *Crops root growth*

4.8.2 (a) *1993 cropping season*

In 1993 only the roots of sole crops were sampled. Root sizes were also not differentiated in the results presented in this section. The mean root length densities of two replicate plots were calculated for separate soil layers and used to map root distribution within the soil profile. The RLD distributions per plant hill to the rooting depth in relation to crop orientation, and the two stages of growth are shown in Figures 4.58-4.63.

During the season, the first root sampling at 4 WAS excluded areas directly below plants and indicates that the root distribution type of each crop showed differences, which were also dependent on the crop genotypes. The RLD values also vary with directions and distances away from the plant stand. The highest root length densities were measured in the 0-20 cm soil depth in the lateral furrow to furrow directions, below the cereal crops. The maximum RLD values for the surface (0-20 cm) layers varied from 0.2 to 0.35 cm cm^{-3} for millet, 0.1 to 0.3 cm cm^{-3} for ICSV 400 and 0.15 to 0.40 cm cm^{-3} for Gaya Early sorghum varieties and 0.05 to 0.25 cm cm^{-3} for the cowpea varieties. The RLD values of the cereal were consistently higher than those of cowpea.

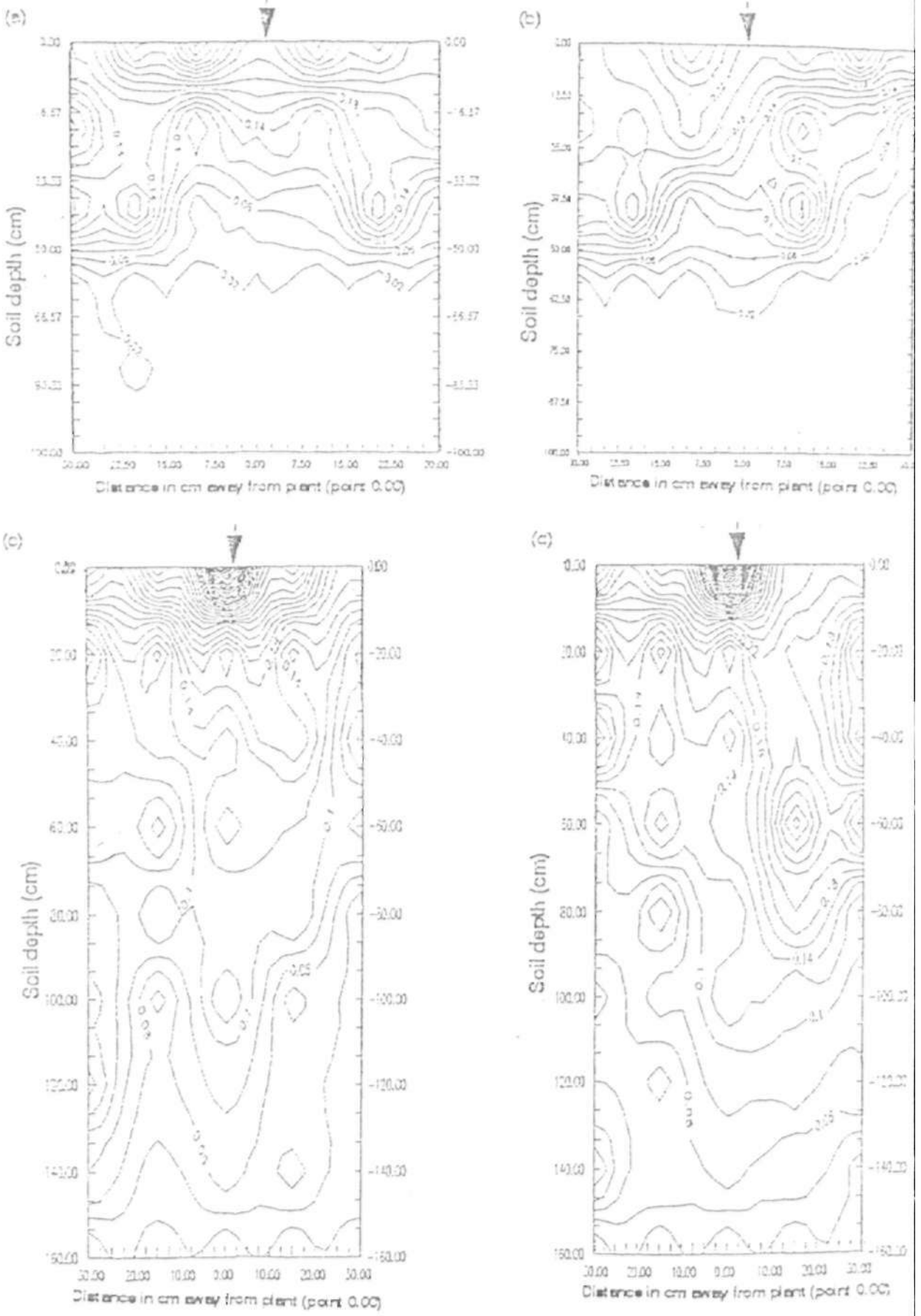


Fig. 4.58. Root distribution under sole millet at 4 WAS (a & b) and at panicle initiation, 10 WAS, (c & d) during 1993 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant.

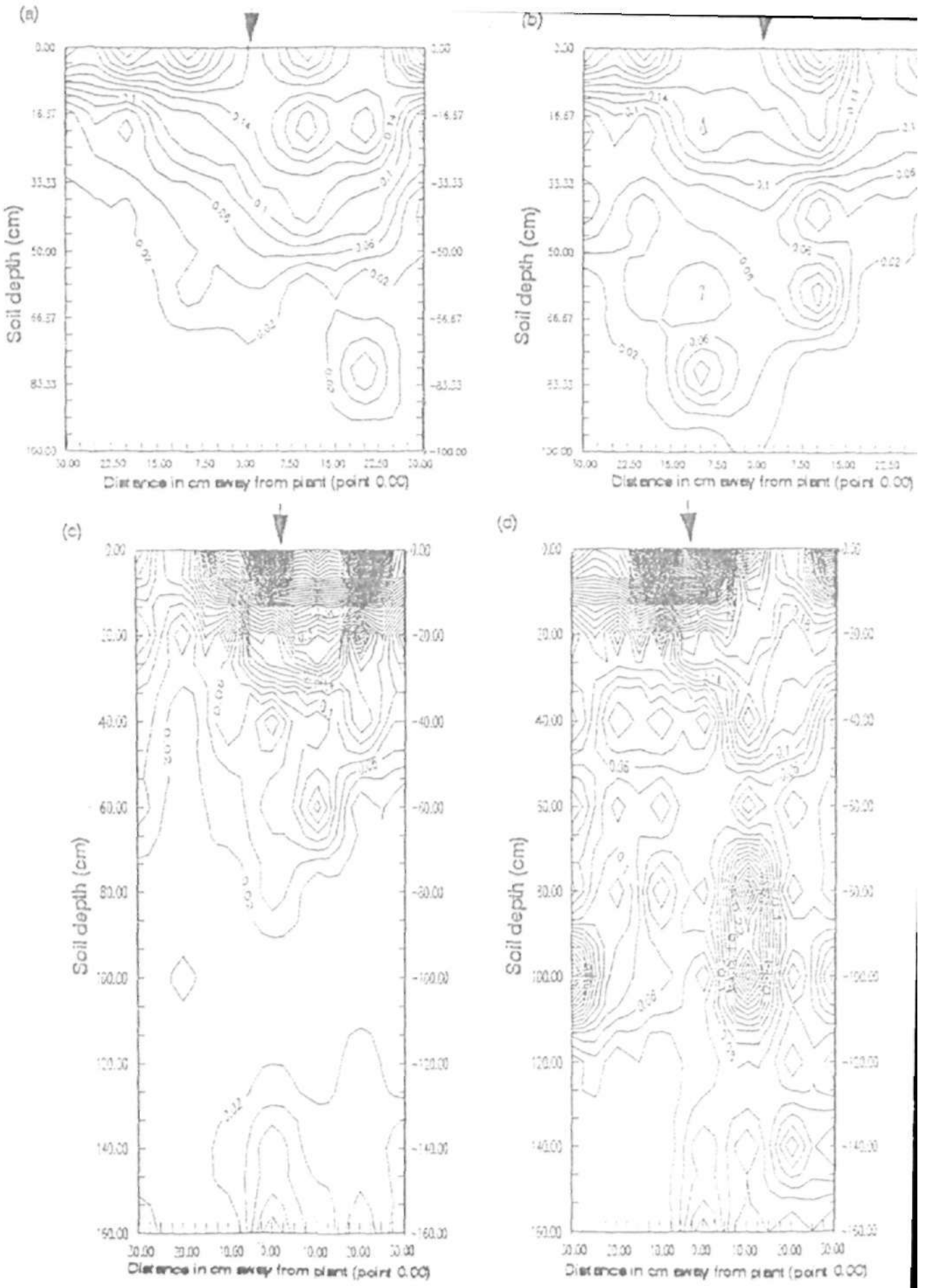


Fig. 4.59. Root distribution under sole sorghum (ICSV 400) at 4 WAS (a & b) and at head formation, 12 WAS (c & d) during 1993 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant.

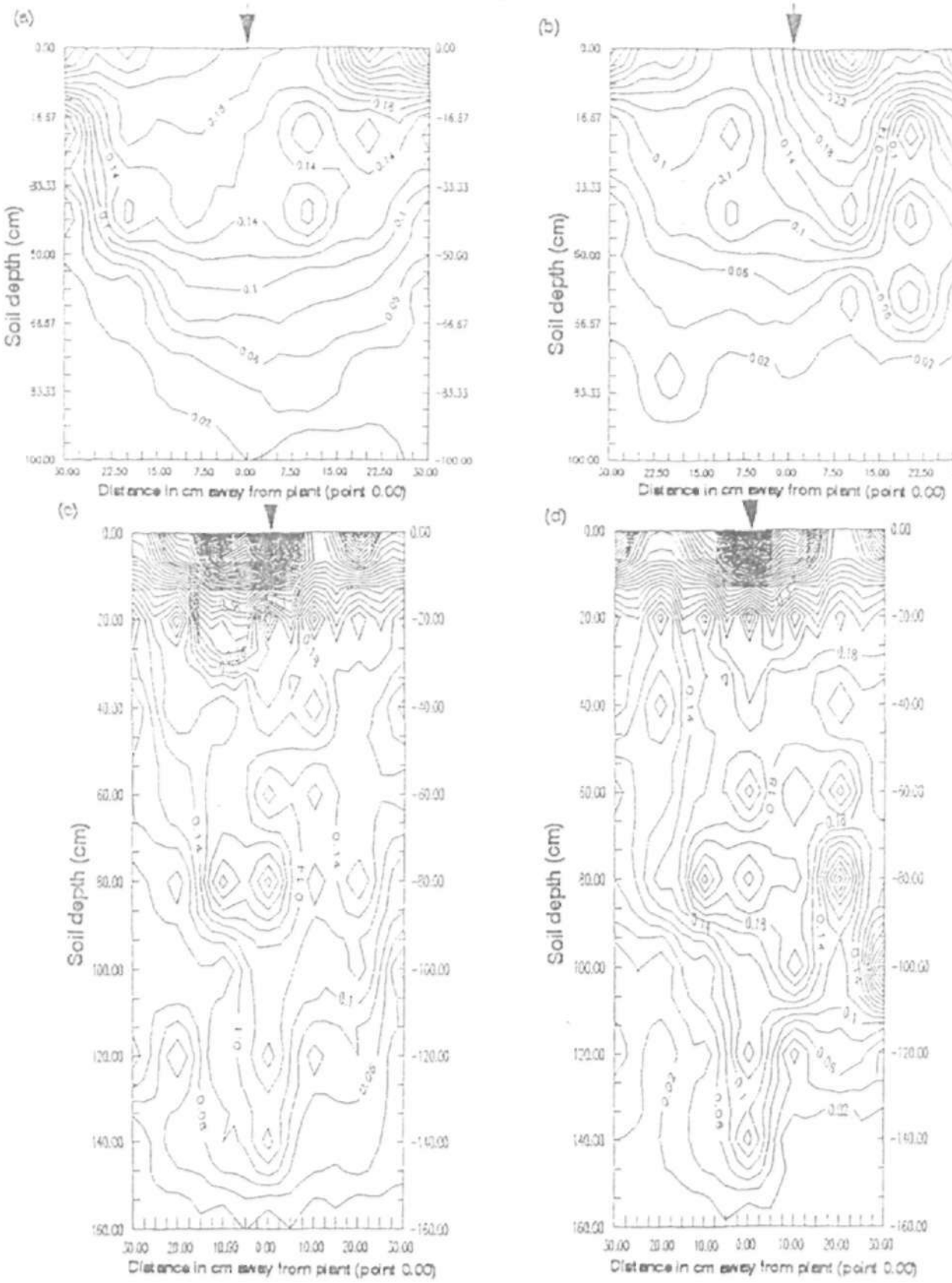


Fig. 4.60. Root distribution under sole sorghum (G. Early) at 4 WAS (a & b) and at head formation 12 WAS (c & d) during 1993 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant. Arrows indicate the position of the plant.

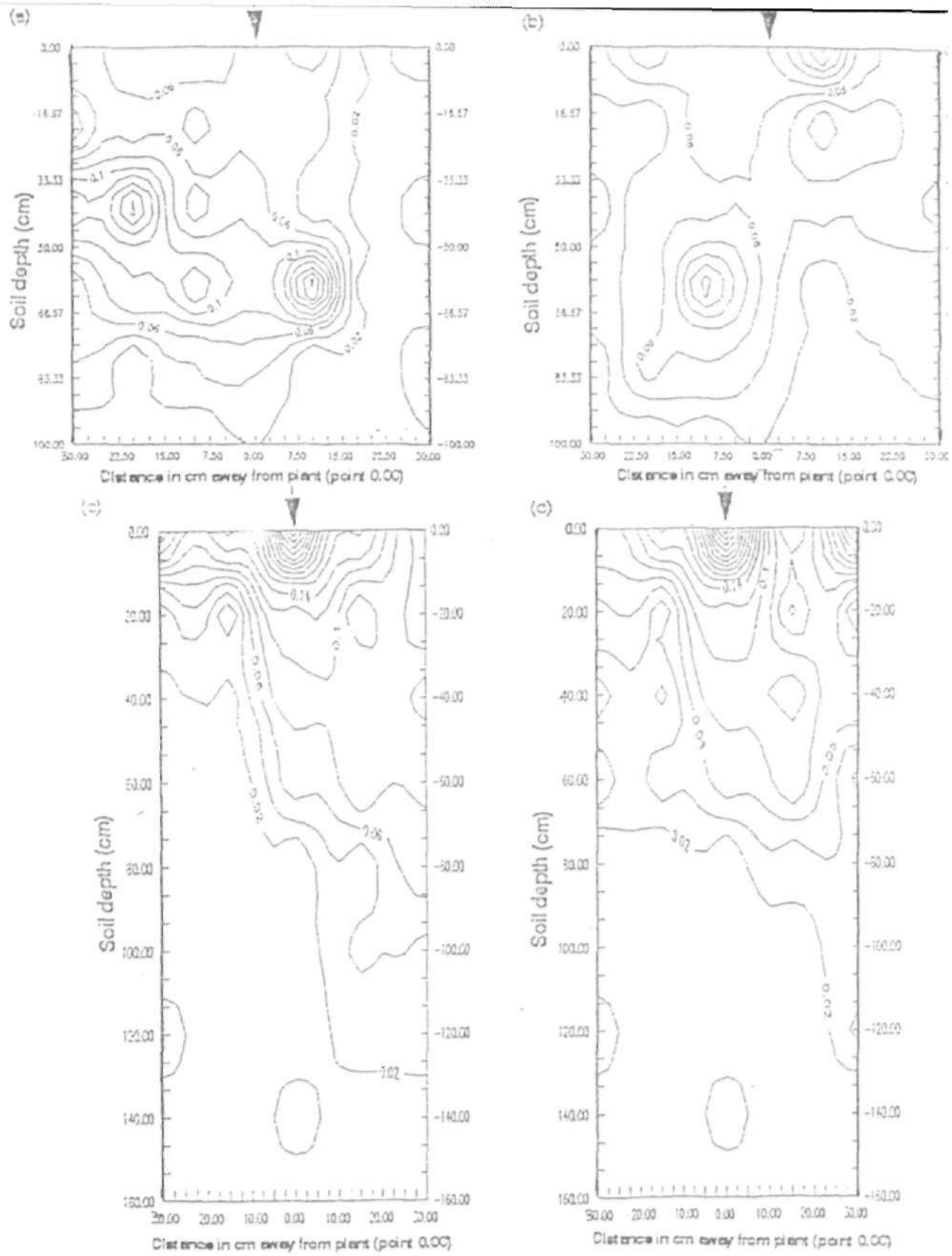


Fig.4.61. Root distribution under acid cowpea (IT86D-719) at 4 WAS (a and b) and at flower initiation 5 WAS (c and d) during 1993 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant.

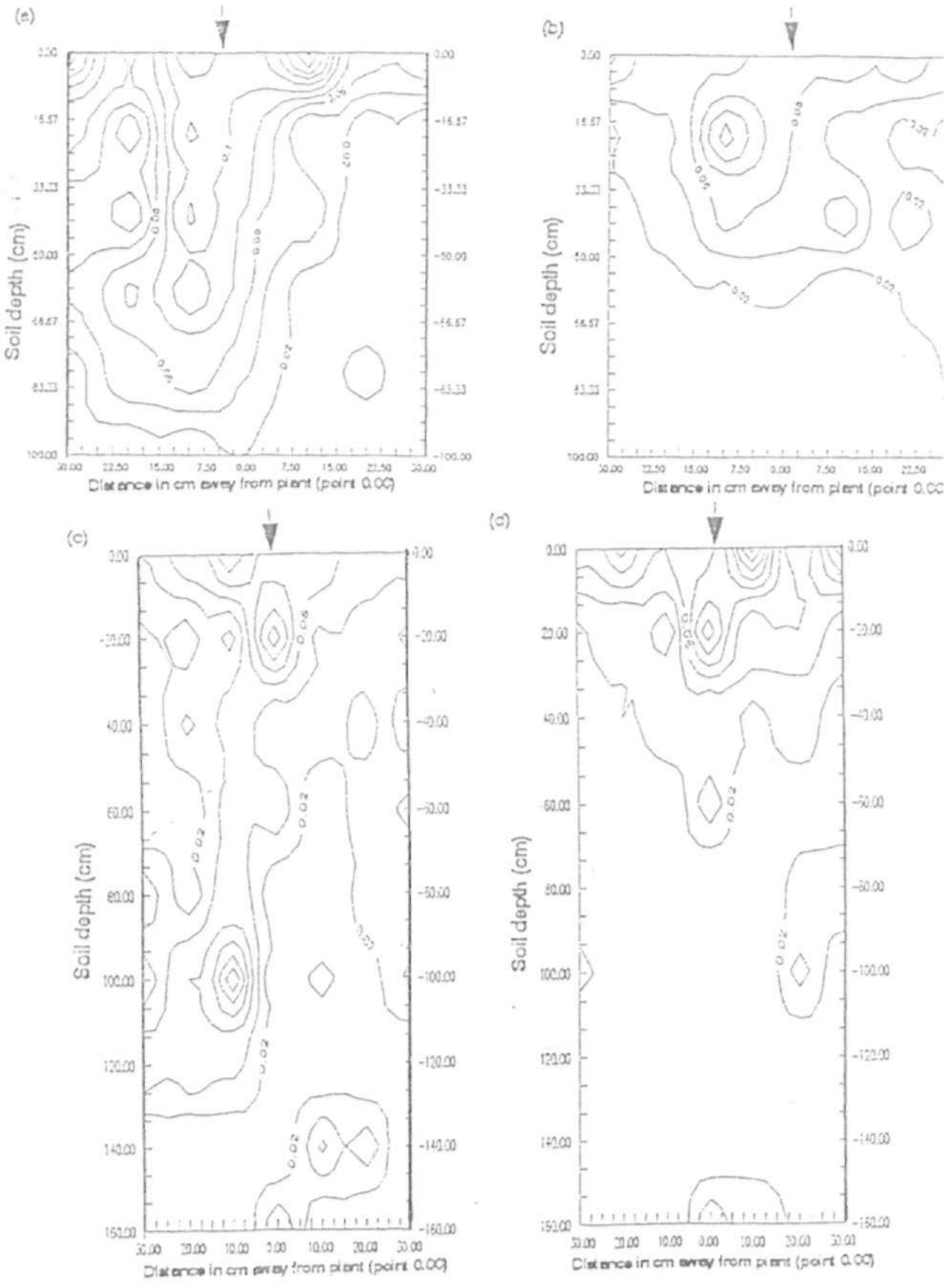


Fig. 4.62. Root distribution under sole cowpea (IT89KD-374) at 4 WAS (a & b) and at flower initiation, 7 WAS, (c & d) during 1993 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant

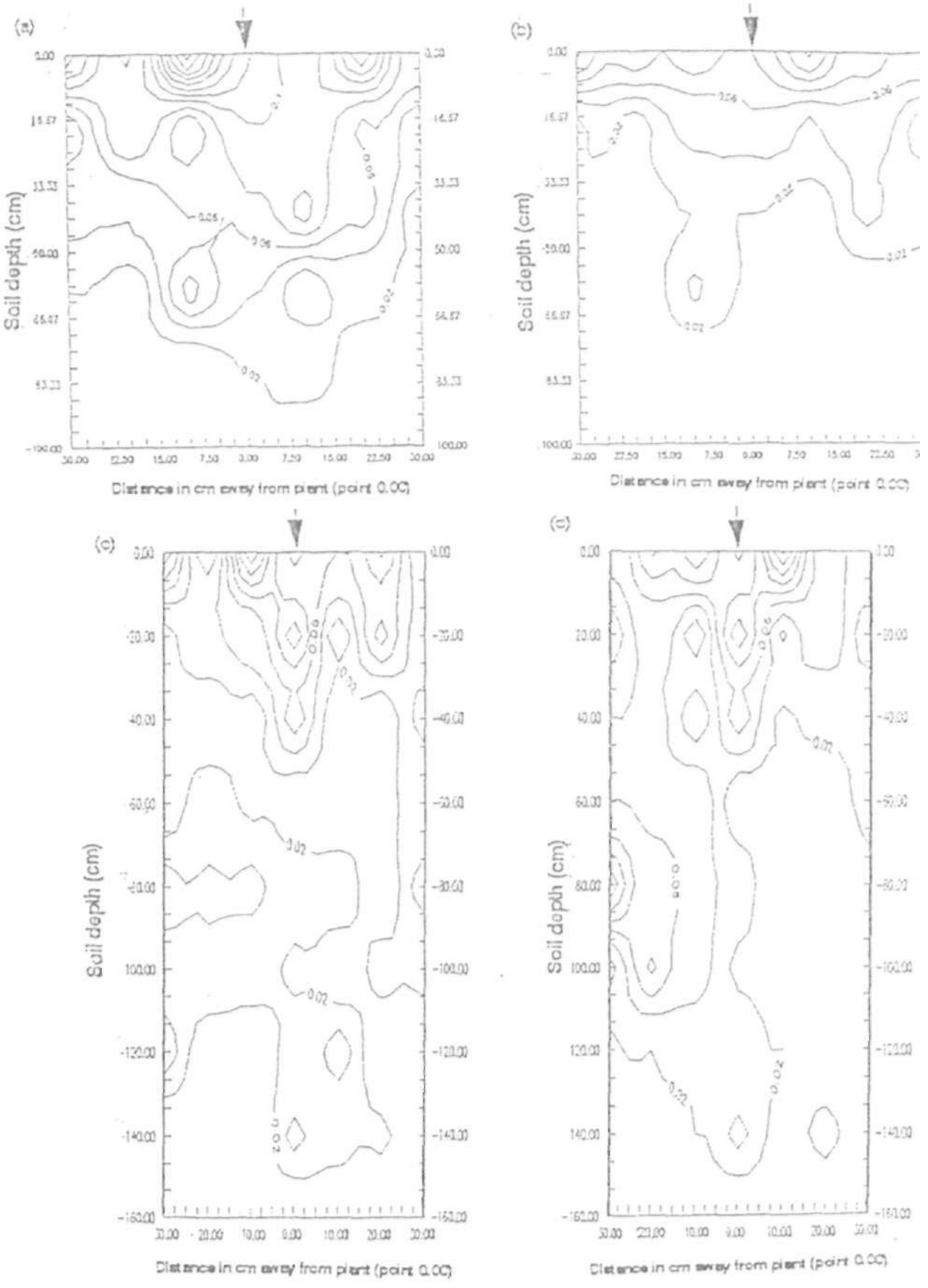


Fig. 4.63. Root distribution under sole cowpea (Dan Illa) at 4 WAS (a & b) and at flowering, 10 WAS, (c & d) during 1993 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant.

Although differences are rather small at first sampling, among the sole cereals systems, millet produced somewhat greater RLD directly below plants in the soil surface layers (0-20 cm). RLD in the Gaya Early had high densities somewhat more away from the plant in the furrow to furrow (A-C) direction and on the ridge (B-D direction) than ICSV 400 sorghum and millet down to the depth of measurement (Figs. 4.58a and b, 4.59a and b, and 4.60a and b). While millet and sorghum cultivar Gaya Early both showed similar root spread and rooting depth in the A-C and B-D direction below the crops, the root distribution and depth of the ICSV 400 sorghum cultivar was less uniform and deeper below the ridge (B-D direction) than in the furrow to furrow direction. The higher root densities under the millet and Gaya Early sorghum cultivar and the greater lateral spread for Gaya Early indicate well-ramified rooting systems for greater exploitation of soil resources.

Among the sole cowpea systems, the erect and early maturing grain cowpea variety, IT86D-719, showed a better root spread and higher RLD below the surface soil layers (0-20 cm) than the semi erect medium maturity IT89KD-374 and the prostrate, relatively later maturing and most vegetative (of the three varieties) cowpea, Dan-illa. The root distributions, inferred from the RLD in the furrow to furrow (A-C) directions, were higher, and also deeper down the soil profile than were observed in the B-D directions, below the ridge for the three cowpea types (Figs. 4.61a and b, 4.62a and b, and 4.63a and b).

The second root sampling, at the commencement of crops reproductive stages, indicates that roots continued to penetrate deeper horizons. Roots were observed below 1 m depth under the plant hill, but the RLDs were much greater in the cereals than in the cowpea varieties, where they were negligible and close to zero below 1m

depth (Figs. 4.58c and d, 4.59c and d, 4.60c and d, 4.61c and d, 4.62c and d, 4.63c and d). The deep sandy soil of the experimental plot, with the bulk density of 1.45 ± 0.06 g cm^{-3}, varying very little with depth, facilitated the growth and penetration of roots down the profile without much restriction and in the absence of other limiting factors, such as soil compaction and high water table among others.

The root distribution among the cereal crops, at the start of reproductive stage, indicates high root densities in the top layers (0-20 cm) of the soil, below the plant. The lateral spread of roots in these layers were relatively uniform below the furrow and ridge directions, but were greater under the sorghum varieties than the millet (Fig. 4.58c and d, 4.59c and d and 4.60c and d). The greatest RLD of millet at panicle initiation (0.75 cm cm^{-3}) was recorded directly below the plant hill, decreasing in all directions away from the plant. Root densities under the ICSV 400 at head formation were greatest directly below the plant (1.15 cm cm^{-3}), and slightly higher in the lateral directions below the furrow directions than under the ridge (Fig. 4.59a and b). The same trend was observed with Gaya Early, which also produced the greatest RLD (1.2 cm cm^{-3}) below plant hill (Fig. 4.60a and b). Gaya Early, of the two sorghum varieties, appears to show more decrease in RLD away from plant. At the depths between 40 and 80 cm under millet, and extending to 120 cm under sorghum, the root densities between plants at positions B to D (under the ridge) tended to be higher at farther points of sampling than at the centre of plants. This indicates the spread of the cereal fibrous root system and/or the intermingling of the roots of neighbouring plants on the ridges (Fig. 4.58c and d, 4.59c and d and 4.60c and d). Lower root length densities were observed at corresponding depths below the furrows. Differences in nutrient status of the soil may be responsible for this trend.

The vertical distribution of roots shows that millet and sorghum (Gaya Early) roots extended to 160 cm depth below the crops in all directions in contrast to sorghum variety ICSV 400, with a similar root depth below the ridge (B-D direction), but shallower rooting depths in the furrow directions.

The lateral and vertical distribution of roots under the sole cowpea systems at flowering are shown in Figs. 4.61c and d, 4.62c and d and 4.63c and d. The root systems among the three sole cowpea treatments showed some differences in their spread and rooting depths. The maximum RLD values for the upper layer (0-20 cm) at flowering varied from 0.10 cm cm^{-3} under Dan-illa to 0.35 cm cm^{-3} under IT86D-719. The grain cowpea variety, IT86D-719 showed a higher amount of roots decreasing laterally away from the centre than under the semi erect IT89KD-374 and the prostrate and more vegetative Dan-illa. The rooting density under IT86D-719 showed a uniform decrease down the soil profile in the directions between the centre of the plant (O) and C (furrow) and D (ridge) i.e. the right angle triangle represented by directions DOC, down to about 1.3 m depth, which indicated the depth of the tap root systems (Fig. 4.61c and d).

However, under the IT89KD-374 and Dan-illa cowpea varieties at flowering, marked differences were apparent between the different sampling positions and the rooting depths. The root densities in positions below the furrows in the surface layer (0-20 cm), tended to be lower than under the ridge surface layer for IT89KD-374 (Fig. 4.62c and d), while under Dan-illa, there were less marked difference in lateral roots distribution between the furrows and ridge directions. The greatest root densities at the surface layer were also recorded at distances away from the centre of the plant. Dan-illa showed better surface soil root distribution than IT89KD-374 at flowering,

particularly in the furrow directions. The vertical root distribution and rooting depth of IT89KD-374 below the furrow directions (Fig. 4.62c) was greater and deeper than was observed below the ridge (Fig. 4.62d), while for the Dan-illa, it was relatively uniform to about the same soil depth. This indicates a better root distribution of Dan-illa than of IT89KD-374, suggesting a better ability of Dan-illa to use soil available resources, especially water, in deeper soil horizons, although some other genetic traits in Dan-illa may have contributed to its adaptation and wide acceptance by farmers in semi-arid and arid Nigeria.

4.8.2 (b) *1994 cropping season*

The root sampling during the 1994 season, in addition to the sole cropping systems, also included those from the different intercropping systems at the two fertility levels adopted.

In the sole cropping systems, the coefficient of variation (CV) resulting from the root sampling method varied from 12% in the surface layers to > 100% in the lower depths of sampling. The variability in RLD data directly below plants was relatively lower than at depths further down the soil horizon. The CV at the surface layers varied from 12% to 76%, increasing with distances farther away from the centre of the plants.

In the intercropping systems, CVs were still higher and varied widely (20-150%). Such a high CV range suggests that the greater part of the total (random) variation represents a high degree of scatter in root distribution, that may be caused by the response of roots to the high spatial variability of soil factors. The

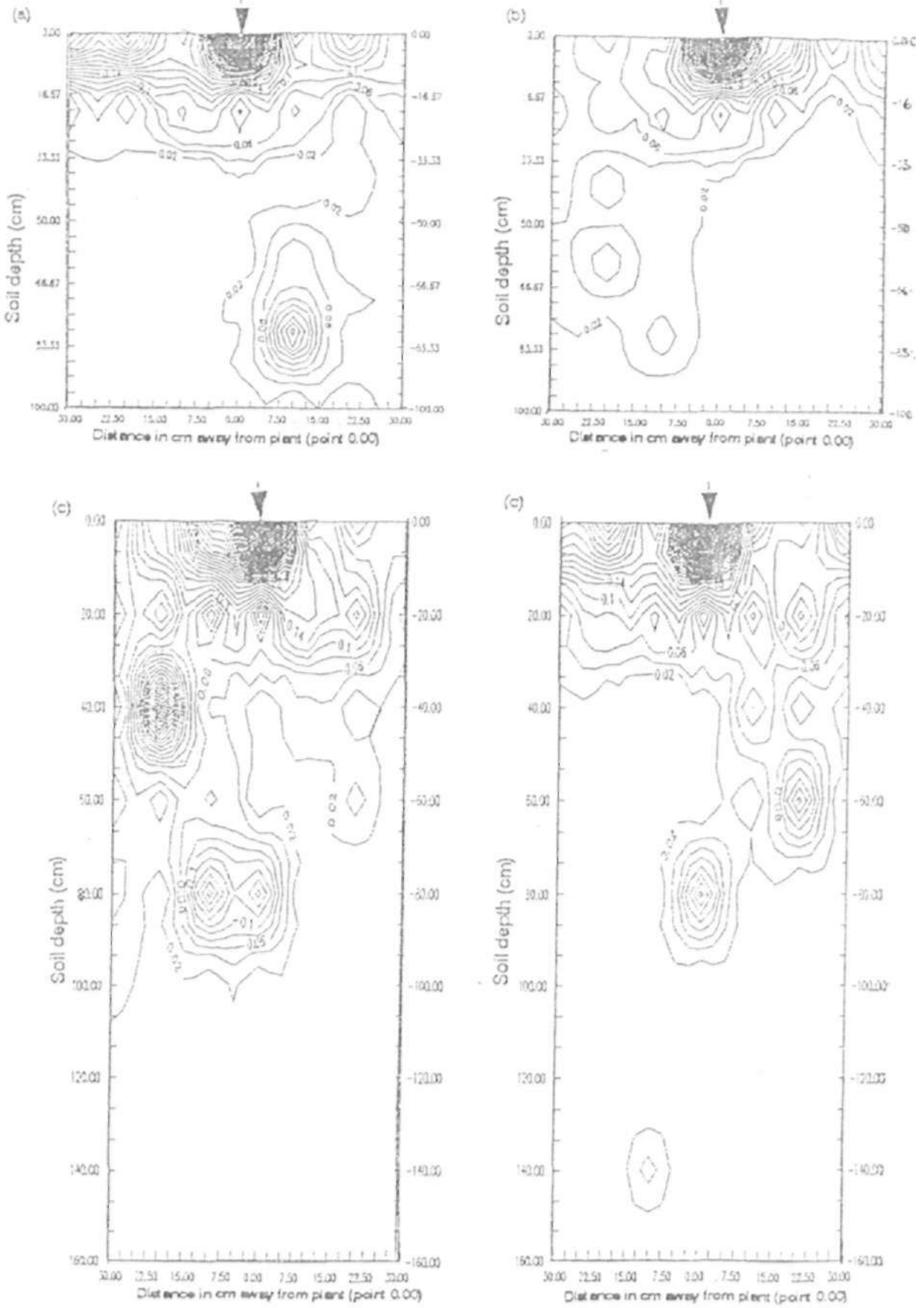


Fig. 4.64. Root distribution under sole millet at 4 WAS (a & b) and at panicle initiation, 8 WAS, (c & d) with organic manure application alone during 1994 cropping season. (a) and (b) are directions from furrow to furrow (i.e. position s A to C), while (b) and (c) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant.

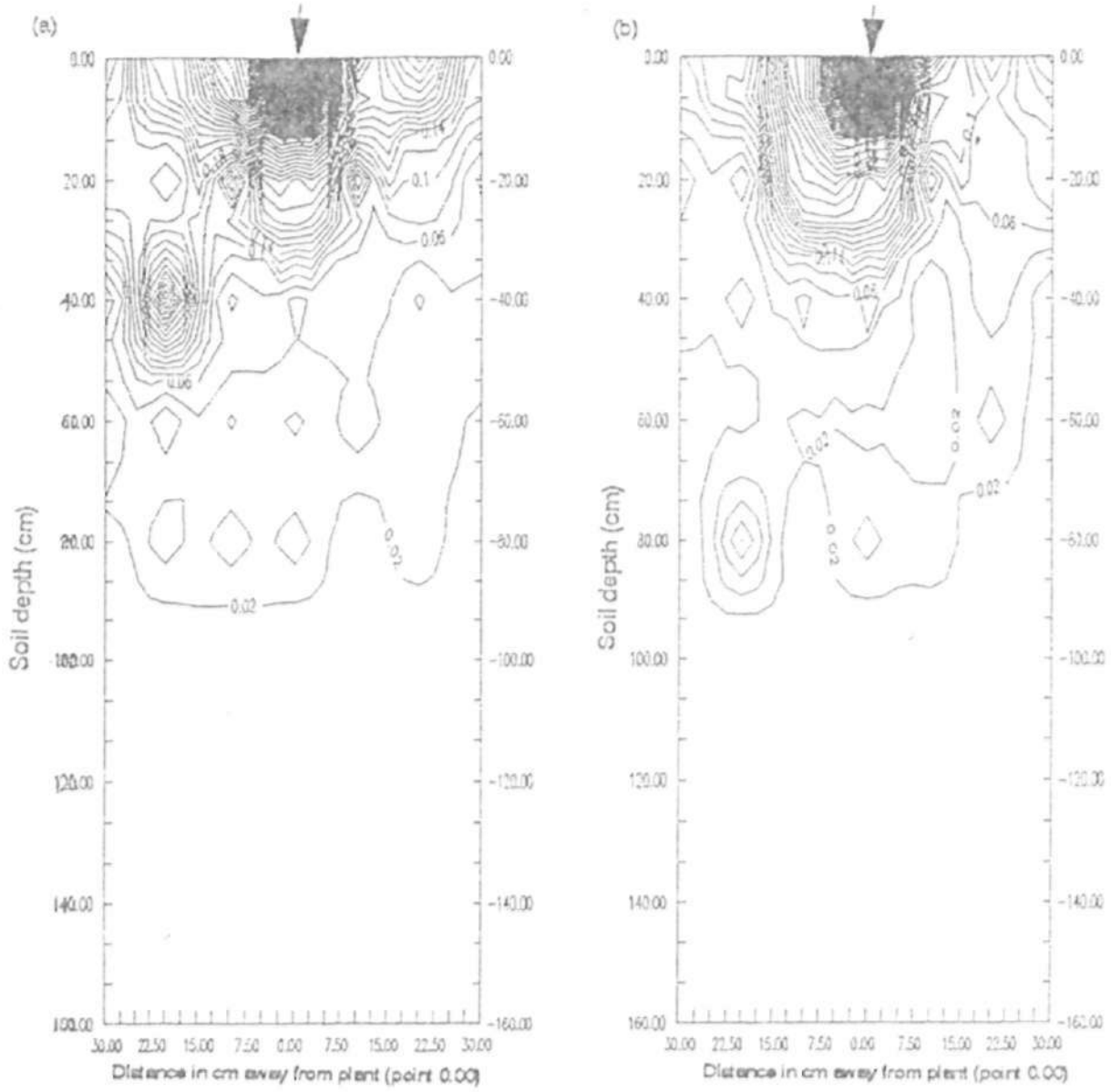


Fig. 4.65. Root distribution under sole millet at panicle initiation, 8 WAS, (a and b) , with additional inorganic fertilizer application , 6 WAS during 1994 cropping season. Arrows indicate the position of the plant.

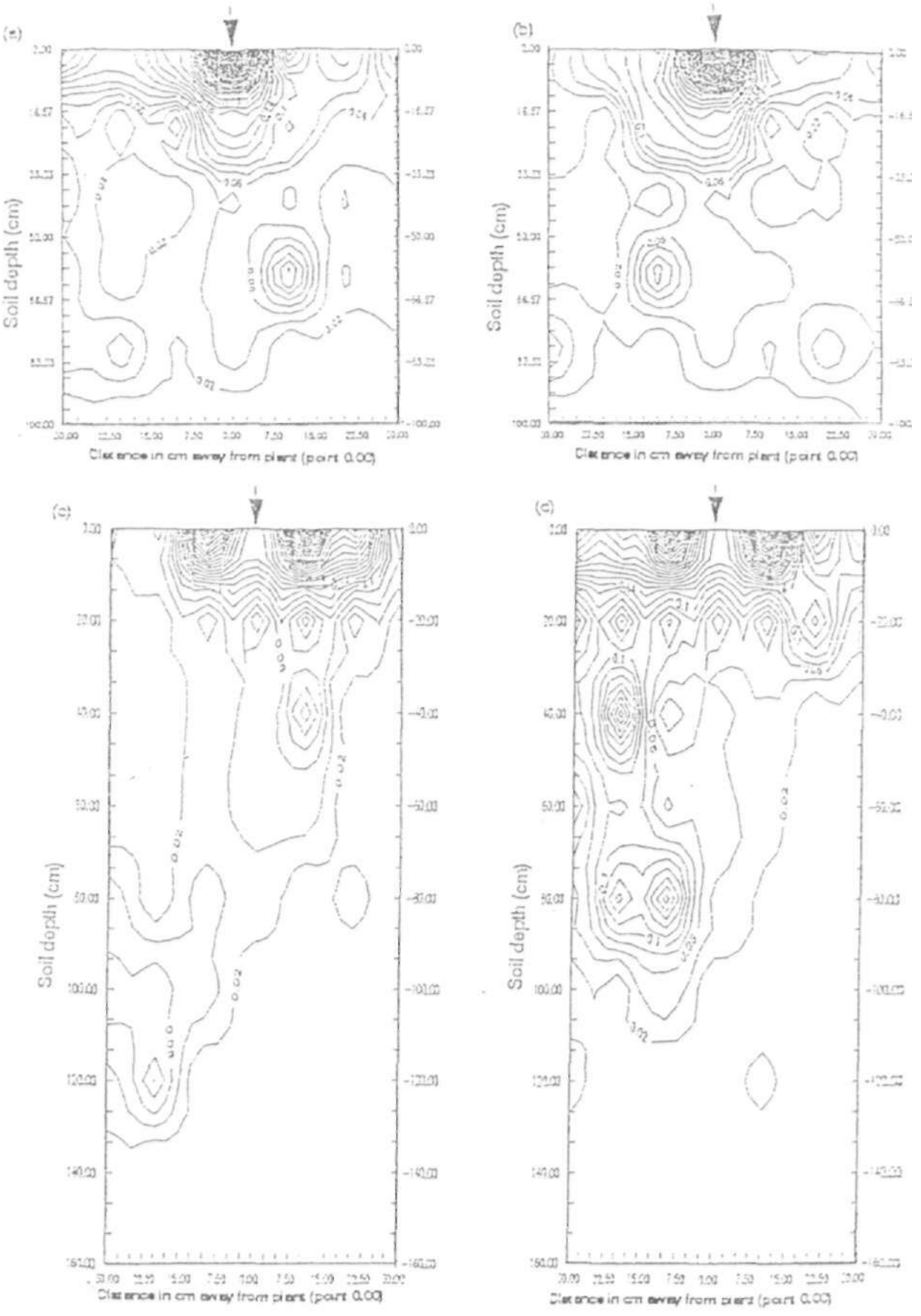


Fig. 4.66. Root distribution under sole sorghum (ICSV 400) at 4 WAS (a & b) and at head formation, 12 WAS (c & d) with organic manure application alone during 1984 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant.

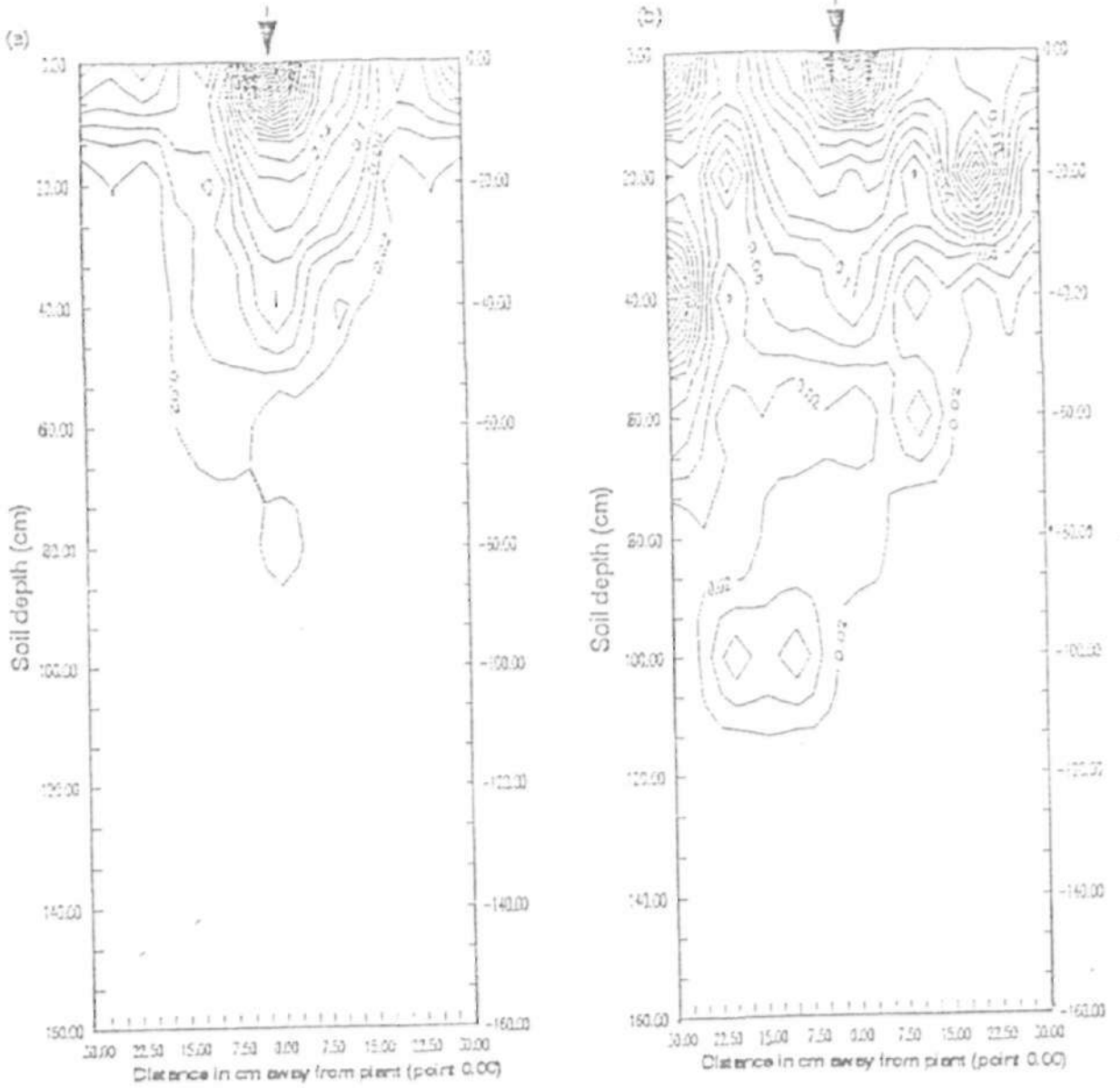


Fig. 4.67. Root distribution under acla sorghum (ICSV 400) at head formation, 12 WAS (a & b) with additional inorganic fertilizer application , 10 WAS during 1984 cropping season. Arrows indicate the position of the plant.

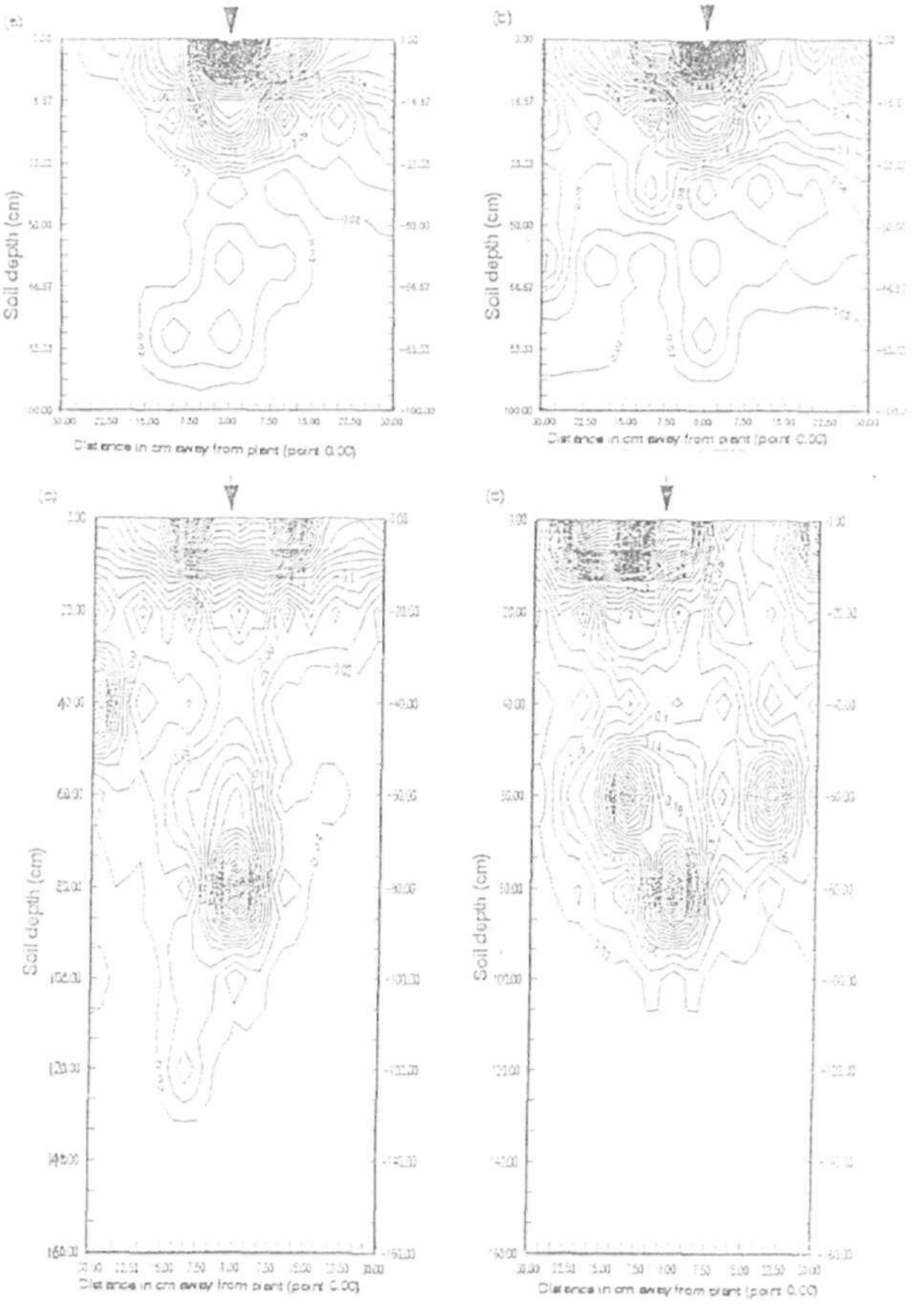


Fig.4.68. Root distribution under sole sorghum (G.Early) at 4 WAS (a and b) and at head formation, 12 WAS (c & d), with organic manure application alone during 199[illegible] cropping season. (a) and (c) are directions from furrow to furrow (i.e. [illegible]ons A to C), while (b) and (d) are directions on the ridge (i.e. positions [illegible]). Arrows indicate the position of the plant.

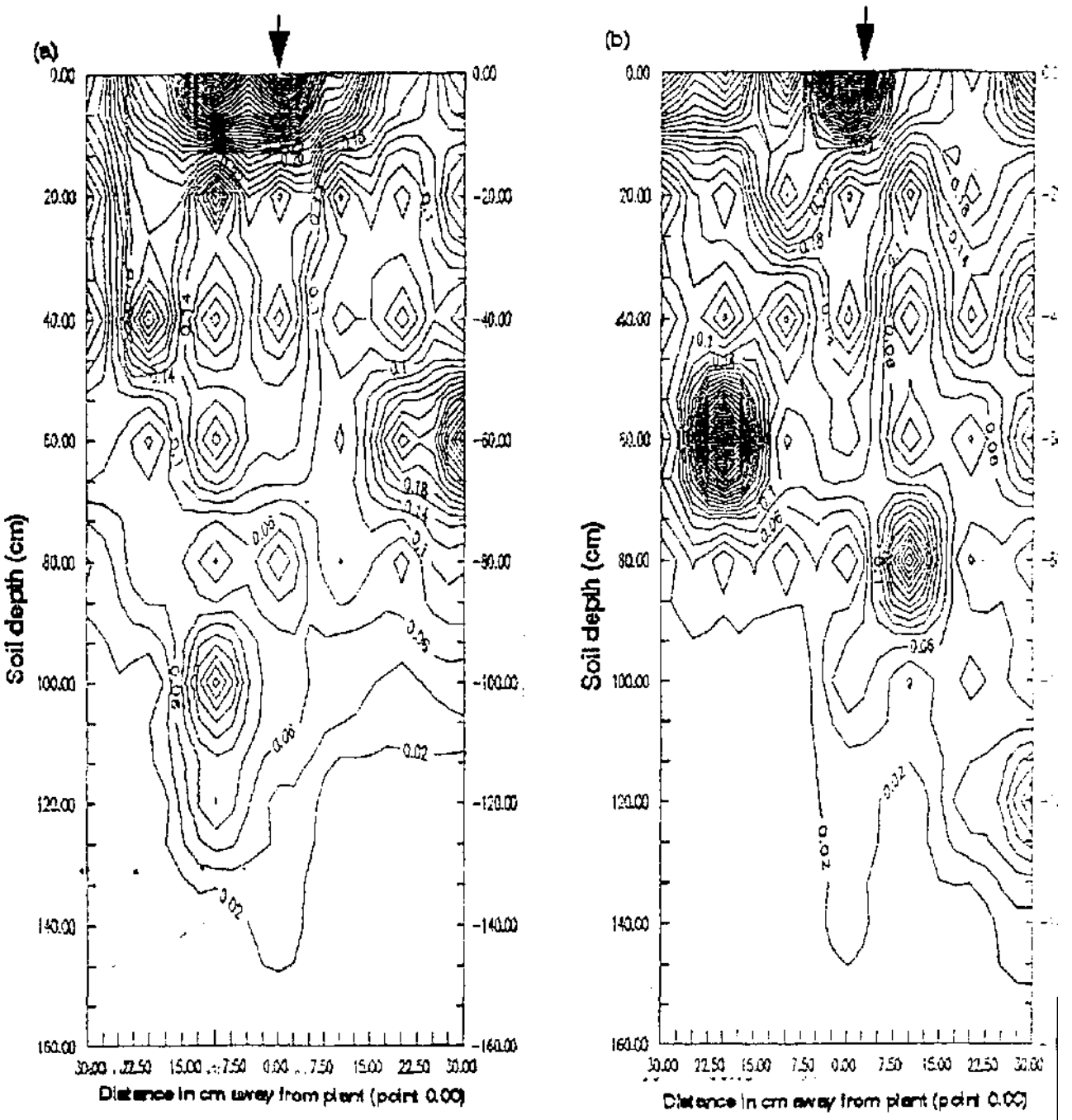


Fig. 4.69. Root distribution under sole sorghum (G.Early) at head formation, 12 WAS (a & b) with additional inorganic fertilizer application , 10 WAS during 1994 cropping season. Arrows indicate the position of the plant.

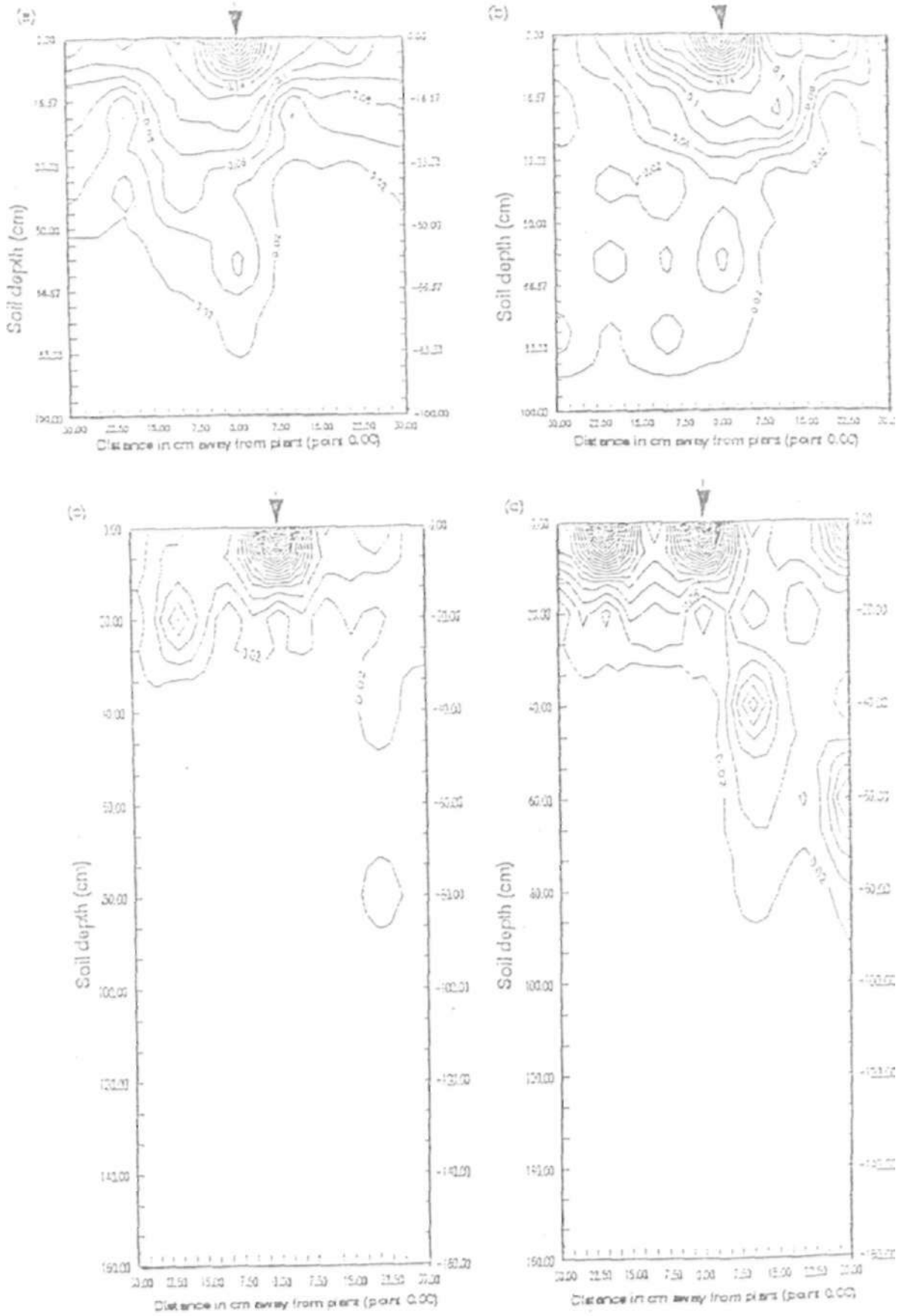


Fig. 4.70 Root distribution under sole cowpea (IT86KD-374) at 4 WAS (a & b) and at flower initiation, 7 WAS, (c & d) during 1984 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plants

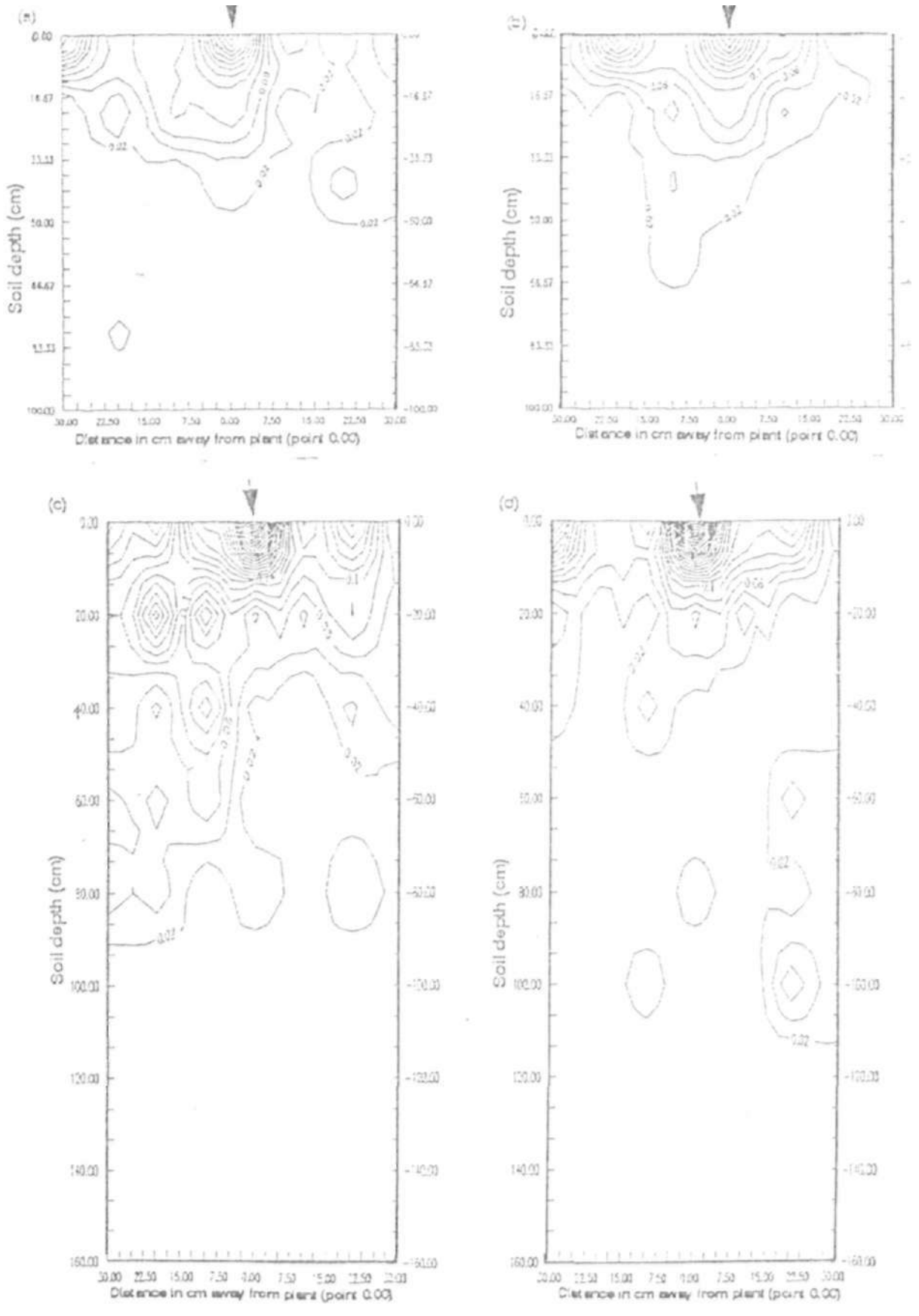


Fig. 4.71. Root distribution under sole cowpea (Dan illa) at 4 WAS (a & b) and at flowering, 10 WAS, (c & d) during 1994 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant.

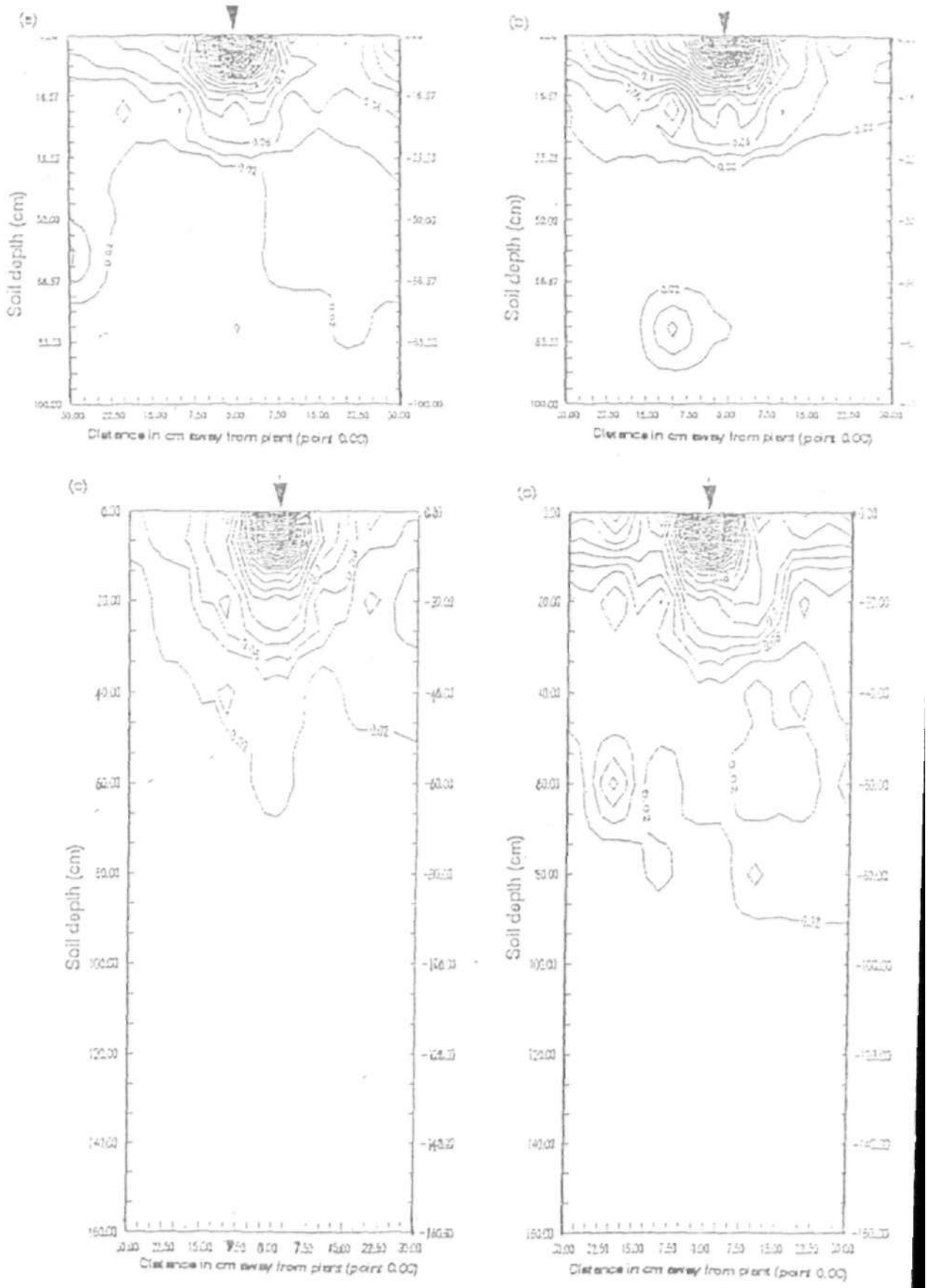


Fig. 4.72 Root distribution under sole cowpea (IT82D-867-11) at 4 WAS and at flower initiation, 6 WAS (c & d) during 1994 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant.

concentrations of soil nutrient ions (Drew, 1975; Vos and Groenwold, 1986), pore size distribution and rigidity (Hamblin, 1985), and soil water availability (Hamblin and Tennant, 1987) are some of such factors known to have some effects on root morphology and branching pattern. The practice of ridging heavily contributes to the variations concerned.

In the sole cropping systems, crop root distribution at the first sampling (4 WAS), indicates maximum RLD values for the upper surface layer (0-20 cm), with highest values obtained directly below plant stands and decreasing with distance from the centre of the plant (Figs. 4.64a and b, 4.66a and b, 4.68a and b, 4.70a and b, 4.71a and b and 4.72a and b). The mean maximum RLD of the cereals varied from 0.70 cm cm^{-3} below ICSV 400 sorghum and 1.1 cm cm^{-3} under millet to 1.3 cm cm^{-3} below the Gaya Early sorghum variety. These values were consistently higher than the maximum RLDs of the cowpea varieties (0.3 cm cm^{-3} for Dan-illa to 0.65 cm cm^{-3} for IT88D-867-11). The differences in RLD between the cereals and cowpea varieties were more evident in the upper layer (0-20 cm) than at lower soil depths, at this first sampling. The highest RLD among the cereals (1.3 cm cm^{-3}), observed directly below sorghum variety Gaya Early, was consistent with that of 1993. Among the cowpea varieties, the determinate and earlier maturing grain type cowpea variety, IT88D-867-11, produced higher RLD than the semi-erect and later maturing IT89KD-374 and the prostrate and most vegetative Dan-illa cowpea, that is latest in maturity of the three cowpea varieties.

The RLDs trend in 1994 was IT88D-867-11 > IT89KD-374 > Dan-illa. This is also in agreement with the cowpea varietal growth habit trend observed in 1993. The lateral distribution of roots in the upper layer (0-20 cm), among the sole cereals,

was denser in the furrow to furrow directions below the millet and ICSV 400 sorghum cultivar, particularly away from the centre, than under the directions below the top of the ridge (Fig. 4.64a and b and 4.66a and b). This probably was in response to more competition for resources by crops within rows, resulting from greater interference by roots of adjacent crops as against within the wider locations between the ridges. However, under the Gaya Early sorghum, where root densities were generally higher than in other cereals, RLDs were slightly more densely distributed laterally below the ridge than in the furrow directions (Fig. 4.68a and b), reflecting a better ramification of roots for soil resources exploitation. The vertical distribution of roots below the upper layer shows lower RLDs for both the cereal and cowpea crops down the soil profile, but some a bit more dense spots are found under millet and ICSV 400 sorghum, for millet in the furrow direction, close to the centre and even an important cluster at depths near the last measurement point. Indeed, the sorghum varieties displayed at these lower depths a broader spread of roots below plants than millet. Among the cowpea varieties, the lateral distribution in the surface layer (0-20 cm) indicates a decrease in RLDs in all directions at distances away from the plant in the improved cowpea varieties (IT88D-867-11 and IT89KD-374), while with the farmers' variety (Dan-illa), high RLDs were also found at points away from the centre of the plant. IT89KD-374 showed a better vertical distribution and spread to the depth of measurement (100 cm) than Dan-illa and IT88D-867-11 (Fig. 4.70a and b, 4.71a and b and 4.72a and b).

The distribution and amounts of rainfall during the different crop's reproductive stages in 1994 ensured that soil available water was always about field capacity and hence the availability of enough soil moisture at relatively shallow soil

depths. The rooting depths of different crops also differ as a result of the difference in the rate and duration of descent of the leading roots in relation to their growth duration. The rooting depths of the various crops were generally shallower in 1994 than was observed in 1993, when soils under crops were not as wet. The root distribution and rooting depths in 1994 showed that the bulk of the roots were restricted to the top 100 cm under millet, cowpea varieties IT88D-867-11 and IT89KD-374 and 120 cm under the later maturing sorghum varieties (Gaya Early and ICSV 400) and Dan-illa cowpea. This differs from the observed trend in 1993, when rooting depths were deeper ($\approx$ 160 cm). The restricted root penetration at the mentioned depths, in 1994, suggests aeration decrease caused by the reduction of air-filled pore space, critical to the oxygen status of roots under a saturated soil water condition (Greacen *et al.*, 1968). The high soil water table resulting from the increase in water volume within the adjacent Jankara lake (300 m from trial plot) must have also aggravated this condition. This seems to agree with the observation that roots usually descend faster in unsaturated than in very moist soils (Squire, 1993).

The root distribution of millet, sorghum and cowpea varieties during their reproductive stages show marked differences. Soil fertility treatments also affected the RLDs and rooting depths in the different soil horizons among the cereals. Relatively higher RLDs were observed in the surface soil layer (0-20 cm), especially directly below millet at the two soil fertility levels and under the two sorghum varieties (Gaya Early and ICSV 400) that received the additional inorganic fertilizer at 10 WAS. The exception were the two sorghum varieties under organic manure application alone that showed voids (ICSV 400) and lower densities immediately below the plants. High root densities were also observed at depths below surface layers, especially in plots with

pre-planting organic manure application alone for millet and the Gaya Early sorghum variety (Fig. 4.64c and d, 4.68c and d). In the sole millet treatment, the application of top dress inorganic fertilizer at 6 WAS resulted in even higher proportions of RLDs in the top 0-40 cm soil layer than was observed under plots with pre-planting manure application alone (Fig. 4.64c and d and 4.65a and b). RLDs below the centre of millet with relatively higher soil fertility was 1.95 cm cm^{-3}, while a 40% lower value was observed under the millet (1.15 cm cm^{-3}) with pre-planting organic manure application alone. However, at millet maximum rooting depths (< 100 cm depths), root densities below the relatively low fertility millet plots were higher than under the high fertility plots (Fig. 4.65c and d and 4.66a and b). A comparison of the two sorghum varieties showed that high RLDs were present at the soil surface layer (0-20 cm), but as indicated already, these root densities were higher at some points away from the centre of the plant than in positions directly below the plant, in the relatively low fertility plots. On the contrary, points directly below plants in the higher fertility soil had greater RLDs than at distances away from the centre of the plant (Fig. 4.66c and d, Fig. 4.67a and b, Fig. 4.68c and d and Fig. 4.69a and b). The side placement of NPK fertilizers to the sorghum stands influenced the proliferation of roots directly below plants and hence the higher RLDs than in distances away from the plant. The spread of roots and their densities below the plant hill were also higher under Gaya Early than with ICSV 400 at the two fertility levels. Gaya Early at the relatively high soil fertility developed denser roots and achieved much deeper rooting depth than the low fertility Gaya Early and ICSV 400 at the two fertility levels, and more so in the direction of the ridge. Sorghum variety Gaya Early hence has a greater capacity to develop a dense network of roots to penetrate and extract water and nutrients from

subsoils, when soil fertility level is adequate and make use of excess soil moisture for growth and development better than ICSV 400 and millet.

A comparison of the sole cowpea systems at flowering stages indicates that Dan-illa had comparatively more roots below 20 cm than IT89KD-374 and IT88D-867-11, but these amounts remained small (Fig. 4.70c and d, Fig. 4.71c and d and Fig. 4.72c and d). While root spread in the lateral and vertical directions under IT89KD-374 and IT88D-867-11 were more below the ridge top than in the furrow to furrow directions, more or less the reverse was the case with the more vegetative and prostrate Dan-illa variety.

In the intercropping systems, the systematic variation in root distributions associated with the planting pattern, soil fertility status and crops in association at 4 WAS millet and sorghum, and at cowpea pod filling 8 WAS are shown for the ridge direction in Figures 4.73a and b, 4.74a and b, 4.75a and b and 4.76a and b. The lateral distribution of roots on the ridge surface soil layer (0-20 cm) of the millet/cowpea intercrops at first sampling (4 WAS) indicates higher root densities directly below plant stands, with millet showing mostly densities greater than at the positions under the cowpea varieties (Figs. 4.73a and 4.74a). A comparison of the two cowpeas in the intercropping system shows the earlier maturing grain type cowpea (IT89KD-374) to have produced denser roots in the surface layer than the later maturity, fodder cowpea (Dan-illa), but the opposite was true at 8 WAS. Although the millet and cowpea varieties are spaced at 1 m apart from one another, there was an evidence of some root overlap in the surface layer between millet and cowpea grain type in the low fertility plot at the first sampling (Fig. 4.73a). The pattern of the vertical extent of root distribution under the millet/cowpea systems also indicates that

the millet and grain cowpea roots overlapped somewhat more and extended over a larger area, deeper in the soil profile than under the fodder cowpea, but theses densities remained low (Figs. 4.73a and 4.74a).

The second root sampling in the millet/cowpea intercropping systems, at cowpea pod filling 8 WAS, which also coincided with millet grain maturity stage, shows great differences in RLDs and roots distribution of component crops in relation to soil fertility status (Figs. 4.73b and 4.74b). The RLD distributions of component crops in millet/cowpea systems seem to extend into those of their adjacent companion crops, especially in the surface layers. These densities of roots were still greater in the high fertility treatment (Fig. 4.74b) than in the relatively low fertility plots (Fig. 4.73b), especially between 0-50 cm depths. The cowpea varieties in the intercrops showed at 8 WAS deeper rooting depths than the millet plant, but this was more pronounced in intercrop with pre-planting organic manure application alone. The rooting depth of cowpea varieties in the intercrops, especially at the relatively low soil fertility status were also greater than under the sole crops plots (Figs. 4.70c and d, 4.71c and d and Figs. 4.73b and 4.74b). These findings indicate that in field situations where water is not a limitation to crop growth, the root system area of cowpea components get more extended and also seem to have increased in number under intercropping compared to sole crop systems. The cowpea varieties in the intercrops also showed higher root densities at the vertical depth limit of root growth, comparable with or sometimes greater than directly under the surface layers, when compared with the sole cowpea systems, where RLDs generally decreased with depth. However, the rooting depth of millet seems largely unaffected by the different cropping system and the fertility levels adopted, when soil moisture status was

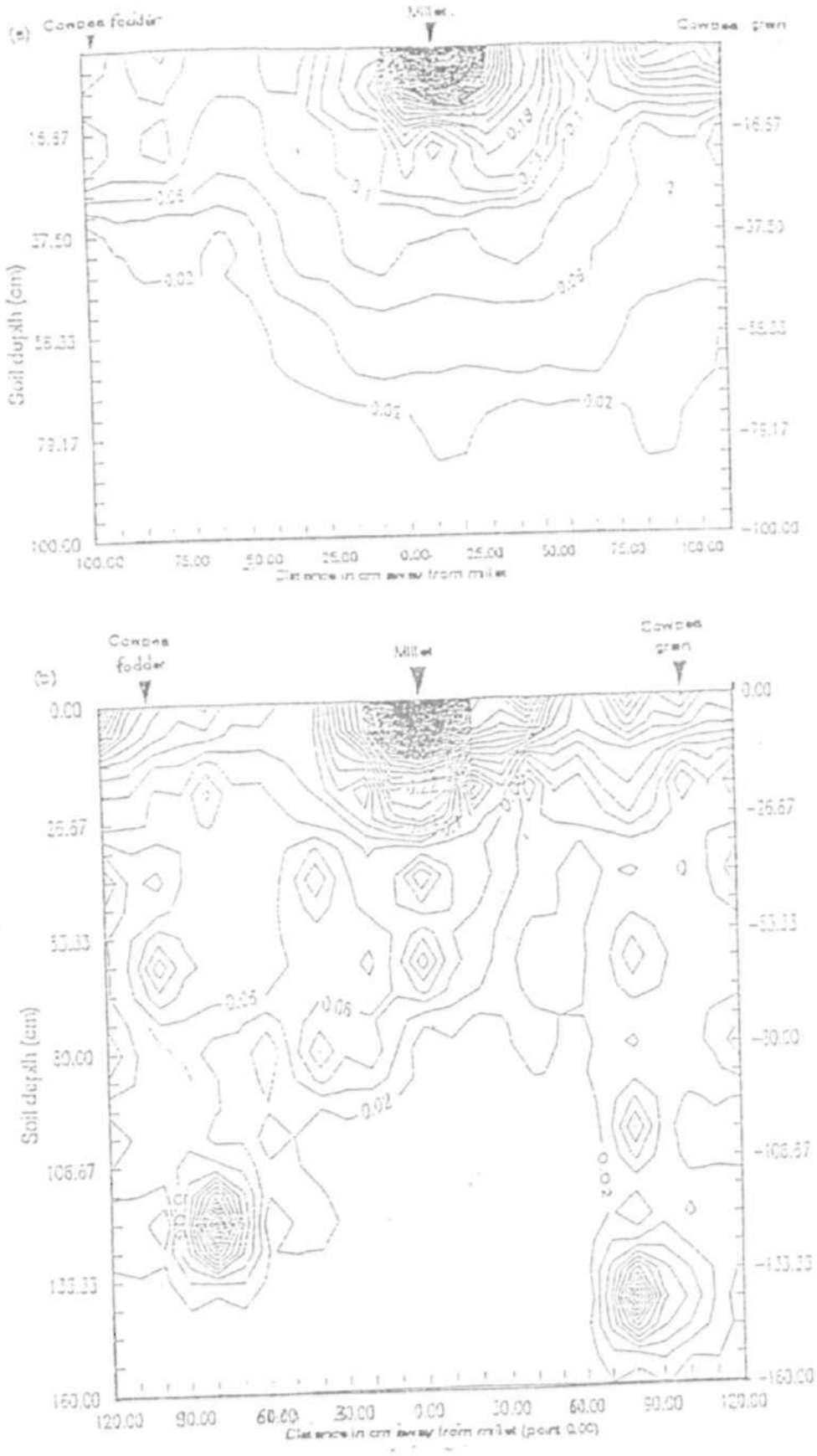


Fig. 4.73 Root distribution under the millet/cowpea system at 4 WAS millet (a) and at cowpea pod filling, 8 WAS (b), with organic manure application alone during 1994 cropping season. Arrows indicate the position of the plants.

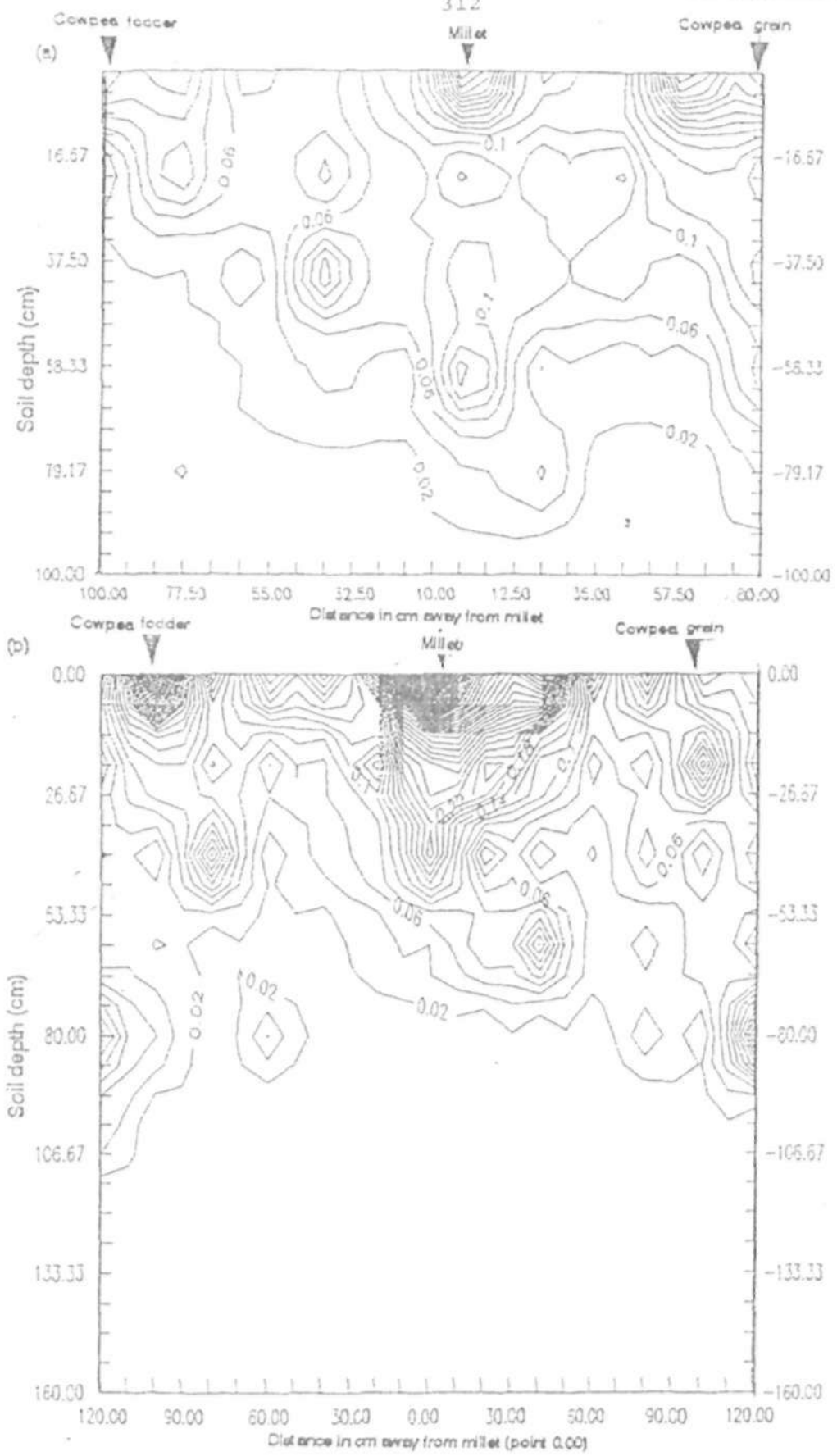


Fig. 4.74 Root distribution under the millet/cowpea system at 4 WAS millet (a) and at cowpea pod filling, 8 WAS (b), with additional fertilizer application 6 WAS during 1994 cropping season. Arrows indicate the position of the plants.

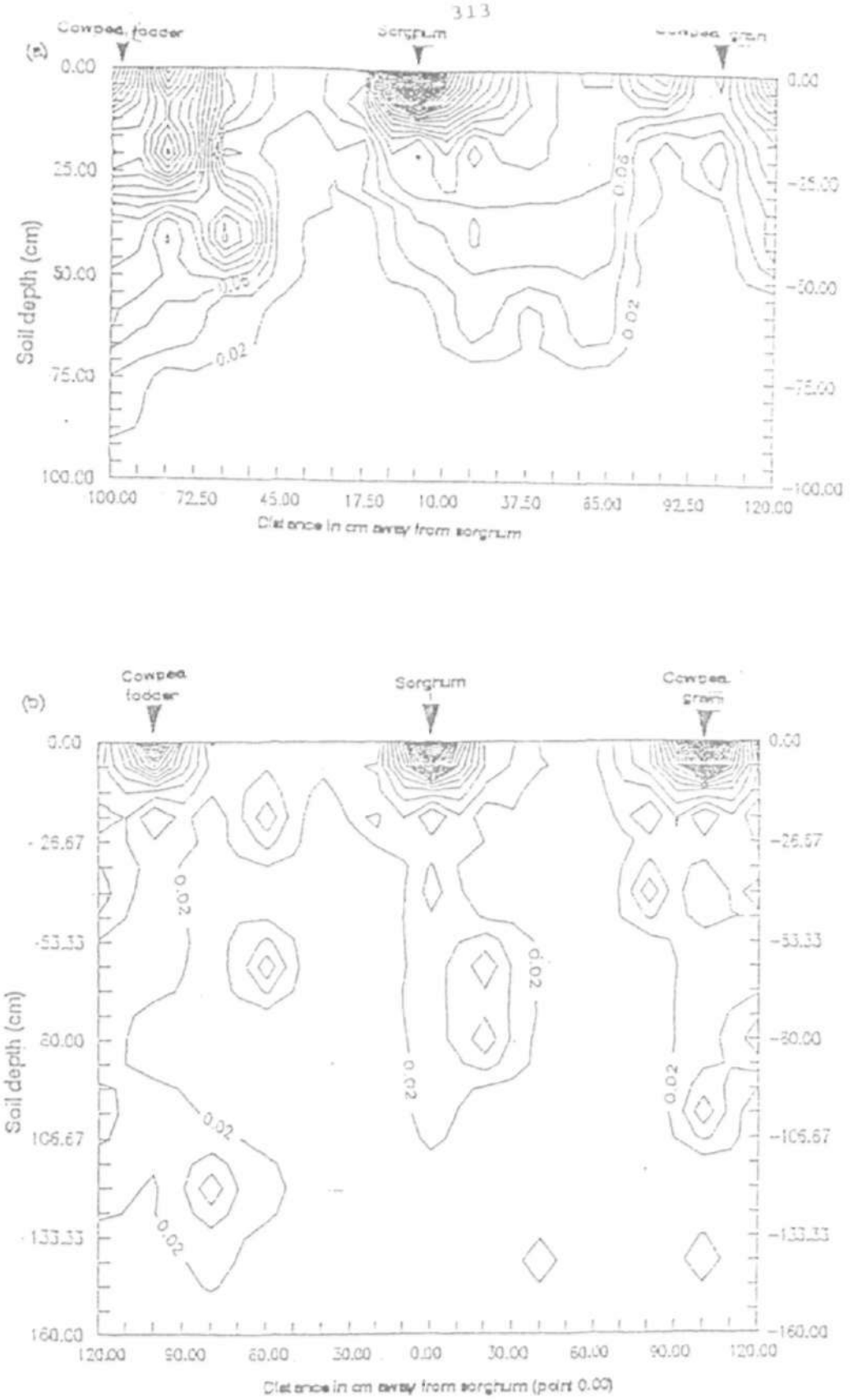


Fig. 4.75 Root distribution under the sorghum/cowpea ridge in the millet/sorghum/cowpea intercrops at (a) 4 WAS sorghum and (b) at cowpea pod filling, 10 WAS Dan illa with organic manure application alone during 1994 cropping season. Arrows indicate the position of the plants.

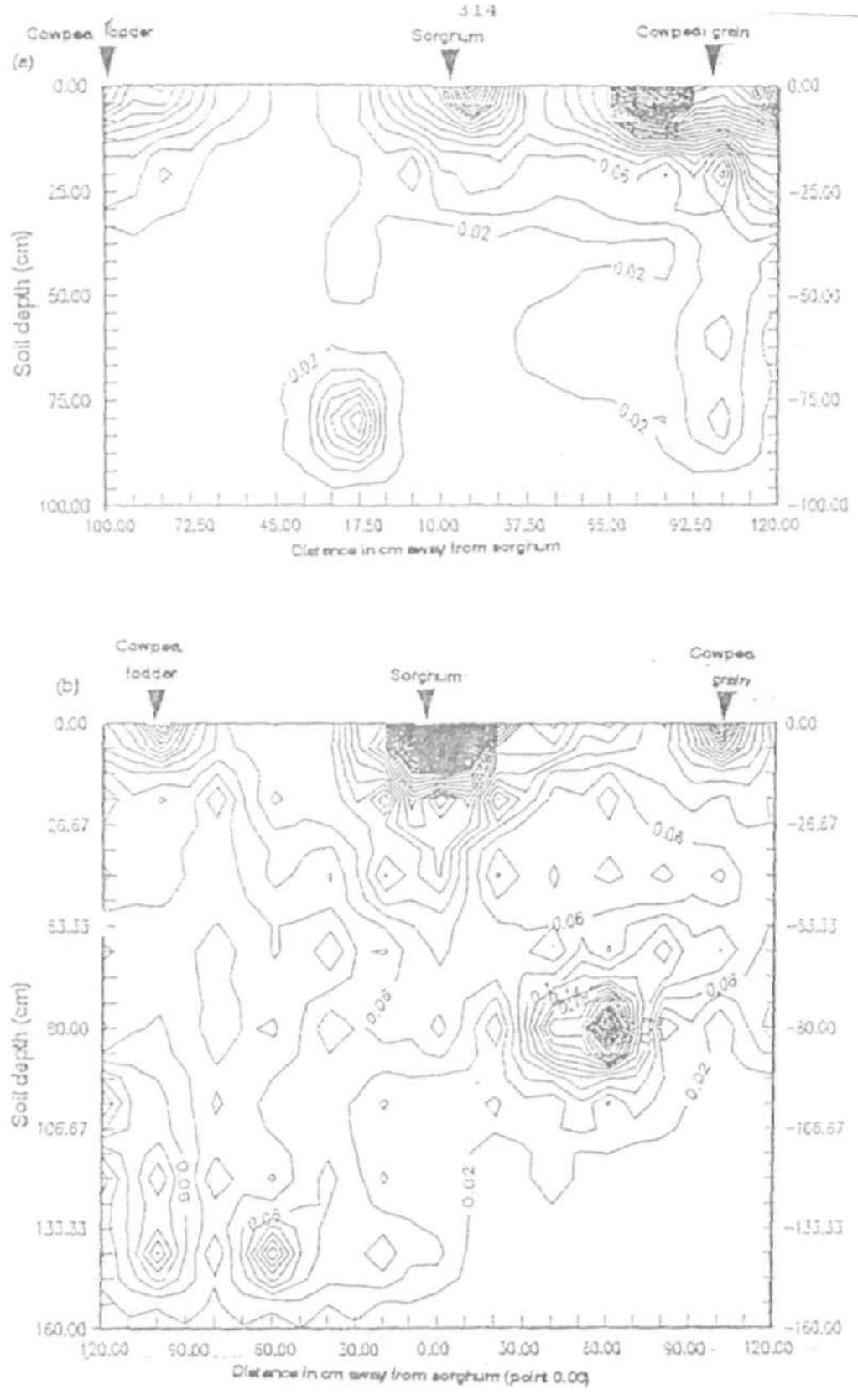


Fig. 4.76 Root distribution under the sorghum/cowpea ridge in the millet/sorghum/cowpea intercrops at (a) 4 WAS sorghum and (b) at cowpea pod filling, 10 WAS Dan Ilia with additional fertilizer application to sorghum 10 WAS during 1994 cropping season. Arrows indicate the position of the plants.

adequate. The rooting depth of millet remained generally less than 100 cm depth (Figs. 4.64c and d, Figs 4.65c and d, Figs 4.73b and 4.74b).

The rooting patterns of sorghum (Gaya Early) and cowpea varieties (same as in the millet/cowpea system) in combination in the millet/sorghum/cowpea intercropping systems are shown in Figures 4.75a and b and 4.76a and b. During the first root sampling at 4 WAS sorghum (5 WAS cowpea), the densities of roots in the surface soil layer (0-20 cm depth), close to and directly below plant stands, were higher than at distances away from plants (Figs. 4.75a and 4.76a). The root distribution of the grain cowpea type seems to have intermingled more with the neighbouring roots of the sorghum plant than the sorghum and the fodder cowpea surface roots. At about 40 cm soil depth, the vertical distribution of the roots of component crops no longer showed any intermingling (Figs. 4.75a and 4.76a).

The characteristics of root distribution within the sorghum/cowpea direction at the pod filling stage of fodder cowpea, 10 WAS Dan-illa and after the application of additional fertilizer to the sorghum component at 10 WAS are shown in Figures 4.75b and 4.76b. The distribution of roots in the surface layer still indicates much higher densities directly under plants than at distances away from the plant. The RLD directly below the sorghum stand was 1.5 cm cm^{-3} in the relatively higher soil fertility treatment, about 60% greater than was observed in the lower fertility plot. However, the cowpea varieties showed denser root distribution in the surface layers, below the centre of plants sown with pre-planting organic manure application alone compared to the relatively higher fertility treatment (Figs. 4.75b and 4.76b).

A comparison of the two fertility treatments also indicates that there were marked differences in the spread and depths of rooting between the two fertility

treatments, particularly for some dense spots in the high fertility treatment. Roots of component crop in the lower fertility treatments were restricted to a short distance away from the centre of the corresponding crops, without much evidence of intermingling. There was a much wider spread and possibly intermingling of the roots of the various crops, particularly at depths between 50 and 100 cm and between the sorghum and cowpea grain type, as the root densities also increased under the high soil fertility treatment (Figs. 4.75b and 4.76b). A deeper root penetration into the soil horizon, but with lower density, was also indicated, possibly jointly with the fodder cowpea and sorghum, for the relatively higher soil fertility as against the treatment with organic manure alone. This indicates that the high soil fertility requirement of sorghum in sole and intercropping systems is also beneficial to the root system development. Therefore a better exploitation of the below ground resources for a higher canopy development and dry matter production takes place, as evident in the comparison with the lower fertility plots. A comparison of sorghum variety Gaya Early root distribution in sole and intercropping situations show remarkable differences. The root densities below the surface layers indicate much higher values in the sole crop system compared to the sorghum in the intercrops at the two soil fertility levels. The differenes were more pronounced for the OM cases (Figs. 4.68c and d, Figs. 4.69a and b and Figs. 4.75b and 4.76b).

The deeper spread and the observed increase in the vertical depths of roots of cowpea varieties in the intercropping systems under sufficient water, especially when the cereal is grown under high fertility status, as compared to their sole plantings, shows the ability of cowpea to adapt to intercropping situations and compete reasonably with cereals under such conditions of medium inputs and sufficient soil

water. The success of the cowpea varieties in these intercrops seem to depend also on their genotypic variation in root morphology, as reflected in species duration of growth and maximum rooting depths. The active root proliferation fronts of cowpea varieties intercropped with cereals were capable of moving to deeper horizons below the cereal maximum rooting depths, to make use of resources. This also tends to agree with the suggestion that cereals develop a well-ramified root system which persists through wetting and drying cycles, whereas legumes (such as cowpea) tend to grow, lose, and regrow roots in response to variations in available soil water and other below ground resources (Smucker, 1984; Hamblin and Tennant, 1987).

4.8.2 (c) *1995 cropping season*

The root studies during the 1995 cropping season focussed more on the intercropping systems, with considerations for a few sole crop systems. The root distribution under millet/cowpea, with IT89KD-374 and Dan-illa as the two cowpea cultivars in association with millet is shown for the two soil fertility levels and different crop development stages in Figures 4.77 and 4.78. At the first root sampling time for millet/cowpea systems, at 4 WAS cowpea, the root distribution of crop components showed differences in spread and densities. The maximum RLDs for the upper soil layer (0-20 cm) were obtained directly below and close to plant stands. These were around 0.35 cm cm^{-3} under fodder cowpea as well as grain cowpea types, and 0.45 cm cm^{-3} under the millet. The millet still gave higher RLD as expected, while root densities decrease with distances away from plants (Fig. 4.78a). The soil horizon depth between 0-40 cm also shows some evidence of the intermingling of the

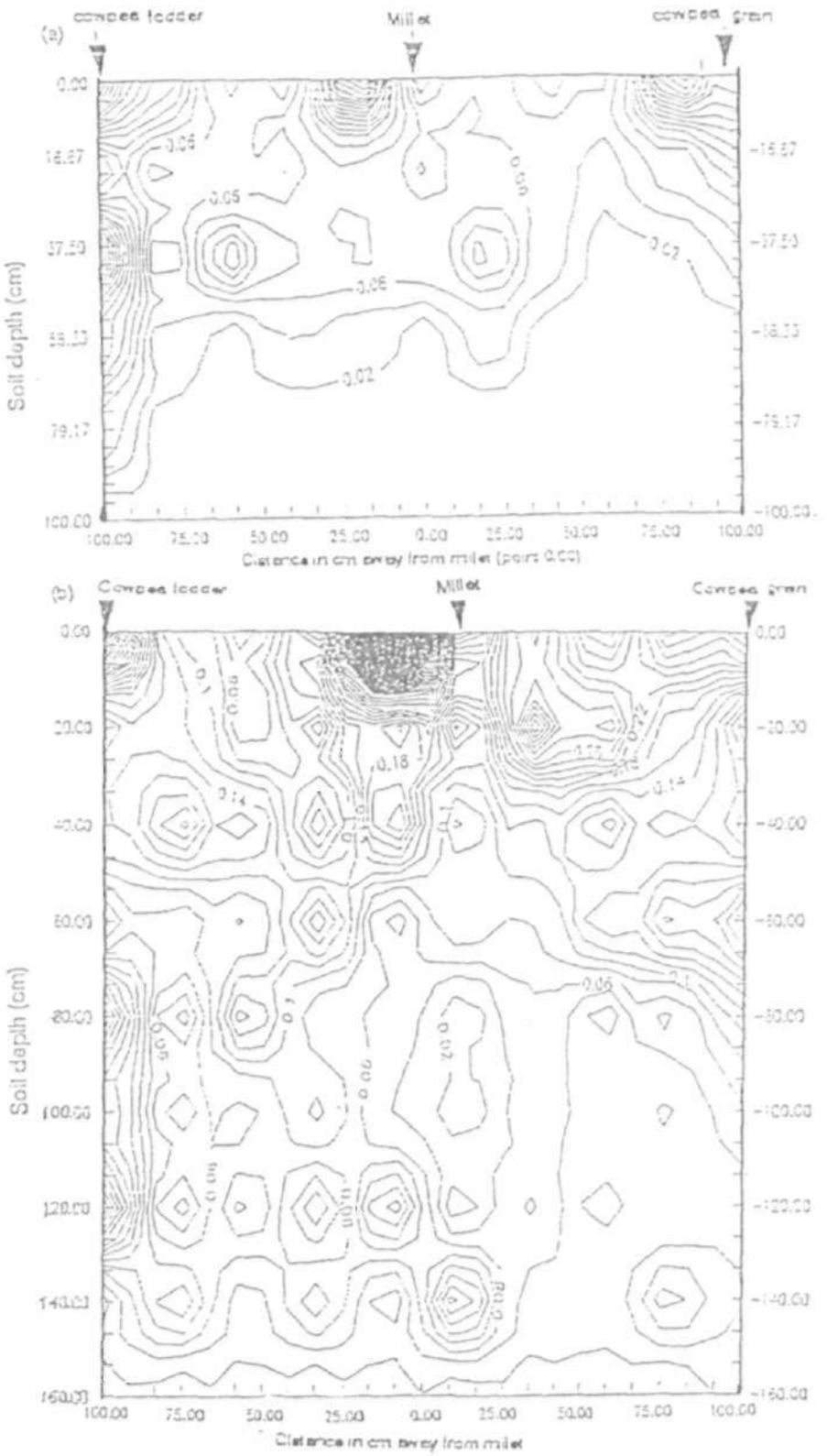


Fig. 4.77 Root distribution under the millet/cowpea system at (a) 4 WAS cowpea and (b) at millet maturity, 12 WAS, with organic manure application alone during 1995 cropping season. Arrows indicate the position of the plants.

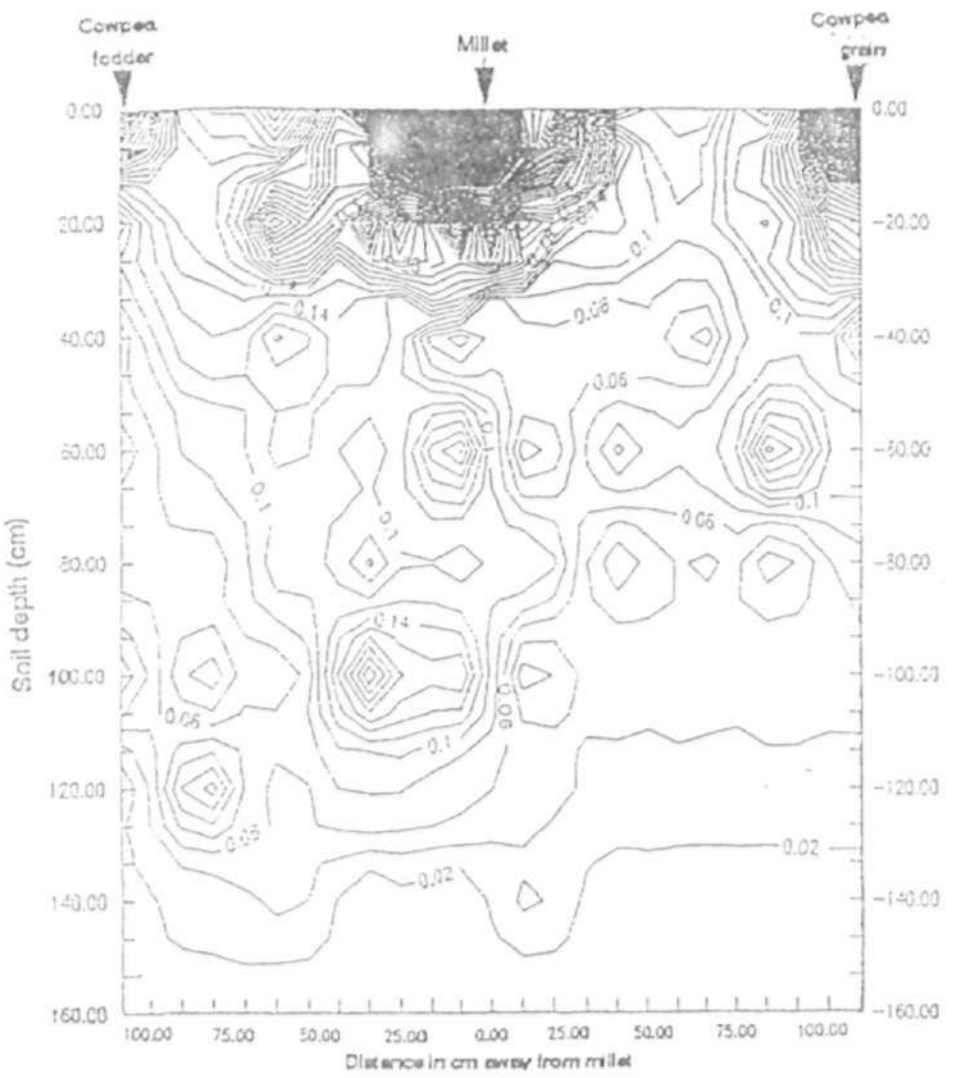


Fig. 4.78 Root distribution under the millet/cowpea system at millet maturity 12 WAS, with additional fertilizer application 6 WAS to millet during 1995 cropping season. Arrows indicate the position of the plants.

roots of millet and the cowpea varieties. The vertical distribution of roots below this upper layer showed the fodder cowpea to have achieved the deepest rooting depth and greater root densities than millet and with an even larger difference than the grain cowpea (IT89KD-374). The vertical decrease in root densities below the millet was relatively higher and faster near the centre of millet than near the cowpea cultivars (Fig. 4.77a). The active root proliferation front of the fodder cowpea (0.35 cm cm^{-3}) and millet (0.15 cm cm^{-3}), seem to have occurred at about 40 cm depth.

The root sampling at millet maturity, 12 WAS, showed marked differences in the lateral and vertical root distribution of crops as affected by soil fertility status (Figs. 4.77b and 4.78). The lateral distribution of roots in the soil surface layer (0-20 cm) under the millet stands shows a higher density and wider spread in the higher fertility treatment than in the plots with relatively lower soil fertility. Highest millet RLD was 4.5 cm cm^{-3} close to the base of the crop in the system with additional application of NPK fertilizer, 6 WAS millet as against 1.7 cm cm^{-3} recorded under millet in the relatively low soil fertility system. Although the RLDs of the fodder cowpea type in the millet/cowpea systems with the two fertility levels were similar (0.55 cm cm^{-3}), the high soil fertility system greatly increased the RLD of the grain cowpea type (1.2 cm cm^{-3}), when compared with the grain cowpea type in the lower fertility treatment (0.35 cm cm^{-3}). There was also the indication that under the relatively lower soil fertility treatment, the root systems of the crops in millet/cowpea intercrop extended deeper into the soil horizon as root densities also increased, but at relatively small densities than in the high soil fertility system (Figs. 4.77b and 4.78).

The higher root density in the relatively lower soil fertility treatments indicate an adjustment response to the competition for below ground resources induced by low

soil nutrient status. The root distribution at low RLD under the cowpea cultivars at deeper horizons were denser in the system with pre-planting organic manure application alone compared to the relatively high soil fertility millet/cowpea intercrop. This suggests the shifting of root proliferation fronts of the crops, and especially in the cowpea cultivars, in response to variation in soil water and nutrient status.

During the 1995 cropping season, the millet within the millet/cowpea intercrops seems to develop profuse roots, with ecreasing density vertically into the soil horizon to about the same depth as the fodder cowpea type (Figs. 4.77b and 4.78). This was probably in response to the competition for soil moisture with cowpea at the upper and middle horizons, since the soil moisture regime was always less than field capacity, while monthly rainfall total did not exceed the estimated potential evaporation around these periods of crop growth. These differences in the competitive effects of millet roots on root development of the cowpea cultivars probably resulted from the differences in canopy development, to maintain an advantageous shoot/root ratio, creating varying levels of competition for nutrients and to a lesser extent, water. The soil water consumption of the local fodder cowpea cultivar, Dan-illa, which was nevertheless lower (see section 4.6.8) than for the earlier maturing grain cowpea cultivar, IT89KD-374, seems to be more of a genetic than an environmental adaptation to its intercropping with cereals in the arid and semi-arid Nigeria.

The characteristics of root distribution in and under the sorghum/cowpea ridges in the millet/sorghum/cowpea intercrops are shown in Figures 4.79, 4.80 and 4.81. The three stages of crop growth considered for root distributions are 6 WAS sorghum (Gaya Early) , at sorghum head formation (12 WAS), and sorghum grain maturity (15 WAS), at the two soil fertility levels adopted. The root distribution at 6 WAS

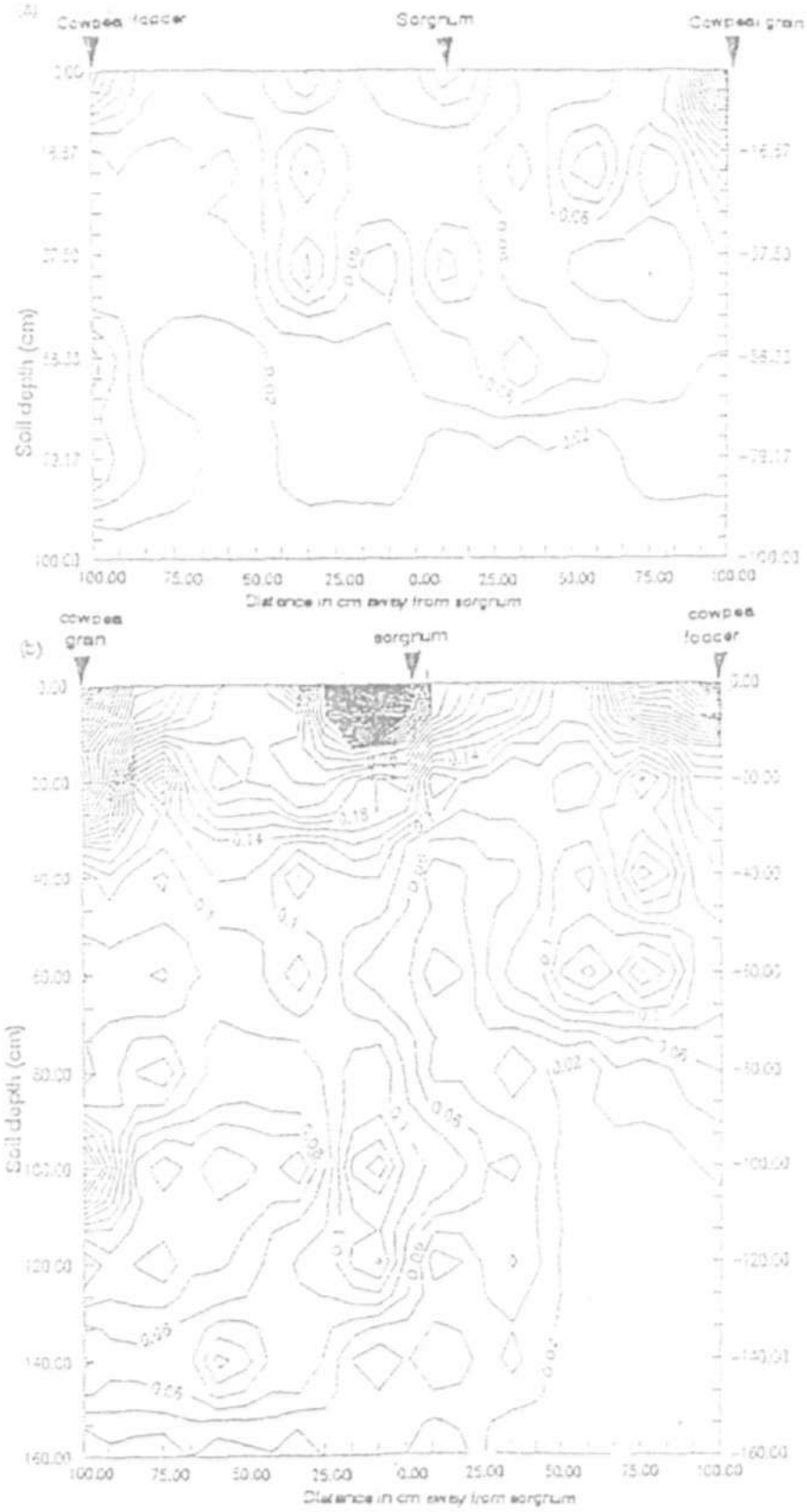


Fig. 4.79 Root distribution under the sorghum/cowpea ridge in the millet/sorghum/cowpea intercrops at (a) 8 WAS sorghum and (b) at sorghum head formation, 12 WAS, with organic manure application alone during 1995 cropping season. Arrows indicate the position of the plants.

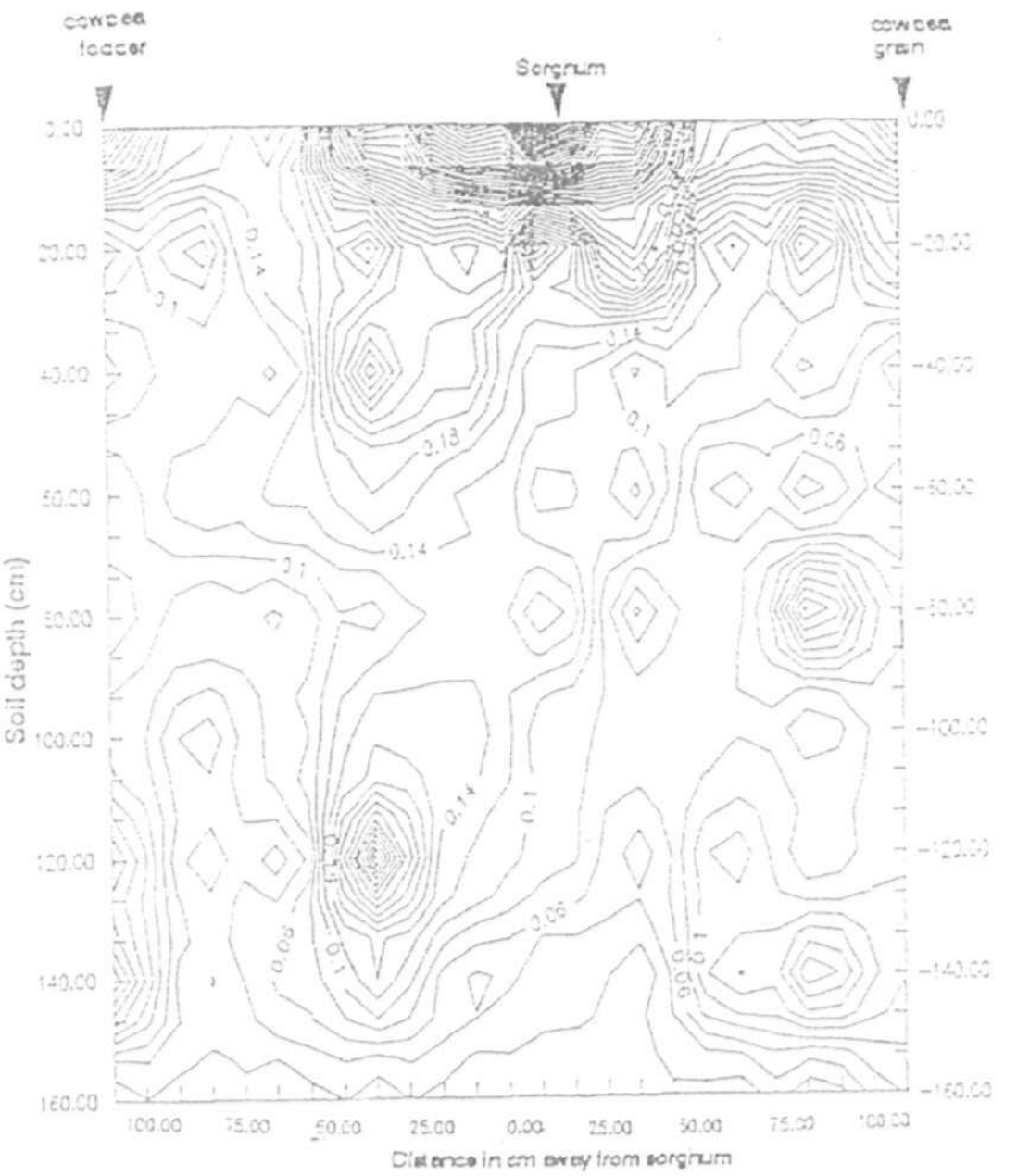


Fig. 4.8() Root distribution under the sorghum/cowpea ridge in the millet/sorghum/cowpea intercrops at sorghum head formation, 12 WAS with additional fertilizer application to sorghum 10 WAS during 1995 cropping season. Arrows indicate the position of the plants.

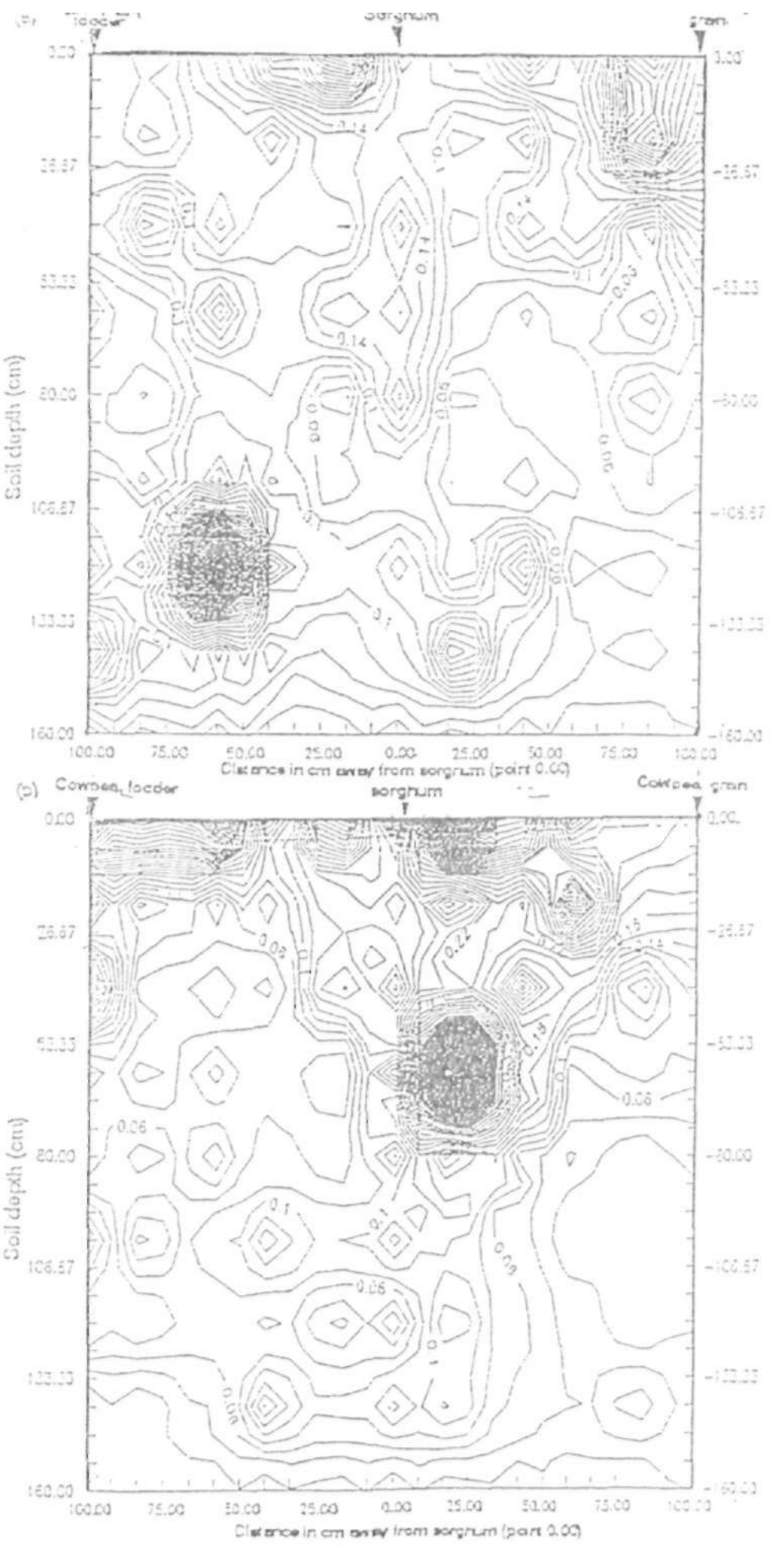


Fig. 4.81 Root distribution under the sorghum/cowpea ridge in the millet/sorghum/cowpea intercrops at sorghum grain filling, 15 WAS sorghum during 1985 cropping season. (a) treatment with pre-planting organic manure application alone and (b) treatment with additional inorganic fertilizer application at 10 WAS sorghum. Arrows indicate the position of the plants.

sorghum (5 WAS cowpea) showed higher root densities under the cowpea components than under the sorghum (Fig. 4.79a). Sorghum, with a slower growth (LAI < 0.60) at this stage of its development, had lower densities of roots compared to the cowpea varieties because the later had already achieved a relatively greater level of canopy development (LAI > 0.7, already high for cowpea). The earlier maturing grain cowpea cultivar within the intercrop produced higher root densities than the fodder cowpea type in the upper 0-40 cm soil depth, but the fodder cowpea had somewhat more roots deeper in the soil horizon (Fig. 4.79a).

Figures 4.79b and 4.80 shows the root distribution at the time of sorghum head formation 12 WAS which also coincided with the physiological maturity stage of the grain cowpea and pod filling in the fodder cowpea (11 WAS). The lateral distribution of roots in the upper soil surface (0-20 cm) shows consistently higher RLDs under the sorghum than the cowpea cultivars. The relatively high soil fertility treatment resulted in greater densities at distances away from the centre of the sorghum stand than under the lower soil fertility system, while surface layer root densities of cowpea cultivars in the high fertility system were lower than in the systems with pre-planting organic manure application alone.

The lateral spread of roots of the various crops also shows an evidence of root systems overlap among the crop components. The vertical distribution of roots below the surface layer showed generally higher root densities under the high soil fertility sorghum/cowpea ridge than in the relatively lower fertility treatment, while roots of crops also inter-penetrated into the area of the adjacent crops. Lateral spread and densities of roots on the ridge at the deeper end of root growth were larger under the high fertility than under the lower fertility treatment. This indicates a response to the

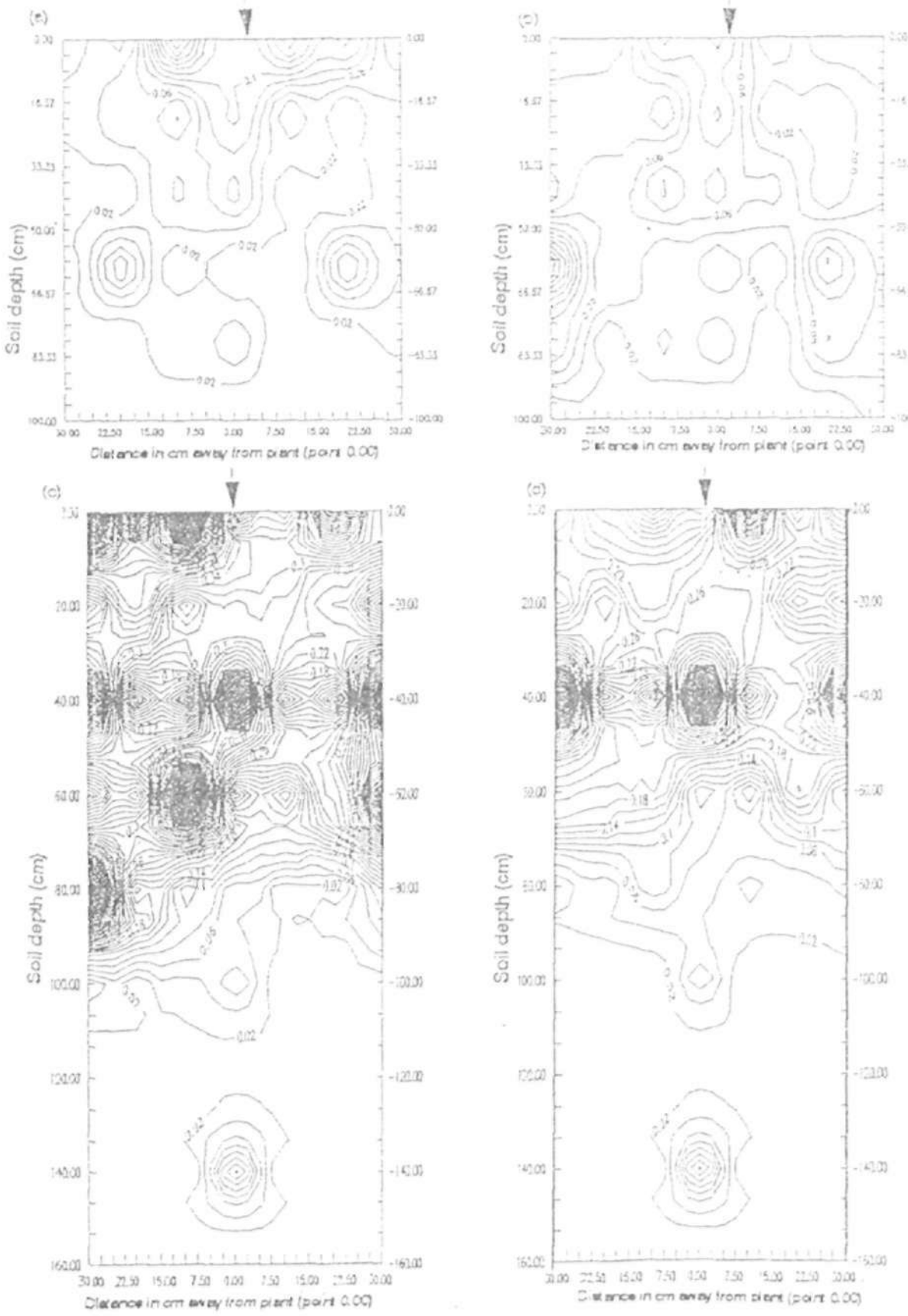


Fig. 4.82. Root distribution under sole sorghum (G. Early) at 6 WAS (a & b) and at head formation 12 WAS (c & d) with additional inorganic fertilizer during 1995 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant.

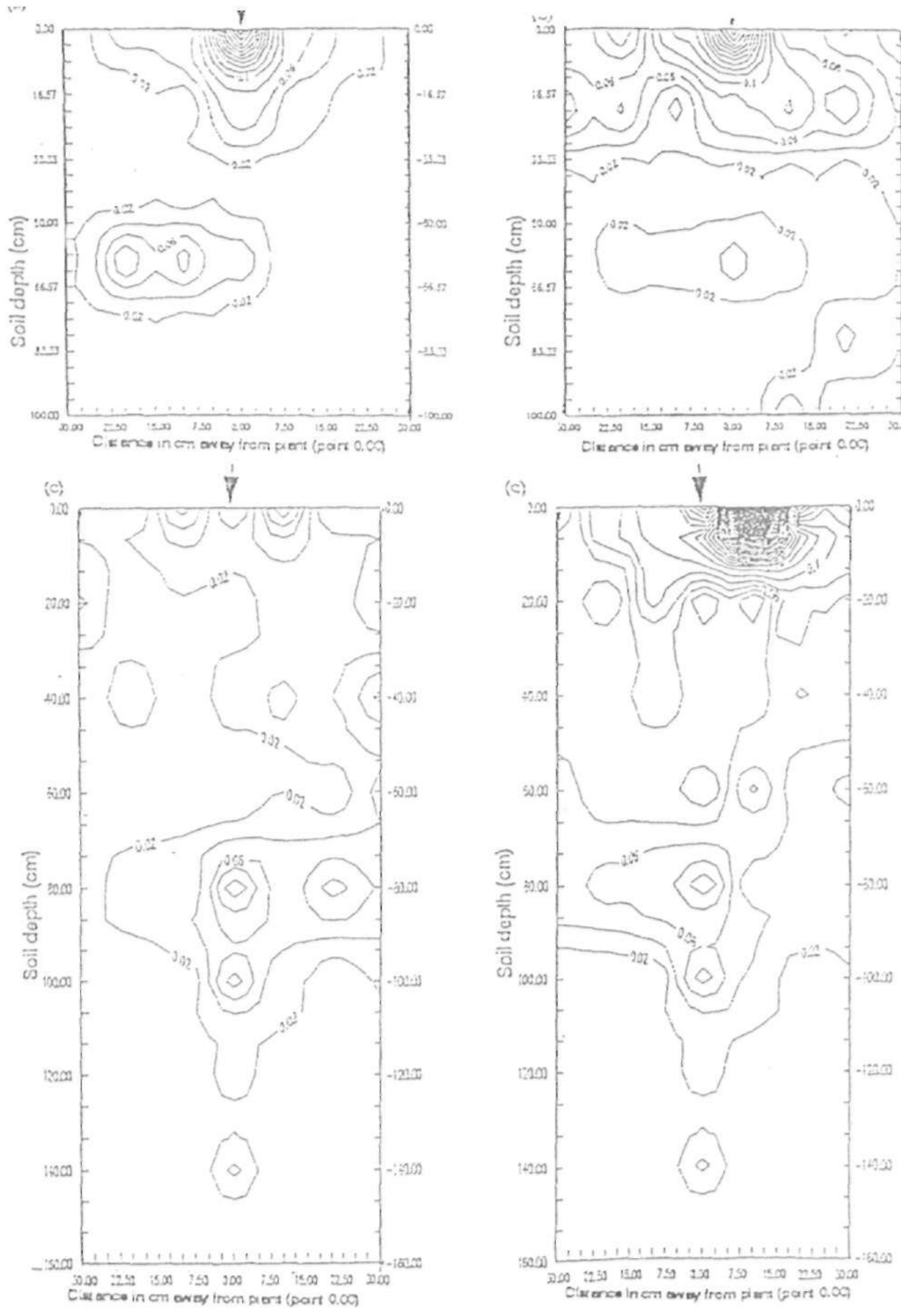


Fig. 4.83 Root distribution under sole cowpea (IT86D-719) at 4 WAS (a & b) and at pod maturity 10 WAS (c & d) during 1995 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant.

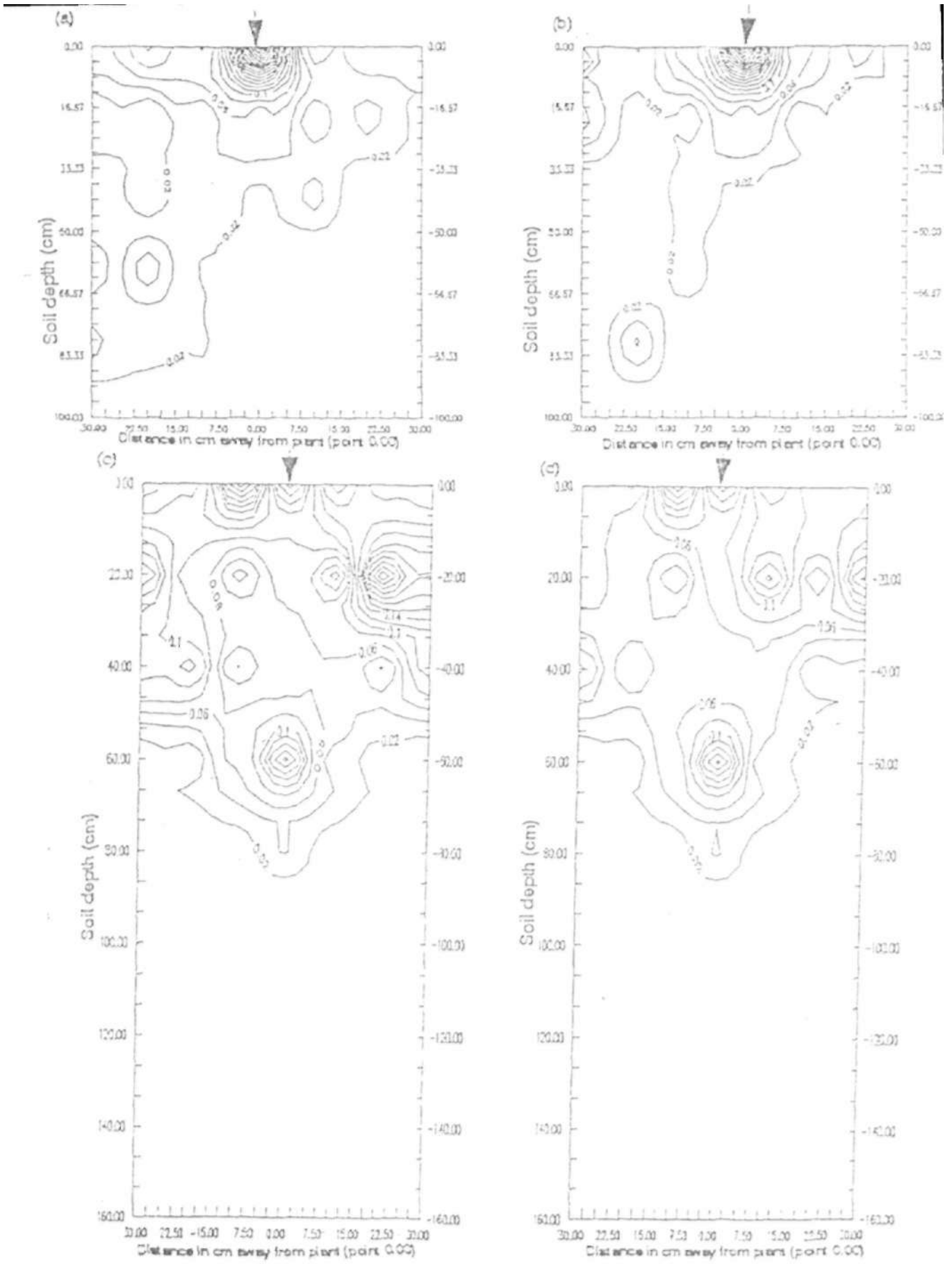


Fig. 4.84 Root distribution under sole cowpea (IT89KD-374) at 4 WAS (a & b) and at pod maturity 11 WAS (c & d) during 1995 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant.

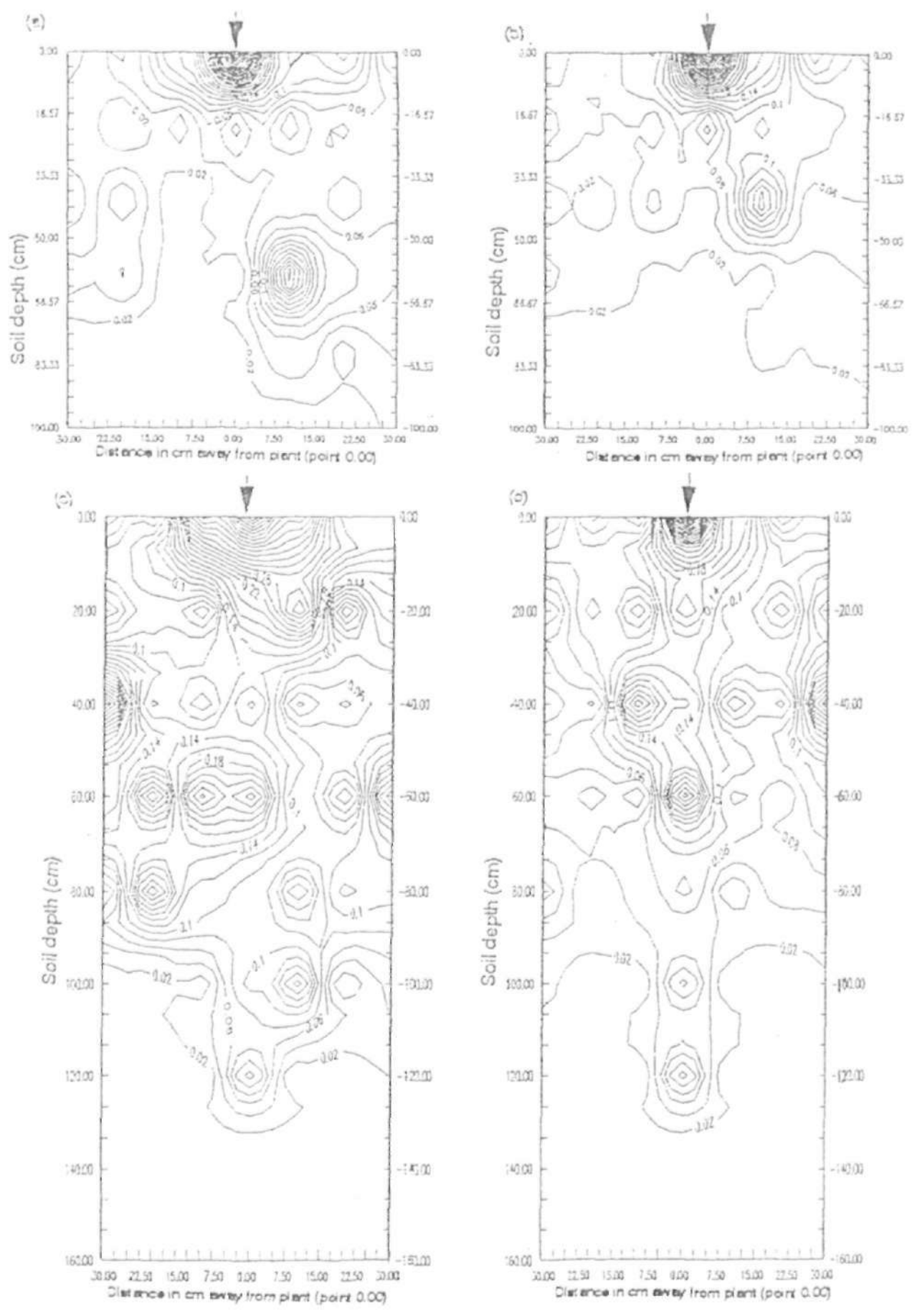


Fig. 4.85. Root distribution under sole cowpea (Dan Ille) at 4 WAS (a & b) and at flowering 10 WAS (c & d) during 1995 cropping season. (a) and (c) are directions from furrow to furrow (i.e. positions A to C), while (b) and (d) are directions on the ridge (i.e. positions B to D). Arrows indicate the position of the plant.

RLDs were greater in the prostrate and more vegetative Dan-illa cowpea than under the less vegetative IT89KD-374 and IT86D-719 (Figs. 4.83c and d, 4.84c and d and 4.85c and d). Under the sole Dan-illa treatment, root densities were relatively higher than under the other sole cowpea treatments, with the exception of the ridge direction of IT86D-719, while the root distribution was decreasing much more slowly with depth. This indicates better root distribution in Dan-illa than either IT89KD-374 or IT86D-719, and suggests a better ability of Dan-illa to use soil available resources in deeper soil horizons.

Some photographs of observed root distribution systems, under sole millet and cowpea (IT89KD-374) at 4 WAS, are shown in plates 4.1 and 4.2 respectively. The roots are held in their original distribution pattern by the nail board. While the cowpea rooting system shows the main tap root and the associated lateral roots extending to the limits of the root box, the fibrous root system of millet showed a more irregularly shaped spread of roots with a near empty to very low rooting densities within the 20-40 cm depth directly below the plant.

A summary of the three years of root studies may highlight the following points for our soils and input levels:

- cowpea produces greater root densities and achieved deeper rooting depths in intercropping than when sown sole.
- The later maturing, prostrate and more vegetative fodder cowpea type (Dan- illa) achieved a deeper rooting depth, with greater root densities, than the grain type cowpea in intercropping systems. This suggests a better ability of the local fodder type cowpea (Dan-illa) to adapt to

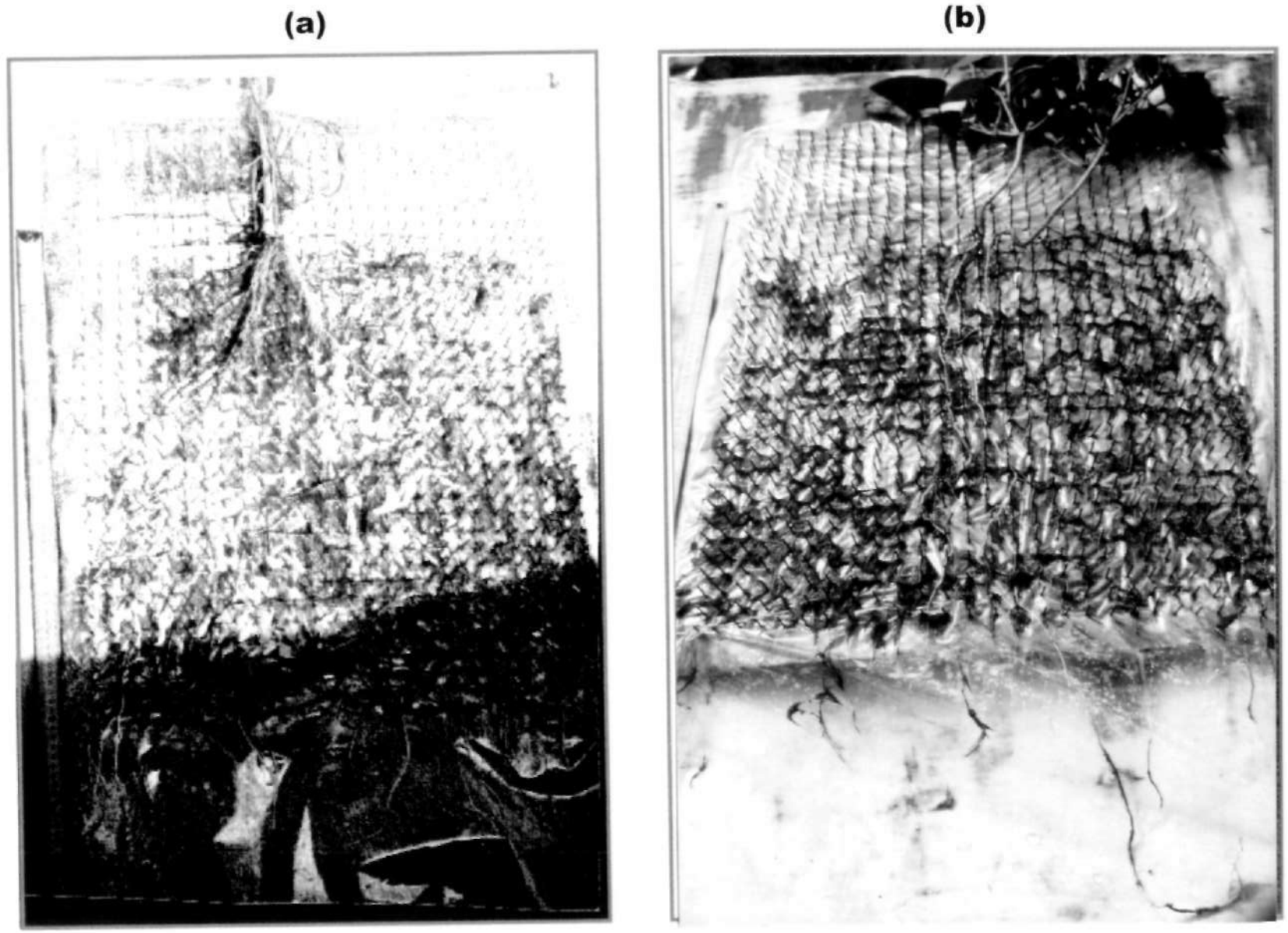


Plate 4.1 (a) The rooting pattern of millet and (b) cowpea held in place by nails in the box after washing away the soil.

the semi-arid conditions and to compete for resources better than the improved grain cowpea (IT89KD-374), when intercropped with cereals.

- The rooting depths of crops under high soil moisture (almost close to field capacity) is always shallower than when soil water content is a limitation.
- The RLDs of cereals below the surface layer (0-20 cm) are higher under a relatively lower soil fertility status than when soil nutrient availability is high.
- The intercropping of millet and sorghum with cowpea varieties showed overlap of the roots of component crops, and hence suggests competition among component crops for below ground resources. The different rooting patterns of these crops under intercropping conditions indicate component abilities to compete and to adapt to limiting resources (water and nutrients).

4.9 Crop yields and yield components

4.9.1 *1993 cropping season*

Data on crop yields and yield components as affected by cropping systems for pearl millet, sorghum cultivars and cowpea varieties are given in Tables 4.20, 4.21 and 4.22. The plant densities of millet in the three different cropping systems greatly influenced the productivity of the millet components. The number of millet plants at harvest in the sole millet system (50234 plants/ha) was the highest, and the millet populations in millet/cowpea and millet/sorghum/cowpea intercrops were 62% and

Table 4.20. Millet yields and yield components as affected by cropping systems at harvest, 1993.

TREATMENT	No. of plants/ha	Days to 50% panicle formation	No. of panicles /hill	No. of panicles /ha	Panicle weight kg/ha	Seed weight kg/ha	Stover weight kg/ha	Total dry matter production (kg/ha)	Harvest index
Sole millet	50234	55	3	75545	2132	1716	4020	6150	0.28
Millet in Mil/Cow int.	19048	55	5	41879	1648	1368	2390	4040	0.34
Millet in Mil/Sor/Cow int.	16715	55	6	45231	1808	1555	2940	4750	0.33
SE (df=4)	5176.1**	NS	0.828*	2914.8**	69.2**	62.1**	443*	430*	0.058NS

Table 4.21. Sorghum cultivars yields and yield components as affected by cropping systems at harvest, 1993.

TREATMENT	No. of plants/ha	Days to 50% Head formation	No. of Heads/ hill	No. of Heads/ ha	Head weight kg/ha	Grain weight kg/ha	Stover weight kg/ha	Total dry matter production (kg/ha)	Harvest index
Sole Gaya Early	50726	85	1.1	27970	800	552	1320	2120	0.26
Sole ICSV 400	50726	73	1.6	40948	2200	1870	3940	6130	0.31
G.Early in Mil/Sor/Cow int.	15996	86	1.3	9065	690	414	1250	1940	0.21
SE (df=4)	2459**	1.17**	0.40NS	6910*	417*	413*	1049*	1440*	0.027*

* P< 0.05; ** P< 0.01; NS Not significant.

Table 4.22. Cowpea cultivars yields and yield components as affected by cropping systems at harvest, 1993.

TREATMENT	No. of plants /ha	Days to 50% flowering	No. of pods/ hill	No. of pods/ ha	Pod weight kg/ha	Seed weight kg/ha	Haulm weight kg/ha	Total dry matter production (kg/ha)	Harvest index
Sole IT89KD-374	38281	50	56	965613	1456	1344	974	2429	0.56
Sole IT86-719	34114	40	32	618688	1048	925	1255	2303	0.41
Sole Dan illa	33896	53	52	934805	1345	1058	2195	3539	0.30
IT86D-719 in Mil/Cow int.	7568	40	12	46933	57	44	44	100	0.43
Dan illa in Mil/Cow int.	6759	65	24.4	167883	290	279	345	635	0.44
IT86D-719 in Mil/Sor/Cow int.	5674	40	16	44696	58	45	52	110	0.40
Dan illa in Mil/Sor/Cow int.	4267	64	8	72130	155	144	190	345	0.30
SE (df=12)	2169*	0.30**	5.6*	66553	80.1	51.5	118.8	137	0.039

* P< 0.05; ** P< 0.01; ns Not significant.

67% lower respectively (Table 4.20). During the 1993 cropping season, the days to 50% millet panicle initiation were not affected by the different cropping systems. However, the different cropping systems resulted in the production of varying numbers of panicles per hill. The cropping system with the least density of the millet component, i.e. millet/sorghum/cowpea, produced the greatest number of panicles per hill, resulting from better tillering, which was significantly ($P < 0.05$) higher than the sole millet system, but not significantly different from that of the millet/cowpea system. The higher millet density in the sole system also produced the highest number of panicles per hectare, which was significantly ($P < 0.01$) higher than in the intercrops. Between the intercropping systems, however, the number of panicles produced were not significantly different (Table 4.20).

The millet panicle and seed yields of the sole crop system were also significantly higher ($P < 0.01$) than those of the intercrops, which were themselves not significantly different statistically, but just slightly higher in the millet/sorghum/ cowpea intercrop. The millet stover yields and total dry matter production in the sole millet were also significantly ($P < 0.05$) higher than those produced in the intercrops, while the harvest indices of the intercropped millets were higher, but not different statistically from the sole millet. Although the millet densities in the intercrop systems were more than 60% less than in the sole crop, the total millet dry matter production at harvest in the intercrop millets compared with the sole millet were 34% and 23% lower for millet/cowpea and millet/sorghum/cowpea intercrops respectively. That the intercropped millets favoured a higher seed production per plant than the sole millet, suggests a higher and better partitioning of assimilates to the reproductive organs at the wider crops spacings in intercropping systems.

The yields and yield components of sorghum in the various cropping systems at harvest were greatly affected by the rainfall duration in 1993. The effective rainfall in 1993 ceased during the second quarter of September, before the commencement of the reproductive stage of Gaya Early sorghum (about September 21), while earlier maturing ICSV 400 was at the grain filling stage. The stored soil water at that time was not sufficient to sustain the later maturing Gaya Early to maturity and hence part of the reason for the low values of grain weight and yield parameters recorded (Table 4.21). Although the sorghum density at harvest in the millet/sorghum/cowpea intercrop was 31% of the sole sorghum systems, the grain and total dry matter production per hectare in the sole Gaya Early was only slightly higher than in the intercrop, with no significant difference statistically. Sorghum (G.Early) was the last crop harvested from the field, in November, and its low density in the intercrop after millet and cowpea had been harvested, ensured a relatively better availability of the already low soil water for reproductive stage developments compared to the competition due to the high sorghum density in the sole Gaya Early system. The competition caused moisture stress conditions which reduced assimilate partitioning to the storage organs of Gaya Early.

The earlier maturing sole ICSV 400 sorghum cultivar produced significantly ($P < 0.05$) higher grain yields and total dry matter than Gaya Early sorghum (in sole and intercrop systems) during the 1993 season (Table 4.21). The stover yield of sole ICSV 400 was also higher than Gaya Early in sole and intercropping systems, but the difference did not show any statistical significance. The trend of stover yield at harvest was sole ICSV 400 > sole Gaya Early > G.Early in millet/sorghum/cowpea intercrop. The ICSV 400 sorghum cultivar also gave a significantly ($P < 0.05$) higher

harvest index than Gaya Early sown sole and in intercrop. The period of soil moisture availability during the 1993 cropping season favoured development of stems and leaves in the Gaya Early sorghum, but was not sufficient at the end of the rainy season to sustain grain production, and hence the lower values of harvest indices when compared to the earlier maturing ICSV 400 that had access to relatively higher soil water. The deeper vertical root development and higher root densities of the cereal components at their maximum depth of rooting in intercropping systems also indicate a larger and deeper root water extraction zone than in their sole treatments.

The different cropping systems had great effects on the performances of the various cowpea cultivars, as shown in Table 4.22. The densities of the different cowpea varieties in the intercropping systems were 22% or less compared to the lowest sole crop densities and hence produced significantly ($P < 0.001$) less grain yields per hectare and had lower yield parameter per hectare as well, compared to the sole systems. The early maturity, erect grain cowpea type, IT86D-719, reached 50% flowering earliest at 40 DAS, in sole and intercropping systems. The later maturity, prostrate and more vegetative Dan-illa cowpea reached 50% flowering later in all the cropping systems adopted. A comparison of the days to 50% flowering of Dan-illa in sole and intercropping systems showed that they varied from 53 DAS in the sole system to 64 and 65 DAS in the intercrops. The delay in flowering of Dan-illa in intercropping could be in response to competition for resources (light and water) with the taller cereals that also developed greater canopy. The shading of the creeping and photoperiod sensitive Dan-illa by the taller cereals in intercropping, caused a reduction in the amount of solar radiation received by the cowpea. These morphological attributes of Dan-illa allow it to adapt better when intercropped with cereals than the

erect, day neutral grain cowpea cultivar (IT86D-719).

Among the sole cowpea systems, the improved semi erect grain cowpea type, IT89KD-374, produced the highest pod and seed weights per hectare, but these were not significantly higher than the values for IT86D-719 and Dan-illa cultivars. The haulm production of the prostrate and vegetative Dan-illa cowpea sown sole was however significantly ($P < 0.01$) higher than in the less vegetative sole IT86D-719 and IT89KD-374 (Table 4.22). The total dry matter production at harvest in the sole Dan-illa cowpea (3539 kg/ha) was also significantly ($P < 0.01$) higher than the values for sole IT89KD-374 (2429 kg/ha) and IT86D-719 (2303 kg/ha).

A comparison of the performances of the two cowpea varieties sown within the intercrops also indicates higher yields and yield components for Dan-illa than for IT86D-719. The yield value of Dan-illa in the millet/cowpea system was higher than in the millet/sorghum/cowpea system, but the difference did not show a statistical significance. The harvest indices among the sole cowpea systems indicate the superiority of the semi erect, improved grain cowpea, IT89KD-374, for which it was significantly ($P < 0.01$) higher than those of IT86D-719 and Dan-illa cowpea cultivars. The partitioning of assimilates to the seed was also significantly ($P < 0.05$) higher in the early maturing grain cowpea (IT86D-719) than in the more vegetative and indeterminate Dan-illa cultivar (Table 4.22). Within the intercropping systems, the lowest harvest index value (0.30) was recorded in the Dan-illa sown in the millet/sorghum/cowpea intercrop.

4.9.2 *1994 cropping season*

The yields and yield components of millet at harvest as affected by cropping

systems in 1994 are shown in Table 4.23. The additional application of inorganic fertilizer to the millet components, before panicle initiation stage of the various cropping systems, did not create any significant difference in the yield parameters considered within the cropping systems. The millet densities in the different cropping systems resulted in significant variations in their performance at harvest. The millet densities in the millet/cowpea and millet/sorghum/cowpea intercrops varied from 23-29% and 11-13% respectively of the sole millet system. These differences in millet densities and the presence of the other crops in mixtures, did not affect the date to millet's attainment of 50% panicle initiation in any treatment. The rainfall distribution, after crop establishment in 1994, ensured adequate soil available water until millet maturity, while soil fertility status seems not to be a constraint to millet productivity under the conditions of this experiment. The conditions also favoured the attainment of the productive capabilities of millet components within the different systems. The low millet densities in the relatively widely spaced intercropping systems resulted in the production of higher numbers of tillers, which were similar within the intercrops, but significantly ($P < 0.01$) higher than in the sole millet systems (Table 4.23). However, the number of panicles produced per millet hill was greatly affected by cropping systems.

The highest number of panicles per hill was produced in the millet/sorghum/cowpea system, and this was significantly ($P < 0.01$) higher than in the millet/cowpea and sole millet systems. The millet hills in the millet/cowpea intercrops also produced significantly ($P < 0.01$) higher numbers of tillers than in the sole millet treatments. However, the greater tillering of millet in the intercropping systems was not enough to compensate for the effects of millet densities in the different systems

Table 4.23. Millet yields and yield components as affected by cropping systems at harvest, 1994.

Treatment	Fertility level	No. of plants/ ha	Days to 50% panicle formation	No. of panicles /hill	No. of tillers /hill	No. of panicles /ha	Panicle weight Kg/ha	Grain weight kg/ha	Stover weight kg/ha	Total dry matter production kg/ha	Harvest index
Sole millet	Org.man. only	53333	55	4.2	8.5	132006	3018	2318	4751	7769	0.29
	Org.man+inorg.fert.	47328	55	5.1	9.4	107989	2986	2255	4429	7415	0.31
Mil/cow int.	Org.man. only	12390	55	8.4	11.4	51962	1601	1324	3548	4950	0.27
	Org.man+inorg.fert.	15291	55	8.2	11.2	56114	2149	1808	2624	4773	0.38
Mil/sor/cow int.	Org.man. only	6687	55	10.6	12.5	33019	1515	1294	1815	3329	0.38
	Org.man+inorg.fert.	6056	55	12.2	11.6	37028	1398	1223	2157	3555	0.35
SE (df=5)		2022*	NS	0.43**	0.44**	2753.5**	151.7**	99.6**	117.5**	119.2**	0.01*

* P< 0.05; ** P< 0.01; NS Not significant.

Table 4.24. Sorghum cultivars yields and yield components as affected by cropping systems and soil fertility status at harvest, 1994.

Treatment	Fertility level	No. of plants/ ha	Days to 50% head formation	No. of Heads/ hill	No. of heads/ha	Head weight Kg/ha	Grain weight kg/ha	Stover weight kg/ha	Total dry matter production kg/ha	Harvest index
Sole sorghum (G.Early)	Org.man. only	47016	85	1.7	44675	1920	1144	4160	6080	0.26
	Org.man+inorg.fert.	50830	86	1.8	46130	2105	1445	3990	6090	0.34
Sole sorghum (ICSV 400)	Org.man. only	25535	71	2.3	25154	1060	643	2200	3360	0.27
	Org.man+inorg.fert.	27664	73	2.0	25549	1202	831	2240	3442	0.33
Mil/sor/cow int. (G.Early)	Org.man. only	4056	86	2.2	4972	200	142	320	520	0.28
	Org.man+inorg.fert.	4500	87	2.8	5639	299	208	420	720	0.33
SE (df=5) cropping systems		739.9**	0.28**	0.18NS	2766.7**	93.1**	149.4*	321*	267**	0.05NS
SE (df=3) fertility		262.5**	0.48NS	0.27NS	2041.3NS	131.6*	77.5NS	454NS	192NS	0.04NS

* P< 0.05; ** P< 0.01; NS Not significant.

in relation to total number of panicles per hectare. This total number of panicles produced by the sole millet system was significantly ($P < 0.01$) higher than that of the millet in the intercropping systems. The relatively higher density of millet in the millet/cowpea systems also resulted in a significantly ($P < 0.01$) higher panicle number per hectare than in the millet/sorghum/cowpea systems. The trend of the total number of panicles recorded was sole millet > millet in millet/cowpea > millet in millet/sorghum/cowpea. This same trend was observed, when panicle, grain, stover and total dry matter weights per hectare were compared.

The conversion efficiency, of assimilates to harvestable organs, at millet maturity, showed that the HI in the intercropped millet that received additional inorganic fertilizer application was higher than in the sole millet with the same soil fertility status. The HI of millet in the millet/sorghum/cowpea system with pre-planting organic manure application alone was also significantly ($P < 0.05$) higher than that in the sole millet and millet/cowpea systems with the same soil fertility status (Table 4.23).

The effects of cropping systems and soil fertility status on sorghum cultivar yields and yield components at harvest within the different cropping systems in 1994 are shown in Table 4.24. Although the number of sorghum plants in the intercrop systems were 12.5% of the sole sorghum systems at planting, the sorghum densities in the different systems show great variations, even among the sole crops at harvest. The sole ICSV 400 density at establishment was greatly affected by the irregularity of rainfall in terms of distribution and amounts, between the second and third quarter in June, such that plant densities at establishment were reduced drastically, the resowing of missing hills notwithstanding. The density of the sole ICSV 400 sorghum

cultivar at harvest varied from 25535 to 27664 plants per hectare, 48-52% of the plant density at crop establishment. However, the local sorghum variety, Gaya Early, had better establishment rates (88-95%) at harvest. The sorghum density in the intercropping systems varied from 61 to 68% of the sorghum population at planting. At the cropping system level, the sorghum density in the sole Gaya Early treatment was significantly ($P < 0.01$) higher than in sole ICSV 400, while sole ICSV 400 sorghum density was also significantly ($P < 0.01$) higher than the sorghum density in the millet/sorghum/cowpea intercrops as expected. The application of the additional inorganic fertilizer to sorghum before head formation (10 WAS), improved the plant density at harvest in the cropping systems. The sorghum population densities in the relatively higher fertility systems were higher than in the systems with pre-planting organic manure application alone, but these showed significant ($P < 0.05$) difference in the sole sorghum systems alone.

The early maturing ICSV 400 sorghum was earlier than Gaya Early, by about 14 days, while the relatively higher soil fertility plots caused differences of only one or two days, within the measuring accuracy, in the attainment of 50% head formation in all the cropping systems (Table 4.24). Although the number of sorghum heads per plant hill was slightly higher in the intercropped sorghum than in sole crop systems, the differences observed did not show any statistical significance. The sorghum density in the different cropping systems are closely related to the total number of heads produced at harvest. Sole Gaya Early sorghum, with the highest plant density, produced a significantly ($P < 0.01$) higher number of sorghum heads than the sole ICSV 400 treatment.

The number of sorghum heads produced in the sole ICSV 400 sorghum

treatment was also significantly ($P < 0.01$) higher than that in the millet/sorghum/cowpea intercrops, where the sorghum density was lower, and varied from about 16-17% of the sole ICSV 400 density. The relatively high soil fertility sorghum based systems produced a greater number of heads, but these were not different from the lower fertility treatments statistically. The trend of sorghum head, grain, stover weights and total dry matter production at cropping systems level was sole Gaya Early > sole ICSV 400 > Gaya Early in millet/sorghum/cowpea intercropping treatments. The differences were statistically significant at $P < 0.01$ in head weights and total dry matter production, while in the grain and stover yields, they were different significantly at 5% probability levels. The relatively high soil fertility treatments also resulted in higher values of grain yields and associated components, but these did not show any differences statistically. Harvest indices were similar at the cropping systems level, but higher in the relatively high fertility treatments in all the cropping systems. The higher HIs of sorghum in the high soil fertility treatments were however not significantly different from those of the systems with organic manure application alone.

The yields and yield components of cowpea cultivars sown sole and intercropped with cereals at the two fertility levels adopted are shown in Table 4.25. The performance of the cowpea cultivars sown sole and within the intercrops was greatly affected in 1994 by the distribution of rainfall and extension of the rainy season into the third quarter of October. The high intensity of rainfall, coupled with periods of relatively high atmospheric humidity and low wind speeds, encouraged the multiplication of disease organisms and insect pests which reduced cowpea foliage.

Among the sole cowpea cultivars, the population density of IT88D-867-11

Table 4.25. Cowpea cultivars yields and yield components as affected by cropping systems and soil fertility below cereal components in intercroppping at harvest, 1994.

Treatment	Fertility level	Cowpea cultivar	No. of plants /ha	Days to 50% flowering	No. of pods/ hill	No. of pods/ ha	Pod weight Kg/ha	Seed weight kg/ha	Haulm weight kg/ha	Total dry matter production kg/ha	Harvest index	No. of striga (Final harvest area)	
												flowering	pod maturity
Sole cowpea	Org.man. only	IT89KD-374	54381	49	43	751477	824	789.3	536	1325	0.60	2.0	2.0
	Org.man. only	IT88D-867-11	35561	45	51	903080	907	696.3	511	1208	0.58	1.5	3.0
	Org.man. only	DAN ILLA	29638	53	85	1256668	1334	1238	779	2017	0.61	3.0	1.0
Mil/cow int.	Org.man. only	IT89KD-374	6296	50	33	104741	123.6	100.7	72.4	173.1	0.58	1.0	3.3
		DAN ILLA	6222	65	26	81667	89.6	80.2	63.4	143.5	0.56	0.0	3.0
	Org.man+ inorg.fert.	IT89KD-374	6217	50	40	123801	126.3	108.4	87.8	196.2	0.55	3.3	3.0
		DAN ILLA	6743	63	28	88207	110.2	88.1	106.7	194.8	0.45	3.2	5.5
Mil/sor/cow int.	Org.man. only	IT89KD-374	6074	50	30	91704	90.8	70.4	42.8	133.6	0.53	3.0	5.0
		DAN ILLA	6000	65	23	81222	88.9	74.7	44.2	129.1	0.58	2.3	10.0
	Org.man+ inorg.fert.	IT89KD-374	6352	50	41	105039	117.6	103.3	69.8	173.0	0.60	2.5	3.9
		DAN ILLA	6797	65	40	140717	166.2	148.3	85.0	233.3	0.63	2.9	6.2
SE (df-19) cropping system			225.5**	0.33**	3.55**	28757**	38.1**	31.9**	23.0**	30.8**	0.035*	1.06NS	2.60NS
SE (df-9) fertility in intercropping			68.9**	0.20** (cowpea cultivar)	2.71** (Cs*Cc)	6241*	7.6**	7.1**	6.7**	11.9**	0.01**	0.52**	1.21**

* P< 0.05; ** P< 0.01; NS Not significant; Cs*Cc- cropping system * cowpea cultivar interaction.

sown at 53333 plants/ha, but at harvest with 35561 plants/ha, was still significantly ($P < 0.01$) higher than in the sole IT89KD-374 and Dan-illa cultivars (35556 plants/ha at sowing), retaining at harvest 97 and 83 % respectively of their sowing densities. The plant density at harvest in the sole IT89KD-374 was also significantly higher than the Dan-illa cultivar sown sole, although both cowpea cultivars were sown at the same density (Table 4.25). The higher resistance to cowpea disease organism by the improved IT89KD-374 as compared to Dan-illa is suggested for the difference in plant population at harvest.

The additional fertilizer application to cereal components in the intercropping systems also improved the stand counts of the Dan-illa cowpea cultivars in comparison to the intercrops with pre-planting organic manure application alone. The numbers of Dan-illa (fodder) cowpea plants in the relatively high fertility intercropping systems were significantly ($P < 0.01$) higher than those in the treatments with organic manure application alone, while the effects of soil fertility treatments did not show any statistically significant difference in population densities of IT89KD-374 in the intercropping systems. A comparison of the days to 50% flowering among the sole cowpea cultivars showed the erect early maturing IT88D-867-11 cultivars to have earliest flowering, and was significantly ($P < 0.01$) earlier than IT89KD-374 and Dan-illa. Dan-illa cowpea cultivar was also significantly ($P < 0.01$) later at reaching 50% flowering than IT89KD-374. While the number of days to the attainment of 50% flowering of the grain cowpea (IT89KD-374) was similar in the sole and intercropping systems, Dan-illa (fodder type) attained 50% flowering significantly ($P < 0.01$) later in the intercrops than when sown sole, as also experienced during the 1993 cropping season (Table 4.25).

The prostrate and most vegetative cowpea (Dan-illa) sown sole clearly produced more pods per plant hill than sole IT88D-867-11 and IT89KD-374 at harvest in 1994, when the rainy season was prolonged. The number of pods per hill of sole Dan-illa was significantly ($P < 0.01$) higher than in sole IT88D-867-11 and IT89KD-374, which were similar. However, cowpea in the intercropping systems, the number of pods produced per hill by the cowpea components did not differ statistically. Although the trend of the total number of pods produced per hectare in the sole cowpea systems was Dan-illa > IT88D-867-11 > IT89KD-374, the differences in the pod numbers did not show a statistical significance. However, pod production per hectare in the millet/cowpea intercropping treatment was significantly ($P < 0.01$) higher in the grain cowpea cultivar (IT89KD-374) than in the fodder cowpea (Dan-illa).

The additional fertilizer application to the cereal components before the commencement of reproductive stages also significantly ($P < 0.05$) improved the number of pods produced by the IT89KD-374 cowpea within the two intercropping systems (Table 4.25). Although higher numbers of pods in the Dan-illa cultivar were produced in the relatively high soil fertility intercropping systems, the effect of the higher soil fertility was only statistically significant in the millet/sorghum/cowpea intercropping system. The performance of cowpea cultivars in terms of the number of pods produced per hill in the intercropping systems were not the same. This is indicated by the significant ($P < 0.01$) interaction between the intercropping systems and the cowpea cultivars.

At the cropping systems level, the trends observed for the number of pods produced by cowpea cultivars per hectare was also the same for the pod, seed and

haulm weights and total dry matter production at harvest. The relatively poor cowpea canopy development in 1994, as compared to 1993, resulted in generally lower values of yields and components in 1994, with much lower overall dry matter production in all sole cowpea systems. The number of cowpea pods per hill and per hectare in 1993 and 1994 were similar, but this does not apply to the pod weights, which were higher in 1993. The higher incidence of diseases and insect pest attacks, on pods also, which resulted from the adverse weather conditions in 1994, must have been responsible for the poor pod filling observed in 1994 relative to 1993 harvests. Dan-illa cowpea in intercropping systems yielded higher values of the parameters considered in 1993 than was observed in 1994. However, the harvest indices in 1994 were generally higher than in 1993, also as a result of the earlier mentioned poor cowpea canopy development in 1994.

A comparison of the harvest indices of sole cowpea in 1994 indicate a similarity among the three cultivars, although Dan-illa cultivar produced the highest seed and haulm weights (Table 4.25). The HI of the cowpea cultivars in the high fertility treatment in the intercropping systems varied widely (0.45-0.63). There was higher HI values in the grain cowpea type than the fodder cowpea cultivar in the millet/cowpea system. In the millet/sorghum/cowpea systems, HI was only 5% greater in the fodder cowpea than in the grain cowpea. The high partitioning rates in the fodder cowpea is indicative of a considerable loss of the very important foliage requirements from the system by the time of seed harvests. The loss of foliage to disease organisms during the season and its later maturity toward the end of the rainy season implies a higher seed to dry matter ratio as shown by the relatively higher HI obtained.

An assessment of the number of the parasitic weeds (Striga gesnerioides) attached to cowpea roots within the marked harvest areas at 50% flowering in cowpea did not indicate any effect of intercropping on *striga* emergence and growth as compared to the sole cowpea systems. Although statistically significant differences were not inferred in the number of *striga* found attached to the cowpea cultivars in sole and intercropping systems at pod maturity, higher numbers of *striga* were attached to cowpea in the intercropping systems than in the sole crop systems. The vegetative and prostrate local cowpea cultivar, Dan-illa, in intercropping systems had more *striga* plants than the improved, semi erect grain cowpea (IT89KD-374). The effect of inorganic fertilizer treatment on cowpea *striga* emergence was also not significant.

4.9.3 *1995 cropping season*

The yield and yield components of pearl millet as affected by the different cropping systems of 1995 are shown in Table 4.26. The soil fertility treatments in 1995, similar to 1994 assessments, did not create any statistically significant differences in the parameters considered. Although 1995 recorded the least annual rainfall of the three years of experimentation, with a value of 564 mm, 22% less than the long term average for Kano, the earlier stability in rainfall distribution and the sufficient amounts in the first until third quarters of June 1995, ensured better crop establishment and the maintenance of high plant densities from emergence through harvest (Table 4.26). The millet density in the millet/sorghum/cowpea and millet/ cowpea intercropping treatments were 11.7% and 25%, respectively, of the sole millet

Table 4.26. Millet yields and yield components as affected by cropping systems at harvest, 1995.

Treatment	Fertility level	No. of plants/ ha	Days to 50% panicle formation	No. of panicles /hill	No. of tillers /hill	No. of panicles /ha	Panicle weight Kg/ha	Grain weight kg/ha	Stover weight kg/ha	Total dry matter production kg/ha	Harvest index
Sole millet	Org.man. only	53333	50	2.41	10.2	70166	2550	2052	3197	5740	0.37
	Org.man+inorg.fert.	53333	50	2.47	9.8	68046	2715	2308	3715	6430	0.37
Mil/cow int.	Org.man. only	13334	52	6.10	11.3	40667	2150	1806	2939	5090	0.36
	Org.man+inorg.fert.	13334	52	7.26	13.4	48389	2320	2012	3275	5590	0.36
Mil/sor/cow int.	Org.man. only	6222	53	10.57	15.7	32889	1560	1355	2066	3620	0.37
	Org.man+inorg.fert.	6222	54	11.11	14.5	34556	1231	1065	1859	3090	0.34
SE (df=10) cropping system		9.31**	0.47**	0.38**	0.48**	2008.2**	168.0**	135.5**	160.5*	1147*	0.028ns

* P< 0.05; ** P< 0.01; ns Not significant

Table 4.27. Sorghum cultivars yields and yield components as affected by cropping systems and soil fertility status at harvest, 1995.

Treatment	Fertility level	No. of plants/ ha	Days to 50% head formation	No. of Heads/ hill	No. of heads/ha	Head weight Kg/ha	Grain weight kg/ha	Stover weight kg/ha	Total dry matter production kg/ha	Harvest index
Sole sorghum (G.Early)	Org.man. only	75136	85	1.4	42345	1585	1457	1530	3115	0.48
	Org.man+inorg.fert.	77386	86	1.8	50883	1683	1502	2340	4023	0.37
Sole sorghum (ICSV 400)	Org.man. only	76497	73	2.1	26045	1122	990	1430	2552	0.39
	Org.man+inorg.fert.	76803	75	2.7	31395	1267	1085	1760	3027	0.36
Mil/sor/cow int. (G.Early)	Org.man. only	10250	86	2.9	9750	660	523	910	1433	0.69
	Org.man+inorg.fert.	9833	87	3.0	11917	851	668	1070	1738	0.69
SE (df=5) cropping systems		894.5**	0.29**	0.11**	1944.3**	122.2**	112.1**	53.1ns	166.8*	0.03*
SE (df=3) fertility		521.9ns	0.50ns	0.11*	1596ns	93.2ns	102.5ns	14.2ns	94.5ns	0.048ns

* P< 0.05; ** P< 0.01; ns Not significant, CS*CC- cropping system * cowpea cultivar interaction.

density. The relatively better plant establishment in 1995, compared with 1994, were favoured by adequate soil available water status, close to field capacity, especially in the intercropping systems, and by reduced cloud cover or higher available solar radiation. These conditions resulted in better canopy development and overall growth of millet and other crops planted in 1995 than in 1994.

The better growth in 1995 resulted in a greater competition for soil moisture (among other environmental factors), especially in the systems with relatively high crop density. The stress created by the higher competition for resources in the sole millets, under the prevailing conditions during the 1995 cropping season (Table 4.26), showed that the millet sown sole was able to compensate for the shortfall in available resources, especially soil water, by regulating the number of tillers produced, and accumulating assimilates quicker to commence its reproductive stages earlier than in the intercropping systems (Squire, 1987). The sole millets attained 50% panicle initiation somewhat earlier than the millets in the intercropping systems, but differences were only significant ($P < 0.05$) between sole millet and the millet/ sorghum/cowpea intercropping treatment. A comparison of the intercropping systems indicate that the millets in the millet/sorghum/cowpea treatment seem to be subjected to less competition for resources, producing more tillers but reaching 50% panicle initiation not long after the millet/cowpea systems (Table 4.26).

The number of tillers produced by millet hills in the different cropping systems indicates that the relatively lower density of millets in the intercropping systems favoured the production of higher number of tillers than in the high density sole millet systems. Millets in the millet/sorghum/cowpea treatment produced the highest number of tillers, followed by the millet/cowpea and sole millet treatments. An assessment of

the number of panicles per millet hill in the different cropping systems, showed a high relationship between the number of tillers produced per hill and the panicle numbers recorded per hill. The number of panicles per hill in the various systems differ significantly ($P < 0.01$) and varied from 11 in the millet/sorghum/cowpea systems to about 2.5 in the sole millet. The percentage of millet tillers that produced panicles varied from 67 to 77% in millet/sorghum/cowpea treatmemt, 54% in the millet/ cowpea and 24% in sole millet treatments. These values suggest that the millet components in the cropping systems exerted a lot of pressure on environmental resources as a result of their faster canopy development, higher dry matter production and earlier maturity in relation to sorghum and the fodder cowpea. The sole millet treatment with the highest millet density also produced significantly ($P < 0.01$) higher numbers of panicles per hectare than in the millet/ cowpea and millet/sorghum/cowpea treatments. Although the addition of inorganic fertilizers in the intercropping systems caused an increase in total panicle numbers produced, this only showed differences that were statistically significant when the high fertility treatment in millet/cowpea was compared with the relatively lower fertility millet/cowpea and high fertility millet/ sorghum/cowpea systems.

The weight of panicles, grains and stover yields of millet indicate the differences in the total assimilate accumulation and partitioning to the harvestable organs of the different systems at harvest. The trend of panicle weights of millet in the different cropping systems was sole millet > millet/cowpea > millet/sorghum/ cowpea. However, the panicle weights in the sole millet systems was only significantly ($P < 0.05$) different from that of millet in millet/sorghum/cowpea systems. The panicle weight in the millet/cowpea treatment was also significantly ($P <$

0.01) higher than in millet/sorghum/cowpea systems. The sole millet systems produced the highest values of grain and stover yields compared to the intercrops, but the differences in yields were only significantly ($P < 0.01$) lower in the millet/sorghum/cowpea systems. The analyses of the total dry matter production of millets in the different cropping systems showed that the yields from the sole millet were higher than in the intercrops, but only the sole millet in the relatively high soil fertility treatment produced significantly ($P < 0.05$) higher total dry matter than the millet in millet/sorghum/cowpea, with relatively lower soil fertility status. The higher ratio of panicles produced to the number of tillers in the intercropping systems than in the sole millets reduced the effects of high millet density on crop yields. The HIs of millet in the different cropping systems were similar in 1995.

The yield and yield components of sorghum cultivars in 1995 as affected by cropping systems and soil fertility status are shown in Table 4.27. The rainfall distribution and amounts, at sorghum sowing through crop establishment in June, ensured the maintenance of the high sorghum density ($\geq$ 96% of the initial density) in the sole sorghum systems until harvest. These final density was $\geq$ 86% compared to the initial density of the intercropped sorghum densities at harvest. Soil fertility treatments in 1995 also did not have an effect on the sorghum densities in the various systems at harvest. Although the days to 50% head formation of sorghum in the different cropping systems were similar in the relatively high soil fertility treatments and in the organic manure only plots, the early maturing sole ICSV 400 sorghum cultivar reached 50% head formation at least 10 days earlier than the Gaya Early, as expected (Table 4.27). Because of the observed number of sorghum plants per hill on farmers' plots in 1994 and the lack of tillering of the sorghum varieties, at thinning

the number of sorghum plants/hill was increased to three in 1995 as against the 2 plants/hill in the previous years of the trial. The influence of cropping systems on the number of sorghum heads produced per hill showed an increase in the number of heads for intercropped sorghum (Gaya Early) which was significantly ($P < 0.01$) higher than that for the sole Gaya Early, at the two soil fertility levels considered. A comparison of the two sole sorghum cultivars showed the early maturing ICSV 400 to produce more heads per hill than Gaya Early, again at the two fertility levels. They were only significantly ($P < 0.05$) higher when the number of sorghum heads in the relatively high soil fertility ICSV 400 system was compared with sole Gaya Early at the two fertility levels and ICSV 400 grown with pre-planting organic manure application alone.

The additional application of inorganic fertilizer to sorghum components before the initiation of reproductive stage caused an increase in the number of heads produced per hill. An assessment of the total number of heads produced per hectare at harvest indicates that the higher plant densities in the sole sorghum systems produced significantly ($P < 0.01$) greater number of heads than the sorghum components in the intercropping systems, with lower sorghum densities as expected. Between the two sole sorghum systems, Gaya Early cultivar produced more heads per hectare at harvest than ICSV 400 ($P < 0.01$, SE= 1944.3). The relatively higher soil fertility treatment also caused an increase in the number of heads produced per hectare in all the systems considered, but these did not show any statistical significance. The trends of the weights of sorghum heads and grain at harvest were similar in 1995, with significantly ($P < 0.01$) higher yields obtained in the sole sorghum systems. Higher soil fertility also caused higher yields in all the cropping systems, but not

significant ($P < 0.35$) statistically. The trends of sorghum head and grain weights were sole Gaya Early > Sole ICSV 400 > Gaya Early in millet/sorghum/cowpea systems. The stover yields of sorghum sown within the different cropping systems were similar to the trends observed in their head and grain production. The effects of the additional soil fertility to sorghum before the commencement of reproductive stage significantly ($P < 0.05$) increased stover yields in the sole sorghum systems. Additional inorganic fertilizers to sorghum in the intercropping treatments also caused an increase in the stover yield, but the difference was not statistically significant.

Total dry matter production of sorghum at harvest in all the systems indicate that the more vegetative, local sorghum variety (Gaya Early) sown sole, at the relatively high soil fertility level produced significantly ($P < 0.05$) higher total dry matter than in its low fertility treatment and ICSV 400 at the two fertility levels. Although the added inorganic fertilizer to sorghum components resulted in an increased dry matter production at the cropping systems level, such yield differences were not statistically significant.

The additional fertilizer application to sorghum before the commencement of reproductive stage favoured more vegetative growth than the reproductive organs, as shown by the higher HI in the relatively lower fertility sole sorghum systems. The harvest indices were lower in the relatively higher soil fertility sole sorghum treatments of the two fertility levels considered. However, the partitioning of assimilates to the harvestable organs in the intercropped sorghum was significantly ($P < 0.05$) higher than in the sole crop systems, as indicated by the higher HIs in the intercropped sorghum than in the sole sorghum systems. The periods of grain filling in the Gaya Early sorghum cultivar coincides with the senescent maturity and harvest

of millet. Hence in the intercropping systems involving millet, sorghum and cowpea, the maturity and harvesting of millet and the grain cowpea components, increased the capacity of the sorghum component to recover from the competitive effect caused by these associated crops, and increase its uptake of growth limiting soil nutrients and water. The higher HIs of the intercropped sorghum suggests better use of resources and hence greater partitioning of assimilates to the harvestable organs than in the sole sorghum systems.

The yields and yield components of the different cowpea cultivars as affected by cropping systems and additional fertilizer application to the cereal components of intercropping systems at harvest in 1995 are shown in Table 4.28. The densities of cowpea plants at harvest varied widely and are closely related to their densities at establishment within the different cropping systems. The plant densities at harvest in the sole cowpea systems were much higher than those of the cowpea components in the intercropping systems as expected. However, the record of the days to 50% flowering, which depends on the morphological attributes of the different cowpea cultivars, were also influenced significantly ($P < 0.05$) by the different cropping systems. The earliest maturing, erect grain type cowpea cultivar (IT86D-719) was first to reach 50% flowering among the sole cowpea systems, while the late maturing, indeterminate fodder cowpea cultivar (Dan-illa) was the last to attain 50% flowering. While the days to 50% flowering among the sole cowpeas did not show any significant difference statistically, the progress in days to 50% flowering of corresponding cowpea cultivars sown in the intercropping systems were later than in the sole crop systems (Table 4.28).

The higher density of plants and the absence of any influence of inorganic

Table 4.28. Cowpea cultivars yields and yield components as affected by cropping systems and soil fertility status below cereal components in intercropping at harvest, 1995.

Treatment	Fertility level	Cowpea cultivar	No. of plants /ha	Days to 50% flowering	No. of pods/ hill	No. of pods/ ha	Pod weight Kg/ha	Seed weight kg/ha	Haulm weight kg/ha	Total dry matter productio n kg/ha	Harvest index	No. of striga (Final harvest area)	
												pod filling	pod maturity
Sole cowpea	Org.man. only	ITS9KD-374	34765	43	70	1217975	1565	1466	968	2434	0.61	5.3	4.3
	Org.man. only	IT88D-867-11	51852	43	43	1108333	1380	1371	869	2234	0.62	3.0	2.3
	Org.man. only	IT86D-719	50741	41	45	1148148	1297	1286	912	2198	0.58	3.0	2.7
	Org.man. only	DAN ILLA	45756	44	53	1158152	1489	1374	1012	2501	0.60	3.8	3.1
Mil/cow int.	Org.man. only	ITS9KD-374	6500	46	39	126083	124	113	106	250	0.58	9.7	10.7
		DAN ILLA	6444	57	41	132306	153	138	157	319	0.51	9.7	10.7
	Org.man+ inorg.fert.	ITS9KD-374	6611	45	31	104056	120	115	91.5	206	0.55	5.7	4.5
		DAN ILLA	6444	55	36	117417	136	122	152.9	299	0.50	4.7	3.2
Mil/sor/cow int.	Org.man. only	ITS9KD-374	6333	50	37	117583	127	120	122.1	246	0.50	5.2	4.7
		DAN ILLA	6556	65	43	141389	173	157	148.6	346	0.57	5.3	4.5
	Org.man+ inorg.fert.	ITS9KD-374	6500	50	39	125000	139	129	125.6	260	0.51	4.2	4.2
		DAN ILLA	6556	65	35	114750	137	122	167.2	290	0.49	4.7	3.2
SE (df=19) cropping system			73.1**	0.38**	2.21**	15009**	17.5**	19.2**	16.5**	17.9**	0.013**	1.12**	1.29**
SE (df=9) fertility in intercropping			59.7**	0.38** (cowpea cultivar)	1.8**	12255**	14.3**	15.7**	13.5* (cowpea cultivar)	14.6** (cowpea cultivar)	0.010**	0.91*	0.91**

* P< 0.05; ** P< 0.01; ** Not significant.

fertilizer in the sole cowpea treatments provoked more competition for environmental resources (e.g. stored soil water, nutrients and radiation). Hence they progressed faster to the growth stage of partitioning assimilates into the reproductive organs than the relatively wider spaced crops in the intercrops, with different morphological attributes. The relatively favourable weather conditions in 1995, as compared to 1994, encouraged faster canopy development of all the crops in the various cropping systems, increasing competition and hence major differences in the adjustments to stress situations of the least competitive crop components (C_3 cowpea plants). The cowpea components in the millet/cowpea systems attained 50% flowering significantly ($P < 0.05$) earlier than those in the millet/sorghum/cowpea systems (with a maximum of 5 days in the IT89KD-374 and 10 days in Dan-illa). This suggests that cowpea flowering is hastened by the competitive effects created by the relatively high density of the faster dry matter accumulating millets in the millet/cowpea intercropping system than in the lower millet density in the millet/sorghum/cowpea system under resource limiting conditions.

During years of relatively lower rainfall amounts (that fell most often over shorter periods), below the long term average, such as 1993 and 1995 as against 1994, when rainfall was 7% above long term average, the grain yield potentials of the early maturing grain cowpea types are better expressed. Among the sole cowpea systems, the grain cowpea type, IT89KD-374, like in 1993, produced significantly ($P < 0.01$) higher number of pods per hill than the other cowpea cultivars sown sole. The competitive effects of earlier planted, taller and faster dry matter accumulating cereals, especially millet, relative to the cowpea components in the intercropped

systems, shade the cowpea components and reduce their photosynthetic abilities. This resulted in the significantly ($P < 0.01$) lower number of pods per hill produced by the intercropped cowpea cultivars compared with their corresponding cowpea cultivars sown sole. In terms of pod and seed weights produced per hectare, the IT89KD-374 cultivar was still superior in yield, when compared with other sole cowpea treatments. The pod and seed yields of cowpea components (IT89KD-374) in the intercropped treatments were however not significantly different for both fertility levels.

Among the sole cowpea treatments, the local, vegetative and indeterminate cowpea cultivar, Dan-illa , produced significantly ($P < 0.05$) higher haulm weight than IT89KD-374, while at the intercropping level, the fodder cowpea type (Dan-illa) also significantly ($P < 0.05$) produced higher haulm weights than the grain cowpea cultivar (IT89KD-374) in both intercropping systems for the two fertility levels (Table 4.28).

The trend of the total dry matter production among the sole cowpea systems was Dan-illa > IT89KD-374 > IT88D-867-11 > IT86D-719. The differences among these sole cowpea systems were also statistically significant ($P < 0.01$). Also at the intercropping level, the fodder cowpea cultivar produced higher total dry matter than the grain cowpea cultivar. The HIs in the sole cowpea systems were generally higher than in cowpea cultivars in the intercropping systems, while in the millet/cowpea systems, the grain cowpea cultivars indicated higher harvest indices than the more vegetative fodder cowpea cultivar (Dan-illa). The additional fertilizer application to the cereal components in intercropping systems before the commencement of the reproductive stages did not influence the yields and yield components of the cowpea components significantly. However, the emergence of the parasitic cowpea striga

plants (Striga gesnerioides), as indicated by the number of the weeds that were attached to cowpea roots within the marked final harvest areas of all the cowpea based systems at pod filling and pod maturity, was related to soil fertility status. During cowpea pod filling, the *striga* counts in the intercropping systems were generally higher than were recorded in the sole cowpea systems, but these did not show statistical significance. However, in the intercropping systems the number of *striga* plants that emerged under cowpea hills was significantly ($P < 0.05$) reduced by the additional fertilizer application to the cereal components before the commencement of their reproductive stages. At cowpea pod maturity in the intercropped systems, the relatively higher soil fertility treatment of the cereal components further reduced significantly ($P < 0.01$) the number of *striga* plants attached to cowpea plants.

The yield and yield components of crops in the intercropped systems in the three years of experimentation have shown clearly the significant cowpea yield decline that occurred when cowpea was sown two to three weeks after millet and/or sorghum, as a result of the competitive nature of the cereals, due to their faster canopy development and higher root density production. The early sowing of the cereals in relation to the cowpea components affords the cereals a better competitive ability. The faster canopy development by the cereals, especially millet, reduces the amount of radiation available for photosynthesis in the low growing cowpea, while the higher root density produced by the cereals more effectively exploits below ground resources than the cowpea components in association. An increase in the density of millet in intercropping systems aggravates the condition earlier mentioned above, while an increase in the sorghum component would imply additional higher below ground competition because of its more ramified rooting system and higher root densities than

millet and cowpea. The increased soil fertility level around the cereal member of an intercropping system also increases the competitive ability of the cereal component through increased root density which exerts more pressure on a limiting below ground resource, as far as this applies to the same soil horizon. A higher biomass production above ground due to increased soil fertility also creates more shade that is detrimental to the low growing cowpea growth and development.

CHAPTER 5

DISCUSSION AND CONCLUSIONS

5.1 General on the effects of weather conditions and crop performances on yields

Among the weather parameters in the semi-arid zone of Nigeria, the most variable is rainfall, as also shown during our three years of experimentation. The amounts of rainfall, its distribution during the early stages of the rainy season as well as its duration are very crucial to the success or otherwise of crop establishment, development and productivity during a cropping season. The prominent features that mark the onset of rainfall in arid and semi-arid zone of Nigeria are the high air and soil temperatures recorded within these periods (May-June) due to the high solar radiation transmission to the almost bare soil surface on most farm lands. These farmlands had already been stripped of the vegetation from the previous rainy season at harvest, and also by animal grazing of the stover during the over 7 months period of the dry season.

The first rains are not as important as the sufficiency in amounts to meet the high evaporative demands of the environment during crop germination and establishment. The duration and distribution of the seasonal rainfall in relation to crop growth stages and duration also determine the yield and grain quality of the different crops at harvest.

The relationship between the performance of the cereal based cropping patterns and the amounts and distribution of rainfall varied widely in the three years of

experimentation. The onset of the rainy season, relative to the farmers' sowing dates as mimicked by our trials, showed that 1993 and 1995 had better crop establishment after sowing in mid June as compared to the 1994 sowings. The amounts of rainfall during the second decade of June were 77 and 62 mm while in the third decade of June, they were 37 and 99 mm in 1993 and 1995 respectively. The amounts of rainfall during the second and third decade in June 1994 were 20 and 12 mm respectively. The rainfall distribution after sowing in 1993 was sufficient until the third quarter of June, while in 1995 it was adequate until early July for emergence and establishment of the crops, without the need for resowing as experienced in 1994. At sowing in 1994, soil moisture from rainfall was after all several times not enough to meet the evaporative demands of the environment and hence the resowing of crops three times before crop establishment, nothwithstanding that the annual rainfall in 1994 (769.8 mm) was 7% above the long term average for Kano, and also highest in the 3 years of experimentation.

The grain and total dry matter yields of millet and sorghum were improved by high annual rainfall amounts. The total dry matter yield of the sole millet system in 1994 was greater by 13% than the yields in 1993 and 1995, while the millet grain yield was only slightly higher in 1994 than in 1995, but 24% above the 1993 yield. Although the annual rainfall in 1993 and 1995 were respectively about 17% and 27% less than the 1994 amount, adequate supply of soil water at least into the second week of September ensured good yields of millet at maturity, by the third quarter of the same September. Water, in essence, was not the most limiting constraint to the productivity of millet during these periods.

In the intercropping systems, the yields of the millet components in relation

to annual rainfall amounts in the three years did not show an increasing trend. The differences in total dry matter were not statistically significant in the millet based cropping systems. This was a result of the high tillering ability of millet sown at low plant density and, in essence the low effects of intercropping on millet total dry matter production. The dry matter and grain yields of millet in the millet/cowpea systems in 1995 (lowest annual rainfall value) were greater than in 1994 and 1993, which had, however higher annual rainfall values. In the millet/sorgum/cowpea system, the greatest millet yield was recorded in 1994. This shows that other reasons than rainfall amount affected millet's performance in intercropping systems. The adequate availabilty of solar radiation in the relatively lower cloud covers of 1995 compared with 1994, in association with sufficient moisture and adequate soil fertility, are suggested for the better millet yields in 1995. During the periods covered by these experiments (1993-1995), soil water and fertility were adequate for millet growth and productivity. The lack of a statistically significant increase in the yields of millet component for all three years of experimentation, with the additional inorganic fertilizer to the pre-planting organic manure application, also implies that the initial soil fertility status of our soil (at Minjibir) at sowing is very crucial to millet growth rate and yield. The annual application of a blanket recommendation of compound fertilizer NPK 15-15-15 at 200 kg/ha before the start of these experiments in 1993 had built up the soil phosphorus levels to near medium availability levels as shown in our soil analysis results, while nitrogen was adequately supplied by the pre-planting organic manure applications. It was also observed in the drier 1995 season that the addition of inorganic fertilizers as top dress before millet panicle initiation did not improve the leaf area accumulation of millet in the three cropping systems involved,

but after a lower maximum, only reduced the rate of LAI decline within the grain filling periods. This also suggests that the application of pre-planting organic manure with the prevailing soil nutrient status ensured that the major soil nutrient requirements of millet were not limiting. In essence, the adequacy of soil fertility status close to the time of sowing of millet would greatly benefit millet productivity.

The yield of sorghum in relation to rainfall amounts and distribution show the importance of the rainfall distribution towards the end of the rainy season, normally in September. The amount of water stored in the soil determines the performance of the later maturing sorghum components (Gaya Early) that matures in late October. The earlier maturing improved ICSV 400 is ready for harvest about 90 DAS and hence was not adversely affected by the rainfall distribution in the three years of field trial. Gaya Early in sole and intercropping systems had good yields in 1994 and 1995 seasons, the influence of the intercrops on growth and development of Gaya Early notwithstanding. However, lower yields were obtained in 1993 as a result of the early cessation of rainfall in September. Gaya Early sorghum productivity in 1993 was about 52% lower, when compared with 1994 and 1995 yields, because the sorghum had to mature under water stress conditions. Although the total amount of rainfall in 1995 was about 12% less than was recorded for 1993, the amounts in the third decade of September 1995 (58.2 mm) as compared to the same period in 1993 (14.1 mm) was enough to ensure the storage and better availability of adequate soil water during Gaya Early sorghum grain filling in 1995 than in 1993. The additional inorganic fertililzer before sorghum heading caused slight increases in grain and total dry matter production which did not show any statistical significance. Apart from the early maturity of ICSV 400 than Gaya Early, it produced lower grain yield and total dry

matter. This was due to the genetic attribute of ICSV 400 when compared with the taller, higher biomass producing and late maturing Gaya Early.

While the relatively higher rainfall in 1994 as compared to 1993 and 1995 was favourable to the millet component and beneficial to late maturing sorghum productivity, the cowpea components, in contrast, were adversely affected by the excessive wetness of the season. The high rainfall amounts in 1994, with a distribution that extended into October, was accompanied by weather conditions that favoured the increase in the incidence of diseases and insect pests. The result was lower total yield and poor cowpea seed quality observed at harvest. The end of the rains in 1993 and 1995 was accompanied by relatively clearer skies, lower relative humidities and higher air temperatures among others. These enhanced higher cowpea yields and better seed quality at harvest than in 1994 after the usual initial competition problems of the relay cropped cowpea that has remaining negative influences on cowpea yields. This implies that soil water availability may not be a limitation to cowpea productivity in these cereal based cropping systems of semi-arid zone of Nigeria (Grema and Hess, 1994), but the performance of cowpea in a continuously wet condition during the growing season may be adversely affected by disease and harvesting problems such as bacterial and fungal attacks resulting from persistent dew formation and insufficient sunshine for drying and threshing of pods. Yields of millet were relatively stable during the 3 years of experimentation, while sorghum productivity was affected by the duration of rainy season in relation to the time of maturity (1993) and cowpea yields reduced in general because of late planting (Ntare and William, 1992), and additionally in the relatively wet year (1994).

The intercropping of millet and/or sorghum with the two cowpea cultivars

(IT89KD-374 and Dan-illa) showed overlap of roots of component crops, in essence suggesting competition among the crops for below ground resources. The different rooting patterns of the cowpea and cereal(s) in intercrops indicate the components' ability to compete and adapt to limiting resources (e.g. moisture and nutrients). The rooting pattern of the component crops in the intercrops as compared with their sole systems have shown that cowpea produced greater root density and achieved deeper rooting depths in intercropping systems involving cereals (millet and/or sorghum) than when sown sole. This is in agreement with Hamblin and Tennant (1987) results which suggest that cereals develop well-ramified root system which persists through wetting and drying cycles, whereas legumes tend to grow, lose, and regrow roots in response to variations in available soil water and other below ground resources. This also suggest that cowpea intercropped with cereals in the semi-arid zone of Nigeria may be a strategy for reducing the effects of drought on cropping system productivity. Table 5.1 show that soil temperature effect may have influenced shoot/root relationship. The farmers' cowpea cultivar (Dan-illa), which is later maturing, prostrate and has more vegetative fodder, achieved a deeper rooting depth, with greater root density than the improved grain cowpea type, when intercropped with cereals. Dan-illa also used soil water more efficiently than the grain cowpea types when compared at the sole system level. This suggests a better ability of the local cowpea cultivar (Dan-illa) to adapt to the arid and semi-arid condition, hence being able to better compete for resources than the improved cowpea varieties.

5.2 Soil temperature and light interception

The soil temperatures measured within the different treatments at cowpea maximum LAIs and high millet canopy development, about 55 DAS millet, in relation to the mean midday percent light intercepted during the 1994 and 1995 cropping seasons are shown in Table 5.1 (a) and (b). The soil temperature trends in the different cropping systems indicate some degree of shading. There was negative correlation between soil temperature under the treatments and the percentage of radiation intercepted by the cropping systems. During 1994 season, when the growth and development of the cowpea components of the different systems were relatively poor, the relationship was weak (r^2= -0.21, P=0.36). During the 1995 season, however, the better growth of the cowpea components improved the degree of ground shading, corresponding to an increase in correlation (r^2=-0.48, P=0.13). The relationship appears to hold better within one cropping system than in the comparison

Table 5.1 (a) Relationship between mean midday percent radiation interception and mean surface soil temperature (11:00-14:00 hr) under different cropping systems at cowpea maximum LAI and high millet canopy development during 1994 season.

Cropping system	Fertility level	Light Interception (%)	Soil temperature (°C)	Correlation coefficient (r^2)
Mil/cow int.	OM + IF	52.0	-	0.21, P=0.36
	OM	42.0	27.9	
Mil/sor/cow int.	OM + IF	46.3	31.4	
	OM	33.8	32.5	
Sole millet	OM + IF	80.8	31.9	
	OM	86.4	25.8	
Sole cowpea	OM	45.0	31.7	

Table 5.1 (b) Relationship between mean midday percent radiation interception and mean surface soil temperature (11:00-14:00 hr) under different cropping systems at cowpea maximum LAI and high millet canopy development during 1995 season.

Cropping system	Fertility level	Light Interception (%)	Soil temperature (^{0}C)	Correlation coefficient (r^2)
Mil/cow int.	OM + IF	75.2	30.4	
	OM	81.5	27.3	
Mil/sor/cow int.	OM + IF	78.8	27.8	
	OM	71.8	30.7	0.48, P=0.13
Sole millet	OM + IF	88.0	28.5	
	OM	83.7	-	
Sole cowpea	OM	76.8	29.7	

of all systems. This is due to differences in shade distributions. The lack of a strong negative correlation in the relationship between surface soil temperatures and the intercepted percentage of radiation incident on the crop combination also suggests inadequate canopy cover, especially in the widely spaced farmers' intercropping systems. The need for a better manipulation of component crops to achieve a better spatial and temporal ground cover of the vegetation to increase light capture, increase ground shading against weed infestation and, in essence, effect an improved system productively is thus identified. In a close sorghum/groundnut (30 x 20 cm sorghum,30 x 10 cm groundnut) intercropping system, a strong negative correlation (r= -0.84), significant at 5% probability level, has been reported (Matthews *et al.*, 1991).

5.3 Soil temperature fluctuations and surface water content

Although soil temperature fluctuation is also reduced by higher soil water contents, due to the higher thermal conductivity and heat capacity of water. The different amounts of shade cast by the sole and intercrops are more likely the main cause of the differences in amplitude, because temperatures were measured directly

below the stem of plants, while phase shift at the same depth is also an important factor (when temperatures at a certain period of the day are compared). The spreading canopy of the low growing cowpea components, already shaded by the taller cereal(s) in intercropping at the peak of canopy development, seem to have created the lower diurnal fluctuations in the intercrops relative to the sole crops early during the 1994 and less pronounced during 1995 cropping seasons. The day/night temperature gradients in the soil is a driving force for movement of water vapour. Soil surface evaporation below a dense crop canopy is reduced, due to shading as well as reduced air movement, the way mulches also influence soil evaporation. The combination of all these factors determines differences in soil moisture near the surface. As observed in section 4.5.2, periods of reduction in soil temperature fluctuations came earlier under the intercropping systems and sole cowpea than under sole cereals. The intercropping systems offered a faster ground cover, creating a better environment for further plant growth and development at the earlier stages of crop growth, when competition for resources is more pronounced. It would also be interesting to investigate soil temperature influences on root growth and the influences of shoot(shade)/root relationship. Table 5.1 suggest little of such influences in seasons like that of 1995, because of the low differences in intercepted radiation, but the OM light interception and temperature data, with differences up to 7^{0}C, suggest such effects may have been present in 1994. In later growth stages, soil temperature and its fluctuations become agronomically less important but may be used as an indication for shade that would determine the quality of microclimate for non shade tolerant weeds.

5.4 Water balance and water use efficiency

Water use efficiency of sole and intercropping systems during the periods covered by these trials may have been biased upward because water uses were computed by assuming that extraction from below 105 cm soil depth was negligible, while in 1994, the non-inclusion of the drainage terms would have increased the bias of upward water use estimations.

The water use and water use efficiency of sole millet, sorghum and cowpea, and the millet and sorghum based cropping systems as influenced by crop maturity duration, soil fertility status and the annual rainfall patterns during 1994 and 1995 growing seasons are presented in Tables 5.2-5.7. The water use efficiencies were compared using grain yields and total dry matter production at the cropping system levels. The abundance of soil available water in 1994, after the initial deficits at establishment but throughout the growing season, caused little variations among the treatments in soil water storage (see section 4.6.8 (a)).

Table 5.2 Total grain yields, total dry matter production (TDM), water use (WU) and water use efficiency (WUE) of the millet based cropping systems, Minjibir, 1994.

Cropping system	Soil fertility	Grain yield (kg/ha)	Dry matter production (kg/ha)	WU (mm)	WUE (grain) kg ha^{-1} mm^{-1}	WUE (TDM) kg ha^{-1} mm^{-1}
Sole millet	OM + IF	2255	7415	388	5.8	19.1
	OM	2318	7769	357	6.5	21.8
Mil/cow. int.	OM + IF	1670	5629	377	4.4	15.0
	OM	2160	5362	351	6.2	15.5
Mil/sor/cow int.	OM + IF	1590	4239	503	3.2	8.2
	OM	1570	4786	493	3.2	9.7
SE	*(df = 3) cropping system*	197*	12.7**	91*	0.56 NS	0.12 *
	(df = 3) fertility	180 NS	288.5 NS	92 NS	0.47 NS	0.63 NS

Table 5.3 Total grain yields, total dry matter production (TDM), water use (WU) and water use efficiency (WUE) of the sorghum based cropping systems, Minjibir, 1994.

Cropping system	Soil fertility	Grain yield (kg/ha)	Dry matter production (kg/ha)	WU (mm)	WUE (grain) kg ha^{-1} mm^{-1}	WUE (TDM) kg ha^{-1} mm^{-1}
Sole sorghum (Gaya Early)	OM + IF	1445	6090	488	3.0	12.5
	OM	1144	6080	489	2.3	12.4
Sole sorghum (ICSV 400)	OM + IF	831	3442	501	1.7	6.9
	OM	643	3360	505	1.3	6.7
Mil/sor/cow int.	OM + IF	1590	4239	503	3.2	8.2
	OM	1570	4786	493	3.2	9.7
SE	(df=3) cropping system	138 *	402 NS	40 NS	0.28 NS	0.81 *
	(df=3) fertility	202 NS	390 NS	39 NS	0.41 NS	0.79 NS

Table 5.4 Total grain yields, total dry matter production (TDM), water use (WU) and water use efficiency (WUE) of the sole cowpea cropping systems, Minjibir, 1994.

Cowpea cultivar	Grain yield (kg/ha)	Dry matter production (kg/ha)	WU (mm)	WUE (grain) kg ha^{-1} mm^{-1}	WUE (TDM) kg ha^{-1} mm^{-1}
IT89KD-374	789	1325	389	2.0	3.4
Dan-illa	1238	2016	386	3.2	5.2
IT88D-867-11	696	1207	400	1.7	3.0
SE (d.f=8)	5.4 *	64.6 NS	6.0 NS	0.013 *	0.16 NS

Table 5.5 Total grain yields, total dry matter production (TDM), water use (WU) and water use efficiency (WUE) of the millet based cropping systems, Minjibir, 1995.

Cropping system	Soil fertility	Grain yield (kg/ha)	Dry matter production (kg/ha)	WU (mm)	WUE (grain) kg ha^{-1} mm^{-1}	WUE (TDM) kg ha^{-1} mm^{-1}
Sole millet	OM + IF	2308	6430	258	8.9	24.9
	OM	2052	5740	215	9.5	26.7
Mil/cow. int.	OM + IF	2272	6100	211	10.8	28.9
	OM	2111	5660	196	10.8	28.9
Mil/sor/cow int.	OM + IF	2011	5140	339	5.9	15.2
	OM	2199	4970	332	6.6	15.0
SE	(df=3) cropping system	156.2 NS	253 *	57.6 *	0.57 **	1.12 **
	(df=3) fertility	143 NS	177 NS	56.1 NS	0.52 NS	0.84 NS

Table 5.6 Total grain yields, total dry matter production (TDM), water use (WU) and water use efficiency (WUE) of the sorghum based cropping systems, Minjibir, 1995.

Cropping system	Soil fertility	Grain yield (kg/ha)	Dry matter production (kg/ha)	WU (mm)	WUE (grain) kg ha^{-1} mm^{-1}	WUE (TDM) kg ha^{-1} mm^{-1}
Sole sorghum (Gaya Early)	OM + IF	1502	4023	341	4.4	11.8
	OM	1457	3115	303	4.8	10.3
Sole sorghum (ICSV 400)	OM + IF	1085	3027	284	3.8	10.7
	OM	990	2552	251	3.9	10.2
Mil/sor/cow int.	OM + IF	2010	5143	339	5.9	15.2
	OM	2200	4967	332	6.6	15.0
SE	(df=3) cropping system	205 *	99 **	32.8 ^{NS}	0.60 ^{NS}	0.31 **
	(df=3) fertility	79 ^{NS}	68.2 *	29.4 ^{NS}	0.24 ^{NS}	0.19 ^{NS}

Table 5.7 Total grain yields, total dry matter production (TDM), water use (WU) and water use efficiency (WUE) of the sole cowpea cropping systems, Minjibir, 1995.

Cowpea cultivar	Grain yield (kg/ha)	Dry matter production (kg/ha)	WU (mm)	WUE (grain) kg ha^{-1} mm^{-1}	WUE (TDM) kg ha^{-1} mm^{-1}
IT89KD-374	1466	2434	191	7.7	12.7
Dan-illa	1374	2501	188	7.3	13.3
IT88D-867-11	1371	2234	204	6.7	11.0
IT86D-719	1286	2198	168	7.7	13.1
SE (d.f=8)	95.5 ^{NS}	106 ^{NS}	12.9 *	0.52 ^{NS}	0.56 *

Such little effects did not bring out the advantages or otherwise, that could be inferred from the combination of genetically and phenotypically different crops in intercropping as compared with their sole crops in relation to the root zone water extraction. For 1995, the effect of higher soil fertility on water use was between 11 and 17% in the sole cereal treatments, but the effects in intercropping were within the measuring accuracies. As stated in section 4.6, this suggests that these intercrops at farmers' levels creates less stress and a better soil water use than in the sole crops.

The calculated crop water use values were higher in 1994, with a high annual rainfall amount (769.8mm) and no drainage term included than in 1995 (564mm).

During the 1995 season, total annual rainfall was 22% less than the long term average and about 80 mm went to deep drainage. During the 1994 cropping season, the relative WUE of the millet based cropping systems as shown in Table 5.2, indicate a better WUE in sole millet over the millet/cowpea intercrops, when compared at the same fertility level. The efficiency of grain production in the relatively high fertility millet/cowpea system was about 25% less than in the sole millet system per unit of soil water used. The relatively poor performance of the cowpea components in terms of biomass accumulation and seed loss to diseases and pests resulting from the excessive wetness and other unfavourable weather conditions in 1994 are suggested for this trend.

The higher WUE (TDM) of the sole millet at the relatively higher plant density than in the intercrops, when soil available water was not limiting, is probably attributable to the better efficiency of the C_4 cereal species. The C_4 cereal species with greater root length densities extracted more soil water and produced greater yields than the C_3 legume (cowpea). The good seed yield of millet in 1994 was also not enough to compensate for the better use of water that could have been derived from cowpea in the intercropping association, if diseases and pests had not affected cowpea productivity. Our root studies embracing the component crops in the millet/cowpea intercropping system (section 4.7) did show the ability of the fodder and grain cowpea components to achieve a deeper rooting depth than millet, and hence make a better use of the soil available water than in their sole crop situation. This is also a reflection of the better competitive ability of cowpea at exploring deeper soil horizons in intercropping situation. This might be the reason for its preference and wide adoption in farmers' intercropping practices involving cereal (millet and/or sorghum) and

cowpea in the Nigerian semi-arid areas. The longer duration of the sorghum component after the harvest of millet and cowpea in the millet/sorghum/cowpea system caused an increase in the system water use.

The WUE of grain production in the sole millet and millet/cowpea systems were higher than in the millet/sorghum/cowpea system. However, these differences in WUE did not show any statistical significance at both cropping system and soil fertility levels. At the cropping system level, considering the millet based systems, the WUE of total dry matter production varied considerably, while soil fertility status did not show any statistically significant effect. The trend of WUE of system dry matter production was sole millet > millet/cowpea > millet/sorghum/cowpea. The higher plants density in the sole millet compared to the intercrop densities, coupled with the poor biomass development of cowpea in 1994, favoured a better WUE in sole millet dry matter production than in the intercropping systems.

The rainfall pattern of 1994, lasting until late October, ensured that soil water was not a limitation to sorghum productivity in the sorghum based cropping systems. The productive capabilities of the late maturing (> 120 days) and higher dry matter accumulating Gaya Early was enhanced by the prolonged rainy season. The WUE of grain production in the sorghum based cropping systems, as shown in Table 5.3 indicate that sole sorghum, Gaya Early and the millet/sorghum/cowpea intercropping system used water more efficiently than the improved ICSV 400 planted sole. The WUEs of the three sorghum based systems for grains were however not significantly different statistically when assessed at cropping system and soil fertility status levels. The millet/sorghum/cowpea systems also show the highest grains WUEs, but for the sole Gaya Early system, this was only true for the OM fertility treatment. In the sole

sorghum systems, the relatively high soil fertility treatments improved WUE compared to the low fertility plots for sorghum grain production by about 25% in both the sole Gaya Early and ICSV 400 systems.

The WUE in terms of system total dry matter production indicate significant variations in cropping systems efficiency, while the two soil fertility status at our levels of inputs did not significantly affect the effectiveness of water use (Table 5.3). At the cropping system level, the trend of WUE in the sorghum based cropping systems is sole Gaya Early > millet/sorghum/cowpea > sole ICSV 400.

In line with the grain and total dry matter production of the sole cowpea systems which were generally low in 1994, the WUE of grain production were also generally low (Table 5.4). The prostrate and strongly vegetative local fodder cowpea (Dan-illa) in sole plots produced the highest grain yield. Because of little differences in water use, it was therefore the most effective in terms of WUE (grain) among the three cowpea varieties planted sole. The superior yield and comparably the same water use of Dan-illa may be the result of its adaptation to the environment of our studies and cause of its wide adoption by farmers in their cereal based intercropping systems, even during wet years as exemplified by the 1994 seasson. Dan-illa was also the most effective total dry matter producer of the three sole cowpea treatments in terms of water use.

In the millet based cropping system during the 1995 season, WUE in grain production was higher in the millet/cowpea system at the two soil fertility levels considered than the sole millet, but these are not different statistically (Table 5.5). The fertility treatments in our trials were not significant on systems WUEs. The slightly higher efficiency of water use in grains production of the millet/cowpea

intercropping system over the sole millet suggests better use of soil available water under the intercropping as compared to the sole millet system in a relatively lower rainfall season. The sole millet and millet/cowpea systems were however more efficient water users as grain producers than the millet/sorghum/cowpea system during the below average rainfall year of 1995 (SE= 0.57, $P< 0.01$). A comparison of the WUE of the millet based systems with reference to dry matter production in 1995 showed the same trend as observed with the grain yields.

In the sorghum based cropping systems, the WUEs of grain production in the sole systems were less than for millet/sorghum/cowpea systems, but these were not different significantly (Table 5.6). The later maturity and higher dry matter producing Gaya Early sorghum utilized more water but used it more efficiently than the shorter duration, improved ICSV 400 sorghum.

The WUE of dry matter production in the sorghum based cropping systems also indicate the superiority of the millet/sorghum/cowpea intercropping system over the sole sorghum systems. The intercropping system significantly ($P< 0.01$) produced higher total dry matter per unit land area, per unit quantity of soil available water used than the sole sorghum systems (Table 5.6). Although the relatively high soil fertility sorghum based systems showed slightly more efficient use of soil water per kilogram of dry matter produced than the systems with pre-planting organic manure application alone, particularly for Gaya Early (15% higher for OM+IF fertility treatment), while others differed by less than 5%, these differences were not statistically significant at the cropping system level. The inference from our results suggests that the relatively high soil fertility treatment seems to have favoured more of vegetative development than the partitioning of assimilates to the reproductive

organs in the sorghum based systems during the 1995 season. Not using the full potentials of grain production from the translocation of assimilates to reproductive organs may be due to the insufficiency of soil available water during 1995 season.

The WUEs of the sole cowpea systems in relation to grain and total dry matter production during the 1995 cropping season are shown in Table 5.7. The WUE (grain) of the determinate grain cowpea types (IT89KD-374 and IT86D-719) were only 5% higher than in the indeterminate and vegetative cowpea (Dan-illa). The sole IT88D-867-11 system was the least efficient of the four cowpea types sown sole in terms of WUE for both grain and total dry matter. The differences in WUE of the sole cowpea systems with reference to grain production were, however, not significant at the 1% or 5% level. The prostrate and most vegetative of the cowpea cultivars (Dan-illa) significantly ($P < 0.05$) used soil available water equally efficiently than grain types IT89KD-374 (difference only 5%) and more efficiently than IT88D-867-11 by 20% in the production of total dry matter. The shortest duration cowpea cultivar IT86D-719, was also comparable to Dan-illa in terms of WUE for total dry matter production.

The WUE of the cereal/cowpea intercropping systems was better enhanced in relatively low rainfall years with precipitation patterns extending into the second decade of September. This is exemplified by the 1995 rainy season, which is typical of the recent trend in the weather situation of the Nigerian arid and semi-arid zone (e.g. Ati, 1995). A typically wet year like 1994, in contrast, seems to favour a more efficient use of soil water in the densely sown sole cereal crop situation compared to intercrops, while productive capability of the cowpea sown sole and in the intercrops are adversely affected by diseases, pests and processing difficulties resulting from the

inadequate drying of pods.

5.5 Crop productivity

The productivities of the intercropping systems relative to the sole millet systems were assessed using the concept of land equivalent ratio (Willey, 1979). The land equivalent ratio (LER) was calculated using the yields in the sole crops of millet at each of the two fertlity levels in our condition. For an explanation and calculated example see Appendix 5.1. Millet was present in all the intercropping systems and was the fastest grower and greatest dry matter accumulator of the three crop types involved in the intercropping systems. The sole millet systems were also sown at a high density (the recommended optimum density in semi-arid Nigeria is 53,333 plants/ha). Cropping systems productivities were assessed in terms of the harvestable organs and the total dry matter production, to express the level of competition or productivity increase in the intercropping systems. While seeds are important for human consumption and as cash crops for their commercial values, the stover and haulm are of immense value to the livestock component of the farming systems in the semi-arid areas of Nigeria.

The LERs of the intercropping systems at harvest in 1993 compared with that of the sole millet system are shown in Table 5.8. In terms of the seed yields in the intercropping systems, LERs higher than 1.0 were obtained, showing the superiority in basic productivity per unit of ground area used of the intercropping systems at the farmer's planting densities over the most productive sole millet system. The millet/sorghum/cowpea system with a LER of 1.3 was more productive than the millet/cowpea system (LER=1.1) during the 1993 cropping season. However, the

comparison of the LERs in terms of the total dry matter produced per system showed that only the millet/sorghum/cowpea intercropping system had, with a LER of about 1.7, a LER larger than 1, while a LER lower than 1 in the millet/cowpea system is indicative of a slightly higher competition for resources at the level of inputs used. Hence, the better productive and less competitive of the two intercropping systems during the 1993 season was the millet/sorghum/cowpea intercropping system.

The harvest productivity of the intercropping systems compared to the sole millet system and as affected by soil fertility status during the 1994 cropping season are expressed as LERs in Table 5.9.

Table 5.8 Productivity of the intercropping systems at harvest compared with sole millet using the concept of Land Equivalency Ratio (LER), Minjibir, 1993.

Cropping system	Millet (kg/ha)		Sorghum (kg/ha)		Cowpea (kg/ha)				LER	
					IT86D-719		Dan-illa			
	Seed	*TDM*	*Seed*	*TDM*	*Seed*	*TDM*	*Seed*	*TDM*	*Seed*	*TDM*
Sole millet	1716	6150	–	–	–	–	–	–	1.0	1.0
Mil/cow int.	1368	4040	–	–	44	100	279	635	1.1	0.9
Mil/sor/cow int.	1555	4750	414	1940	45	110	144	345	1.3	1.7

Table 5.9 Productivity of the intercropping systems at harvest compared with sole millet using the concept of Land Equivalency Ratio (LER), Minjibir, 1994.

Cropping system	Fertility level	Millet (kg/ha)		Sorghum (kg/ha)		Cowpea (kg/ha)				LER	
						IT[illegible]D-374		Dan-illa			
		Seed	*TDM*	*Seed*	*TDM*	*Seed*	*TDM*	*Seed*	*TDM*	*Seed*	*TDM*
Sole millet	OM + IF	2255	7415	–	–	–	–	–	–	1.0	1.0
	OM	2318	7769	–	–	–	–	–	–	1.0	1.0
Mil/cow int.	OM + IF	1808	4773	–	–	108	196	88	195	1.01	0.94
	OM	1324	4950	–	–	101	173	80	144	0.85	0.86
Mil/sor/cow int.	OM + IF	1223	3555	208	720	103	173	148	233	0.89	0.88
	OM	1294	3329	142	520	70	134	75	129	0.82	0.70

Table 5.10 Productivity of the intercropping systems at harvest compared at harvest with sole millet using the concept of Land Equivalency Ratio (LER), Minjibir, 1995.

Cropping system	Fertility level	Millet (kg/ha)		Sorghum (kg/ha)		Cowpea (kg/ha)				LER	
						IT89KD-374		Dan-illa			
		Seed	*TDM*	*Seed*	*TDM*	*Seed*	*TDM*	*Seed*	*TDM*	*Seed*	*TDM*
Sole millet	OM + IF	2308	6430	–	–	–	–	–	–	1.0	1.0
	OM	7052	5740	–	–	–	–	–	–	1.0	1.0
Mil/cow int.	OM + IF	2012	5590	–	–	115	206	122	299	1.1	1.1
	OM	1806	5090	–	–	113	250	138	319	1.1	1.1
Mil/sor/cow int.	OM + IF	1065	3090	668	958	129	260	122	290	1.1	1.0
	OM	1355	3620	523	751	120	246	157	346	1.2	1.1

A comparison of the intercropping systems total LERs in terms of seed yields suggests that only the millet/cowpea intercropping system at the relatively high soil fertility status (LER= 1.01) was able to slightly increase productivity compared to the sole millet system. The lower LERs of the intercropping systems were the result of the poor yields obtained from the cowpea components during the relatively wet year i.e. annual rainfall of 7% above the long term average for Kano and a distribution with much rain later in the season.

The additional application of inorganic fertilizers to the cereal components before the commencement of reproductive stages in the intercropping systems resulted in varying degree of LER increases in the seed yields of some cereals cum grain cowpea systems in the intercrops. The relatively high fertility milllet/cowpea system had about 25% higher LER for seeds than the low fertility treatment (OM), while in the millet/sorghum/cowpea system the improvement in seed LER was less than 10%. In terms of the total dry matter production, the wetness of 1994, especially at cowpea flowering and podding, caused an increased incidence of foliage diseases and insect pest problems. The resultant low haulm yield of the cowpea components in the

intercropping systems had adverse effects on the overall system productivity when compared with the sole millets. The total dry matter production LERs in the intercropping systems were all lower than one, while the millet/cowpea systems showed higher total dry matter LERs than the millet/sorghum/cowpea system. This increase varied from about 10% in the relatively high soil fertility status (OM+IF) to about 25% in the intercrops that received pre-planting organic manure application alone.

The LERs of the cereal based intercropping systems compared with the sole millet system as affected by soil fertility status at harvest during the 1995 season are shown in Table 5.10. LERs are again compared using system seed yields and total dry matter productions. The LERs in the two intercropping systems fot both soil fertilities show values of between 1.0 and 1.2. In summary, the cereal/cowpea intercropping system at the farmer's planting density show in most cases some superiority in productivity over the most productive sole millet system with high densities, considering our input levels, weather conditions and the later relay sowing of cowpea. This is true in terms of both seeds and total dry matter produced at harvest, and for both fertility levels with only one exception, TDM for millet/sorghum/cowpea.

The main advantage of cereal/cowpea intercropping systems in terms of better productive capability than sole crop systems, is hence established for our conditions. It confirms the better use of environmental resources as been suggested by previous works in the field of intercropping (e.g. Baldy and Stigter, 1997). Although farmers' planting densities in intercropping situations are generally lower (< 50%) than recommended in sole crop situations, the system productivity in the cereal/cowpea

intercrops of the semi-arid zone of Nigeria is still comparable to the high density sole millet system in seasons with a good rainfall distribution and high light interception (e.g. 1995) at low to medium level input situations. The seed and haulm output from the grain and fodder cowpea types intercropped with the millet (in most cases) and in combination with sorghum in some cases, thus represent an increase in the efficiency of the utilization of resources, especially soil water. In cases of shade adaptation, as shown by the higher dry matter production of the fodder cowpea type (Dan-illa) under millet/sorghum, there is also a better use of solar radiation. The longer maturity duration of the local fodder cowpea cultivar (Dan-illa) and sorghum in the intercrops enabled them to make effective use of soil available water stored after millet and grain cowpea harvests by mid-September, which would have been lost to evaporation and deep drainage during the long period of dry season (mid-October to April). The relatively higher percentage light interception recorded among crop components in intercrops in 1995 also corresponded with the greater canopy development and TDM production than was observed in 1994.

CHAPTER 6

FINAL CONCLUSIONS AND WEATHER ADVISORIES

This research was carried out to quantify the environmental factors and resulting productivities within millet, sorghum and cowpea planted sole, at the recommended optimum densities, and intercropped, at farmers' low planting densities in representative semi-arid agricultural fields in the Kano area of northern Nigeria. There is a need for designing low input sustainable intercropping system involving cowpea, millet and/or sorghum with soil protection because of the reduced inputs of fertilizers resulting from Government Structural Adjustment Programmes. The research work differed from most agricultural microclimate studies in that the cropping systems comprised different crop mixtures which mirror the farmers' patterns and varieties at low densities and were therefore very heterogenous. Crop varieties in the intercropped systems were grown concurrently with their sole crops and the sole crops of tested improved varieties of similar genotypes which have 'high' yield potentials. The improved varieties are also reported to have multiple disease and insect pest resistance and hence serve as possible replacements for similar components in current intercropping systems.

Crop yields in relation to rainfall and its distribution from 1993 to 1995, give an initial insight into the relationships that could be established for "weather advisories", and/or for something as "response farming" and the possibility for an earlier warning on crop performances and measures to improved system productivity. when rainfall records are quickly made available, appropriate advisories may be passed to the farmers, among other on sowing time (Ati, 1995). Determination of crop varietiy sensitivity to rainfall distribution in the present agricultural systems, on

a larger scale to involve several years, would be of a great use to agricultural planners.

The farmers' practice of planting millet and/or sorghum earlier in the intercropping systems relative to the relay planted cowpea components furnishes the cereal components, especially millet, with a relatively faster initial rate of assimilates accumulation, more competitiveness for resources than the other crops in association. An implication of this practice is the negative effects on cowpea yields as shown in our case. Several reports from replacement cereal based intercropping trials at the same total plant densities as the sole cereal systems, have also indicated the depression of the cereal component yields by the simultaneously planted legume component, while the legume suffered more and produced poor yields within the intercrops (Allen and Obura, 1983; Ntare and Williams, 1992; Watiki *et al.*, 1993). In our field, the tillering ability of the faster growing millet in the relatively widely spaced intercropping systems, seems to have caused (slightly) lower depression in the yield of millet compared to the sole millet system, while the total productivity of the intercropping system was increased i.e. had a LER greater than 1.0 (1993 and 1995 seasons).

The density and morphological characteristics of crops in association influence the microclimate within the various cropping systems (Baldy and Stigter, 1997). The reduction of soil radiative heat gain and heat loss (reduced near surface soil temperature fluctuation) by a well developed low growing cowpea component in an intercropping system, is capable of reducing direct soil evaporation earlier in the season better than in the sole cereal systems and hence offers a better soil water conservation practice in the arid and semi-arid zone of Nigeria.

In the arid and semi-arid area under consideration, deep drainage loss has been

confirmed as an important component of the water balance due to the sandy nature of the soil (Agrew, 1982; Grema and Hess,1994). The amount of soil water lost to deep drainage of about 80 mm, even during a low rainfall year (1995) shows the importance of the efficient use of the limiting soil water content. A consistent incorporation of organic manure at seasonal level is probably a way of improving soil physical and chemical conditions aimed at conserving soil water by increasing water holding capacity. The generation and increased use of farmyard manure during this period of annual removal of government subsidy on inorganic fertilizer, would enhance soil water availability in these farming systems. The improvement of the soil nutrient status by an increased application of organic manure may also encourage the manipulation of the intercrop components such that an increase in plant densities would make better use of soil water that would otherwise have been lost to deep percolation beyond the rooting zones.

A knowledge of the way in which resources and related microclimatic variables interact has shown to be methodologically revealing on the appropriateness of varieties and their densities in the cereal/legume intercropping systems of the Nigerian arid and semi-arid zone. Integrating production parameters as Water Use Efficiency and Land Equivalent Ratio were suitable for characterising these cropping systems and to point to necessary improvements in these intercrops. There remains also the need for the breeding of superior cowpea genotypes (grain and fodder) with better vegetative and prostrate growth, with less competitiveness for resources in the intercrops and better resistance against some major pests and diseases. These would, in turn, improve intercropping (cereal/legume) system microclimate, while the growth and development of the intercrop constituents are enhanced. The fodder cowpea with its prostrate nature and strong vegetative growth offers great potentials for the

improvement of microclimate. A step at researching with a view of improving the cereal/legume systems in the Nigerian arid and semi-arid zones should therefore include genetically superior crop cultivars and the manipulation of the component densities along with measurements of microclimatic variables.

An improvement of the cereal/legume intercropping systems in terms of microclimate improvement may involve a reduction in plant density of the tillering and faster dry matter accumulating millet component, while the low growing and ground covering cowpea component density is increased. The sorghum component density may also be increased, but the present late maturing cultivar, which is the farmer's preference, stands the risk of low productivity in low rainfall years. The introduction of shorter duration sorghum into the intercropping systems must combine superior yield with the farmers' desirable traits that would meet their socio-economic needs.

The results of our field trials had to cope with the fact that the cereal components (C_4) require greater amounts of soil water than the cowpea component (C_3). Hence an increase in the density of the cowpea components may result in more efficient use of soil water while the intercropping systems radiation interception, soil water conservation, ground shading for weed suppression and reduced soil temperature fluctuations are enhanced.

Our results confirm that the rooting depths of crops in sole and intercropped systems are shallower when soil water condition is near field capacity than when soil water is limiting. It was also found that the root length densities of millet and sorghum below the soil surface layer (0-20 cm) were much higher under a relatively lower soil fertility status than when soil nutrient availability is high. Such abilities should also be better quantified for different crop varieties and soil conditions.

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Appendix 3.1

Mouse ceptometer
Program for polycorder

PGM
light

Line no.	Opcode	parameter
1	26 CON	0.2
2	14 STO	6
3	26 CON	24
4	14 STO	5
5	53 AON	
6	11 DLY	5
7	31 OPN	MMOUSE
8	29 VUM	ENTER
9	67 KYS	
10	29 VUM	OK
11	15 RCL	5
12	14 STO	9
13	26 CON	0
14	14 STO	8
15	14 STO	7
16	23 SCN	1.101
17	15 RCL	0
18	14 STO	4
19	15 RCL	6
20	80 SUB	
21	5 JLZ	31
22	15 RCL	4
23	15 RCL	7
24	80 SUB	
25	5 JLZ	16
26	26 CON	1
27	14 STO	8
28	15 RCL	4
29	14 STO	7
30	1 JMP	16
31	15 RCL	8
32	2 JPZ	16
33	15 RCL	7
34	37 VUA	
35	77 STF	
36	61 ICP	
37	23 SCN	1.102
38	15 RCL	0
39	37 VUA	

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40      77 STF
41      61 ICP
42      10 DJN   9.13
43      22 SNG   35
44       1 JMP   8
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Appendix 4.1(a)

1994 PRE-PLANTING SOIL ANALYSIS RESULTS

	Particle size Analysis				pH	%	%	mg/kg	Exchangeable Bases (cmol(+)/kg soil)					Extractable Micronutrient			
Block No.	Clay %	Silt %	Sand %	T.Class	H_2O 1:1	OC	TN	Av.P	Ca	Mg	K	Na	CEC	Cu	Zn	Mn	Fe
														(mg/kg)			
1	8	8	84	L.Sand	7.1	.32	.056	14.7	.66	.24	.06	.01	1.8	.17	1.1	6.2	8.5
2	8	4	88	Sand	6.6	.26	.056	19.7	.63	.29	.07	.01	2.1	.21	1.7	8.0	9.0
3	8	6	86	L.Sand	6.1	.30	.042	17.0	.64	.29	.06	.04	1.8	.19	1.8	8.6	8.9
4	10	4	86	L.Sand	5.9	.28	.056	22.4	.53	.25	.05	.03	1.4	.25	1.8	8.7	9.5
5	8	8	84	L.Sand	5.8	.38	.056	17.0	.68	.29	.07	.09	1.6	.20	2.2	7.6	8.2
6	8	6	86	L.Sand	5.8	.24	.028	15.2	.72	.30	.05	.10	2.0	.30	1.5	6.4	7.5
7	8	4	88	Sand	6.4	.34	.056	14.3	.77	.41	.08	.08	1.9	.15	0.8	5.7	7.0
8	8	6	86	L.Sand	5.6	.38	.042	10.8	.60	.26	.04	.08	1.5	.19	0.8	6.6	8.3
9	8	6	86	L.Sand	6.0	.38	.056	14.3	.84	.33	.08	.09	2.0	.19	0.9	5.6	6.9
Avg.	8	6	86		6.1	.32	.050	16.2	.67	.30	.06	.06	1.8	.21	1.4	7.0	8.2
STD	.63	1.5	1.3		.45	.05	.01	3.2	.09	.05	.01	.03	0.2	.04	0.5	1.1	0.9

T.Class- Textural Class OC- Organic carbon TN- Total Nitrogen L.Sand- Loamy sand
S.Loam- Sandy loam

Appendix 4.1(b)

1994 POST-HARVEST SOIL ANALYSIS RESULTS

	Particle size Analysis				pH % % mg/kg				Exchangeable Bases (cmol(+)/kg soil)					Extractable Micronutrient			
Treat	Clay %	Silt %	Sand %	T.Class	H_2O 1:1	OC	TN	Av.P	Ca	Mg	K	Na	CEC	Cu (mg/kg)	Zn	Mn	Fe
..SC	10	10	80	S.Loam	6.2	.12	.056	10.75	2.3	.53	.34	.16	3.5	.55	5.3	38.5	35.0
MSC	8	8	84	L.Sand	6.1	.18	.042	18.82	2.3	.63	.28	.26	3.5	.25	5.5	39.5	15.0
MSC*	6	8	86	L.Sand	6.0	.56	.070	23.01	2.9	1.2	.35	.37	4.8	.85	6.1	47.5	17.3
MC	8	12	80	L.Sand	5.7	.32	.042	14.34	1.9	.45	.21	.16	2.8	.98	4.4	30.5	13.0
MC*	6	8	86	L.Sand	5.4	.12	.028	17.92	1.5	.34	.26	.24	2.4	.78	8.5	22.5	18.8
MC	8	8	84	L.Sand	6.1	.22	.042	10.75	1.4	.38	.21	.37	2.4	.95	4.8	36.0	17.8
S.M*	4	10	86	Sand	5.7	.34	.056	32.26	1.8	.67	.25	.30	3.0	.85	5.5	34.0	16.8
S.M*	6	8	86	L.Sand	6.0	.32	.042	27.78	2.1	.83	.35	.33	3.6	1.3	5.0	37.5	17.5
S.M	8	6	86	L.Sand	5.2	.12	.028	14.34	1.5	.35	.14	.23	2.2	.71	6.0	31.5	10.8
S.S (G.E)	8	10	82	L.Sand	5.8	.22	.056	12.54	2.0	.45	.22	.20	3.0	.58	4.7	31.5	12.5
S.S (G.E)	6	8	86	L.Sand	5.7	.28	.035	12.54	1.3	.35	.17	.21	2.1	.68	4.5	29.8	12.7
S.S* (G.E)	8	6	86	L.Sand	6.0	.18	.014	25.09	1.4	.38	.21	.26	2.3	.98	4.5	43.5	12.4
S.S (400)	6	6	88	Sand	5.5	.22	.042	14.34	1.3	.39	.18	.18	2.1	.29	6.9	29.6	14.8
S.S* (400)	6	4	90	Sand	6.1	.32	.042	19.71	1.8	.60	.25	.32	3.0	.92	6.1	35.5	17.5

Appendix 4.1(b) contd.

1994 POST-HARVEST SOIL ANALYSIS RESULTS CONTINUED

Treat	Clay %	Silt %	Sand %	T.Class	H_2O 1:1	OC	TN	Av.P	Ca	Mg	K	Na	CEC	Cu (mg/kg)	Zn	Mn	Fe
S.Cow(374)	10	10	80	S.Loam	o.0	.60	.070	10.30	2.0	.57	.25	.20	3.1	.95	6.4	35.0	12.5
S.Cow (374)	8	10	82	L.Sand	6.4	.24	.035	14.34	1.5	.41	.20	.35	2.5	1.3	3.3	32.5	14.3
S.Cow (Dil)S	6	10	84	L.Sand	5.0	.22	.042	12.54	1.5	.48	.24	.22	2.5	.75	4.5	34.5	13.4
.Cow (Dil)S	6	10	84	L.Sand	6.1	.14	.023	8.06	1.8	.48	.23	.23	2.9	1.3	4.0	31.5	12.6
.Cow (-11)	8	6	86	L.Sand	5.0	.22	.042	14.78	1.4	.35	.15	.23	2.2	.71	6.3	27.5	12.7
S.Cow (-11)	6	10	84	L.Sand	6.9	.32	.042	17.02	1.8	.46	.22	.28	2.8	.80	4.1	25.1	16.3
Avg.	7	8	85		5.8	.26	.043	16.56	1.8	.52	.24	.26	2.8	.82	5.3	33.7	15.7
STD	1.5	2.0	2.6		0.5	.13	.01	6.14	0.4	.20	.06	.06	0.6	0.3	1.2	5.8	5.0

S.M - Sole millet
S.S - Sole sorghum
* - Cropping system with pre-planting organic manure application plus inorganic fertilizer application to cereal components before the initiation of reproductive stage.
MC - Millet/cowpea intercropping system
MSC - Millet/sorghum/cowpea intercropping system

Appendix 4.2(a)

1995 PRE-PLANTING SOIL ANALYSIS RESULTS

	Particle size Analysis				pH	%	%	mg/kg	Exchangeable Bases (cmol(+)/kg soil)					Extractable Micronutrient		
Block No.	Clay %	Silt %	Sand %	T.Class	H20 1:1	OC	TN	Av.P	Ca	Mg	K	Na	CEC	Cu	Zn (mg/kg)	Mn
1	6	8	86	L.Sand	7.0	.22	.034	14.7	1.4	.52	.15	1.42	3.5	.5	1.9	27.6
2	6	8	86	L.Sand	6.9	.31	.029	13.7	1.2	.44	.12	.34	2.2	.3	1.6	21.8
3	6	6	88	Sand	7.0	.24	.028	16.3	1.2	.56	.16	.33	2.3	.5	.8	25.4
4	4	8	88	Sand	6.8	.28	.028	15.1	1.1	.50	.18	.35	2.1	.4	.4	21.8
5	4	8	88	Sand	6.7	.28	.027	19.7	1.3	.62	.18	.32	2.4	.5	1.4	24.7
6	4	8	88	Sand	6.7	.25	.003	17.5	1.9	.62	.14	.33	3.0	.4	1.7	18.6
7	6	6	88	Sand	7.2	.31	.031	14.1	2.2	.89	.15	.30	3.6	.2	1.0	19.3
8	4	10	86	L.Sand	7.3	.38	.039	12.9	1.2	.49	.28	.40	2.4	.4	1.1	30.2
9	6	8	86	L.Sand	6.6	.29	.028	10.7	*	*	.19	.34	*	.3	.3	22.5
Avg.	5	8	87		6.9	.28	.031	15.0	1.4	.58	.17	.46	2.7	.4	1.1	23.5
STD	1.0	1.1	1.0		0.2	.04	.04	2.5	0.4	.13	.04	.34	0.6	.1	0.5	3.6

Appendix 4.2(b)

1995 POST-HARVEST SOIL ANALYSIS RESULTS

	Particle size Analysis				pH	%	%	mg/kg	Exchangeable Bases (cmol(+)/kg soil)					Extractable Micronutrient			
Treat	Clay %	Silt %	Sand %	T.Class	H_2O 1:1	OC	TN	Av.P	Ca	Mg	K	Na	CEC	Cu (mg/kg)	Zn	Mn	Fe
MSC	8	4	88	Sand	6.9	.35	.031	13.9	1.9	.40	.20	.30	2.9	.40	2.9	18.9	6.2
MSC	10	4	86	L.Sand	7.1	.38	.036	12.3	2.2	.40	.20	.20	3.1	.90	3.0	22.3	6.2
MSC*	8	4	88	Sand	6.7	.27	.029	19.1	1.8	.20	.20	.30	2.6	.90	2.6	21.1	6.9
MSC	10	2	88	L.Sand	6.9	.28	.032	12.0	1.5	.30	.20	.30	2.5	.90	2.3	22.5	6.5
MC	10	4	86	L.Sand	7.4	.31	.033	17.2	2.4	.40	.40	.40	3.7	.90	4.0	23.1	9.3
MC	8	4	88	Sand	6.6	.34	.029	15.1	1.8	.30	.20	.30	2.7	.50	3.3	19.0	6.5
MC	8	4	88	Sand	7.1	.26	.030	12.2	1.7	.40	.30	.30	2.8	.80	2.2	18.0	5.5
MC*	8	4	88	Sand	6.7	.33	.028	18.2	1.3	.40	.30	.30	2.4	.40	1.6	16.2	7.4
S.M*	10	2	88	L.Sand	6.6	.23	.027	24.7	1.6	.20	.30	.30	2.5	.70	2.5	19.5	7.2
S.M	10	2	88	L.Sand	6.9	.55	.030	17.5	1.6	.30	.30	.30	2.6	.90	2.2	18.3	5.8
S.S (G.E)	10	2	88	L.Sand	6.5	.28	.027	15.2	1.7	.30	.20	.30	2.6	1.2	2.2	17.5	7.1
S.S* (G.E)	10	2	88	L.Sand	6.4	.31	.029	23.3	1.7	.30	.10	.20	2.4	1.2	2.2	18.1	7.1
S.S* (400)	6	4	90	Sand	5.9	.29	.030	22.7	1.6	.20	.20	.20	2.4	.50	3.0	22.0	8.4

Appendix 4.2(b) contd.

1995 POST-HARVEST SOIL ANALYSES RESULTS CONTINUED

Treat	Clay %	Silt %	Sand %	T.Class	H_2O 1:1	OC	TN	Av.P	Ca	Mg	K	Na	CEC	Cu (mg/kg)	Zn	Mn	Fe
S.S (400)S	6	4	90	Sand	6.9	.30	.025	17.7	1.4	.40	.10	.20	2.2	.40	1.7	15.0	7.7
.Cow (374)	10	4	86	L.Sand	6.5	.33	.032	9.8	1.7	.30	.20	.20	2.5	1.0	2.3	21.4	6.4
S.Cow (Dil)S	10	2	88	L.Sand	6.6	.29	.030	10.0	1.7	.30	.10	.20	2.4	.90	2.0	20.2	7.2
.Cow (719)	8	4	88	Sand	6.5	.29	.028	15.7	1.5	.30	.20	.20	2.3	1.1	2.5	17.9	7.5
S.Cow (-11)	8	4	88	Sand	6.5	.29	.028	11.7	1.5	.30	.10	.20	2.2	1.0	2.1	20.9	7.3
Avg.	9	3	88		6.7	.32	.03	16.0	1.7	.30	.20	.30	2.6	0.8	2.5	19.6	7.0
STD	1.4	0.9	1.0		0.3	.07	.002	4.3	0.3	.10	.10	.10	0.3	0.3	0.6	2.2	0.9

S.M - Sole millet
S.S - Sole sorghum
* - Cropping system with pre-planting organic manure application plus inorganic fertilizer application to cereal components before the initiation of reproductive stage.
MC - Millet/cowpea intercropping system
MSC - Millet/sorghum/cowpea intercropping system

Appendix 4.3
Calculation of crop water use (0-105 cm soil depth) from using the water balance equation

(a) Sole millet treatment with organic manure application alone as an example during 1994 cropping season

Date	Cummulative amt. soil H_20 (mm)	Rainfall (mm)	Total soil H_20 (mm)	Measured soil H_20 (mm)	Evapotransp. (mm)
19/7/94				68.25	
25/7/94	68.25	19.32	87.57	84.47	3.1
4/8/94	84.47	124.74	209.21	242.97	-33.76
11/8/94	242.97	89.5	332.47	187.31	145.16
15/8/94	187.31	17.5	204.81	167.86	36.95
23/8/94	167.86	45.9	213.76	161.07	52.69
31/8/94	161.07	36.1	197.17	160.42	36.75
14/9/94	160.42	94.2	254.62	172.61	82.01
22/9/94	172.61	14.8	187.41	122.07	65.34

Total crop water use (ET)= 388.34

(b) Sole millet treatment with organic manure application alone as an example during 1995 cropping season

Date	Cummulative amt. soil H_20 (mm)	Rainfall (mm)	Deep drainage (mm)	Total soil H_20 (mm)	Measured soil H_20 (mm)	Evapot. (mm)
5/7/95			0.0		112.16	
10/7/95	112.16	5.8	0.0	117.76	104.5	13.46
19/7/95	104.5	29.47	0.0	133.97	77.0	56.97
10/8/95	77.0	113.82	31.51	159.31	122.23	37.08
17/8/95	122.23	17.27	12.96	126.54	75.07	51.47
25/8/95	75.07	34.0	5.8	103.27	104.79	-1.52
5/9/95	104.79	71.14	21.87	154.06	109.7	44.36
11/9/95						

Total crop water use (ET)= 201.82

(c) The cropping system mean water use with the millet/sorghum/cowpea intercrops as an example was done by calculating the averages of soil water measurement determined by the neutron probe method for every depth measurement (15 cm interval) of the four aluminium access tubes tagged to every component in this system. The sum of these averages for 0-105 cm soil depth gives the system profile soil water content (mm) per day of measurement. After the harvest of millet and cowpea in the system, the measured soil water below the remaining sorghum alone is used for the system water use calculation. An example of the millet/sorghum/cowpea system (OM+IF) during the 1995 cropping season is shown below:

Date	Cummulative amt. soil H_20 (mm)	Rainfall (mm)	Deep drainage (mm)	Total soil H_20 (mm)	Measured soil H_20 (mm)	Evapot. (mm)
5/7/95			0.0		107.1	
10/7/95	107.1	5.8	0.0	112.9	105.3	7.6
19/7/95	105.3	29.47	0.0	134.77	101.6	33.17
10/8/95	101.6	113.82	31.51	183.91	107.9	76.01
17/8/95	107.9	17.27	12.96	112.21	97.3	14.91
25/8/95	97.3	34.0	5.8	125.5	98.7	26.8
5/9/95	98.7	71.14	21.87	147.97	105.6	42.37
11/9/95	105.6	33.7	7.79	131.51	112.2	19.31
20/9/95	112.2	20.82	0.34	132.68	128.0	4.68
4/10/95	128.0	58.9	3.47	183.43	131.9	51.53
18/10/95	131.9	0.0	0.0	131.9	99.6	32.3
6/11/95	99.6	0.0	0.0	99.6	69.1	30.5

Total crop water use (ET)= 339.18

Appendix 5.1

Calculated examples of land equivalent ratio (LER) and partial LERs for the millet/cowpea and millet/sorghum/cowpea intercropping systems. Using 1994 as an example and sole millet (OM+IF fertility treatment) as our reference crop (LER=1), LER of grain production is the sum of partial LERs. For the millet/cowpea intrcrop,

LER (millet/cowpea intercrop, OM+IF treatment)= LER_{millet} + $LER_{grain\ cowpea}$ + $LER_{fodder\ cowpea}$

$$\text{i.e. LER (mil/cow intercrop grain production)} = \frac{1808}{2255} + \frac{108.4}{789.3} + \frac{88.1}{1238}$$

LER = 0.80 + 0.14 + 0.07

LER = 1.01

For the milet/sorghum/cowpea system in 1995, LER for seed productivity was calculated for the OM fertility treatment by using sole millet (OM) as our reference crop.

LER (M/S/C OM only)= LER_{millet} + $LER_{sorghum}$ + $LER_{grain\ cowpea}$ + $LER_{fodder\ cowpea}$

$$\text{i.e. LER (mil/cow intercrop grain production)} = \frac{1355}{2052} + \frac{523}{1457} + \frac{120}{1466} + \frac{157}{1374}$$

LER = 0.66 + 0.36 + 0.08 + 0.11

LER = 1.2