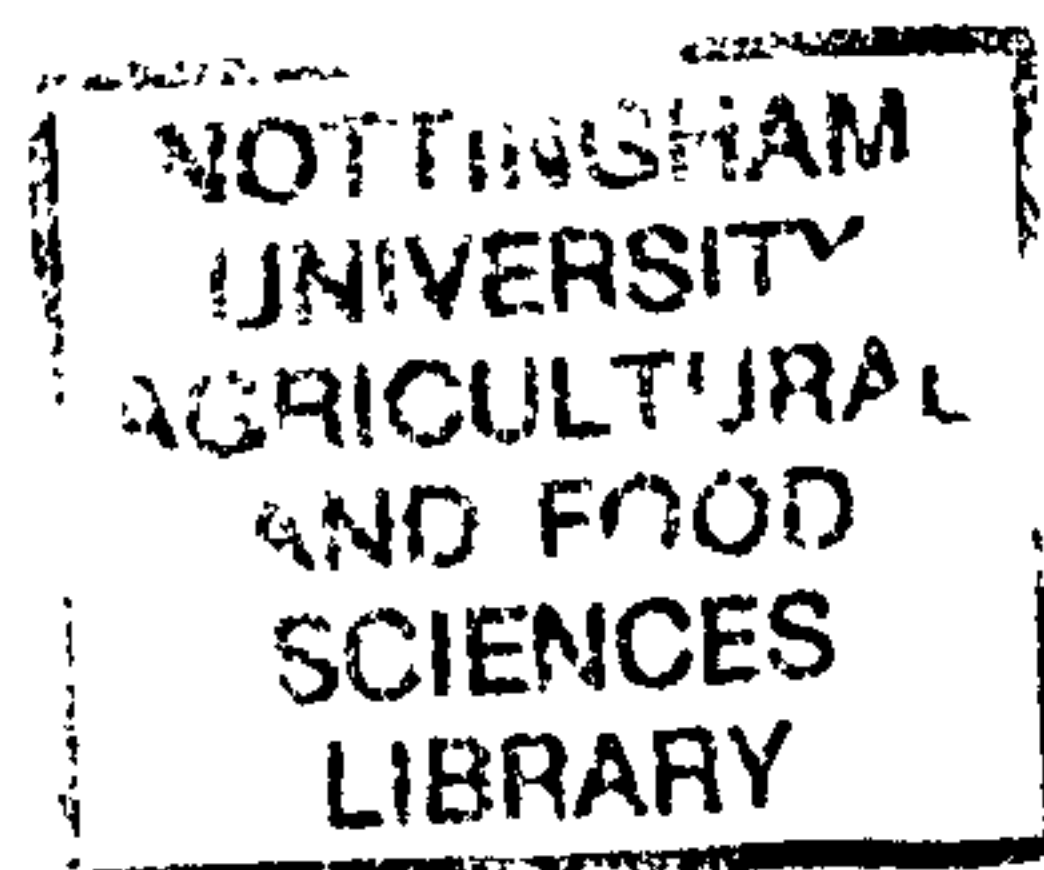


**Resource Partitioning and Productivity
of Perennial Pigeonpea/Groundnut
Agroforestry Systems in India**

by

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ABSTRACT

The productivity of two spatial arrangements of a perennial pigeonpea/groundnut agroforestry system was examined in relation to the capture and use of light and water and alterations in microclimatic conditions. Line planted (5.4 m alleys) and dispersed arrangements (1.8 x 1.2 m spacing) of pigeonpea were compared, using populations of 0.5 plants m² for pigeonpea and 33 plants m² (0.3 x 0.1 m spacing) for groundnut in both treatments. Sole pigeonpea and groundnut treatments were included for comparison.

The experiment was conducted between July 1989 and March 1991 on a 0.6 ha plot of Alfisol at ICRISAT Center, Andhra Pradesh, India, using a randomised block design with four replications. The first groundnut harvest took place in October 1989, while pigeonpea was harvested for grain and fodder in January 1990, and was cut to a height of 0.5 m during the 1990 dry season and again in August 1990 after a second groundnut crop was sown. The second groundnut harvest took place in November 1990 and the final pigeonpea grain harvest was in January 1991.

Light interception, soil and leaf temperatures and saturation deficit were continuously monitored in all treatments and at various distances from the pigeonpea in the line and dispersed treatments, whilst windspeed was monitored at a single location in each treatment. Regular destructive samples of groundnut were used to establish effects on growth and development and the results were considered in relation to the concurrent physical measurements to determine the environmental factors influencing productivity.

In order to establish a water balance, rainfall records were maintained, runoff plots were installed and soil moisture content was measured regularly throughout the drying cycle. Transpiration by pigeonpea was monitored using a heat balance technique, while transpiration by groundnut and soil surface evaporation were estimated from micrometeorological data.

As pigeonpea is initially slow growing, there was little reduction in groundnut yield

in either the line or dispersed treatments in 1989 and there was a slight intercrop advantage in overall biomass production when expressed in the terms of the land equivalent ratios. In 1990, groundnut pod yield was reduced by 20 and 44 % in the line and dispersed treatments relative to the sole crop, despite substantial increases in the light conversion coefficient for the shaded groundnut. The lower pod yield resulted from the delayed onset of pod initiation and a slower rate of development, and was mainly due the effects of shading by the pigeonpea canopy, although mild water stress may have been a minor contributory factor. The small reductions in saturation deficit and soil and leaf temperatures experienced by the shaded groundnut had a negligible effect on growth and development. There was a considerable increase in overall biomass production in the line and dispersed treatments as compared with 1989 due to rapid pigeonpea growth, which reflected an increase in overall resource use rather than in the light conversion coefficient or water use ratios of the systems.

The influence of spatial arrangement on the growth and productivity of pigeonpea became apparent after the 1990 dry season. Biomass production by pigeonpea in the dispersed treatment was approximately double that of the line planting between August 1990 and January 1991. This was entirely due to increased transpiration by the dispersed pigeonpea as a result of greater utilisation of stored soil moisture and reduced losses by surface evaporation and deep drainage. There was no difference in the water use ratio. To examine further the mechanisms responsible for the differences in productivity and water use by the line and dispersed pigeonpea, trench profile methodology was used to examine the root systems in December 1990. The root system of the dispersed pigeonpea was distributed over the entire 2.0 m depth x 2.7 m width exposed soil profile, whilst that of the line arrangement occupied no more than 50 % of the same area.

The results of this work are discussed in relation to previous studies of resource use and productivity in intercropping and agroforestry systems, and possible applications and future developments are considered. Finally, the major physical and socio-economic factors determining the potential of perennial pigeonpea/groundnut agroforestry systems for adoption by farmers in semi-arid India are discussed.

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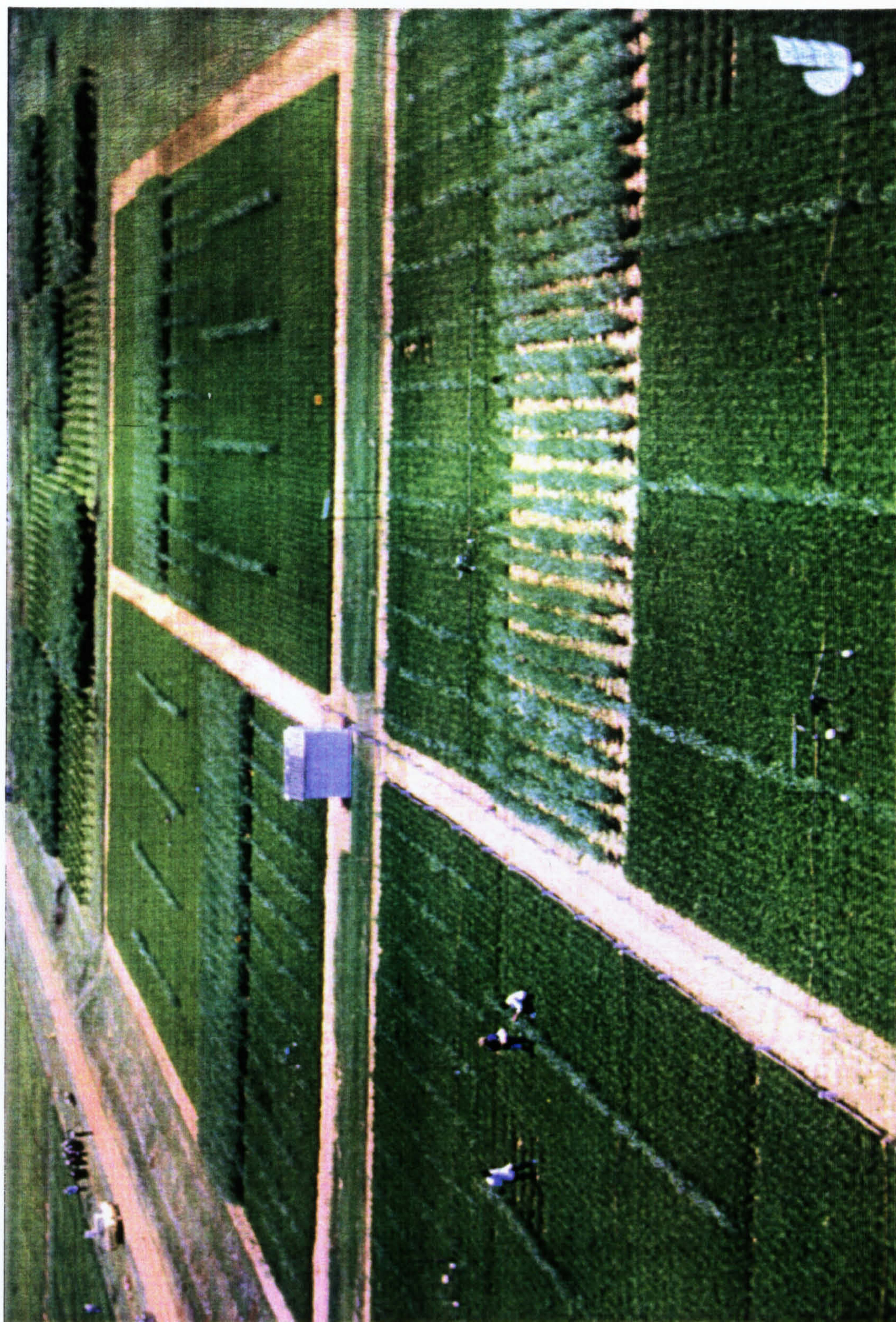
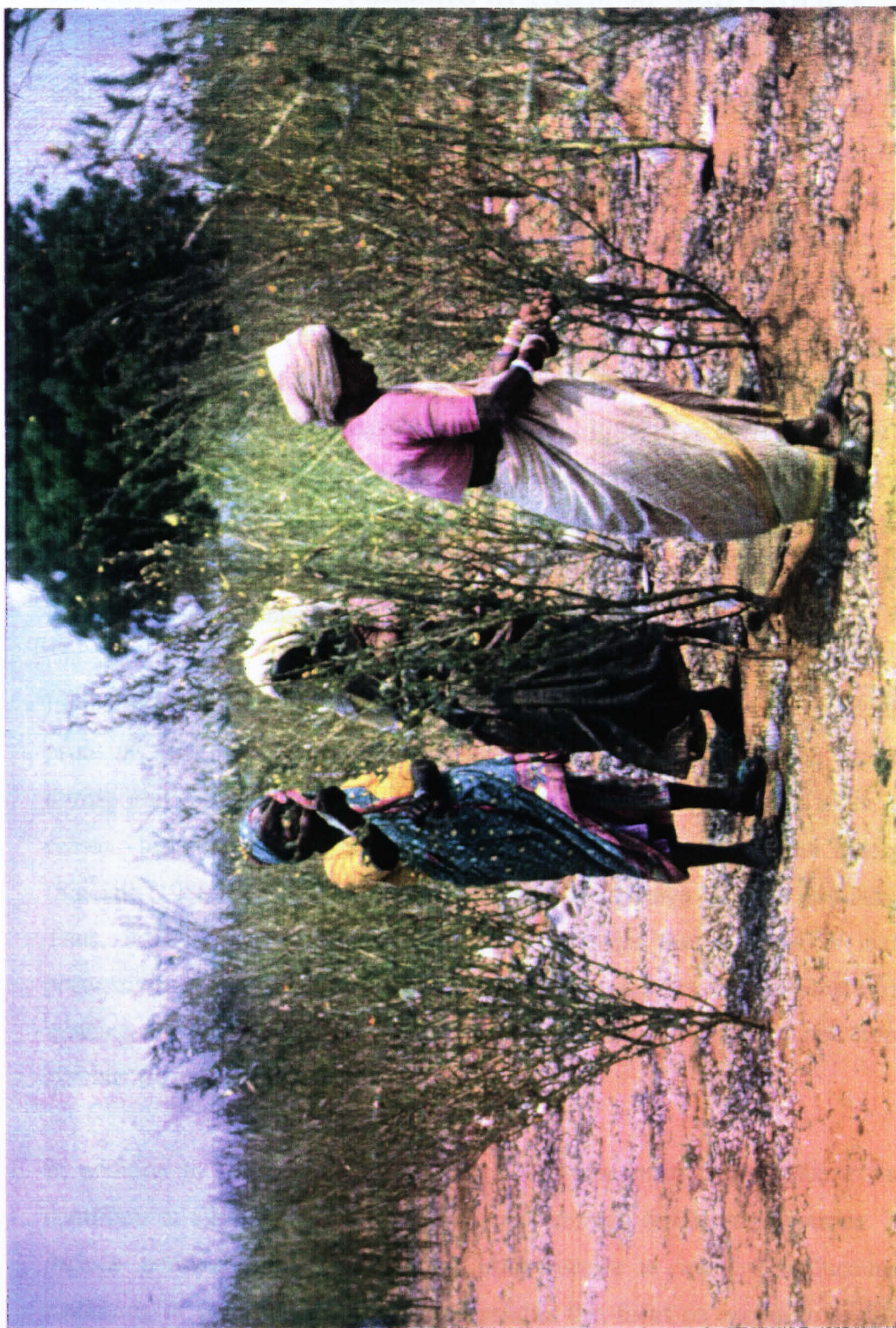


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1.1 CONSTRAINTS TO FARMING IN THE HIGHLAND TROPICS



(1993).

Chapter 1: INTRODUCTION

1.1 CONSTRAINTS TO FARMING IN THE SEMI-ARID TROPICS

Whilst population pressure has made it necessary to forego the traditional fallow periods, farmers face an ever-increasing challenge to maintain the productivity of intensively farmed areas within the constraints of the tropical environment (Dennett, 1984). Physical, chemical and biological deterioration leads to a rapid decline in the fertility and structure of tropical soils (Young, 1976), resulting in a progressive depletion of renewable resources and rapid land degradation. Extensive deforestation is causing further land degradation and destroying water-sheds, leading to increased risk from droughts and floods (Rocheleau *et al.*, 1988). The energy crisis in India and elsewhere, which has led to the commercialisation of fuelwood (Dendukuri *et al.*, 1993), is accelerating this process. In addition, the scarcity of fuelwood forces the rural poor to use animal dung and crop residues for fuel which might otherwise have been used to improve the soil.

In the semi-arid tropics (SAT), the limited cropping period creates additional problems, such as scarcity of fodder during the dry season and labour shortages during peak periods. Not only is crop production generally confined to the rainy season, but periods of drought at this time may cause major yield reductions (Sinclair, 1988). There is also a risk of extensive damage by pests and diseases. Thus, it is necessary to adopt agricultural practices that maintain or increase productivity and also stabilise yields during the poorest years. In traditional farming systems, the risk of complete crop failure may be reduced by using mixed cropping systems (Ruthenberg, 1980).

In addition to the environmental constraints, numerous socio-economic factors contribute to a lack of security of food supply in many developing countries. These include political instability, lack of infrastructure to support production and marketing of agricultural products and policies that focus on export crops (Brady, 1993).

1.2 AGRICULTURAL DEVELOPMENT STRATEGIES IN THE TROPICS

It became clear in the early 1970s that development policies to replace forests and increase agricultural production were not adequately addressing the problems of the rural poor (Nair, 1989). For example, although 'green revolution' technologies had proved tremendously successful in increasing overall food production in some countries (Brown, 1970; Simmonds, 1979), resource-poor farmers were not able to participate. The spectacular success of the green revolution in India has led to self-sufficiency in food grain production but, whilst considerable efforts were made to include small scale-farmers (Brady, 1993), those with good physical and biological farming environments benefitted most (Sharma, 1992). In addition, tree planting programmes were generally planned by and for the benefit of foresters to produce economic yield, often at the expense of the natural forest and the rural poor. For example, in community forestry programmes in India, grazing land is often replaced by non-browsable species that are planted for cash rather than rural needs (Chambers *et al.*, 1989).

Whilst early development projects attempted to introduce agricultural technologies, often developed in temperate regions, there was little research to test the efficacy and improve the productivity of indigenous agricultural production systems (Nyagah, 1979). Although there may be a case for importing certain universal technologies, these must be integrated very carefully with indigenous technologies and adapted to local needs (Wilson, 1993). The linkages between farmers and the many organisations involved in development must be improved, and an integrated approach to development adopted. By this means, development strategies which combine alleviation of poverty with sustainable agricultural production and environmental protection can be pursued.

1.2.1 Agroforestry

A need for research into land-use technologies that spanned the established disciplines of forestry and agriculture was recognised in the early 1970s. There are

numerous definitions of agroforestry, but the following description has been extensively used by the International Centre for Research in Agroforestry (ICRAF, Nairobi), and has been widely accepted by the research community (Nair, 1989):

'Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc) are deliberately used on the same land management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence. In agroforestry systems there are both ecological and economical interactions between the different components (Lungren and Raintree, 1982).'

Agroforestry provides the opportunity to apply specialised knowledge and skills to adapt or develop sustainable rural production systems in the light of new constraints on production, and to maintain or restore soil and water resources (Rocheleau *et al.*, 1988). Agroforestry is also an important technology for addressing the particular problems of the rural poor because the use of multipurpose trees can meet subsistence needs, whilst also increasing income and security (Chambers, 1989). Agroforestry systems may be based upon the skills and traditions of the rural people and can be successfully adopted within the existing available resources. Successful agroforestry combines the environmental benefits of tree planting with complementary tree/crop interactions, to create productive and sustainable systems that are appropriate to local needs. By providing a viable alternative to existing agricultural practices, the adoption of agroforestry addresses the wider concerns of environmental degradation and depletion of energy resources.

Agroforestry is not a new practice, but has been carried out for centuries in many developing countries including India. In the predominantly agrarian economy of semi-arid and arid India, livestock has an important role in agricultural activities and multipurpose tree species such as *Prosopis cineraria* (khejri) and *Acacia nilotica* are grown for fodder (Sharma, 1992). Whilst villagers in many areas provide protection for multipurpose tree species that occur naturally in their cultivated fields, in the arid and semi-arid regions of Rajasthan, Gujarat, Punjab and Haryana, multipurpose trees

are deliberately grown with crops to maintain the productivity of agricultural land, and also as a contingency in years of crop failure (Shankarnarayan *et al.*, 1989; Sharma, 1992). Other agroforestry systems such as taungya (growing agricultural crops in a tree plantation for three or four years until the trees become established) have developed with the emphasis on commercial forestry products. Agroforestry research provides the opportunity to increase the productivity and economic returns of these traditional systems, whilst identifying potentially successful agroforestry systems for wider use.

Some of the earliest formal agroforestry research was carried out in the 1970s by the International Institute of Tropical Agriculture (IITA, Nigeria) using alley-cropping systems. ICRAF was established in 1977, and agroforestry research at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT) began in 1984.

1.3 SUSTAINABILITY OF AGROFORESTRY SYSTEMS

The biological success of an intercropping or agroforestry system is assessed by its productivity and sustainability. Biologically sustainable systems are those which can maintain productivity by avoiding depletion of natural resources and degradation of the land on which they are grown. Agroforestry systems can play an important role in maintaining the productivity of continuously cropped land (Nair, 1989).

Improvements to soil fertility and structure

In order to maintain crop productivity without increasing inputs, nutrients must be recycled more rapidly and/or nutrient losses reduced relative to other systems. It is widely assumed that the root system of the tree component is able to recycle nutrients from deep in the soil profile and return them as leaf fall or mulch (Young, 1987). Evidence from natural systems indicates that below-ground litter recycling from root decomposition is also responsible for a large proportion of the transfer of nutrients from vegetation to soil (Szott *et al.*, 1991). Nutrient loss can be reduced

by minimising erosion, runoff and leaching (considered in detail in Section 1.4.3). In addition, by using leguminous trees, nutrient inputs to the system can be increased to an extent which depends upon the soil, climate, species and management practices (Szott *et al.*, 1991). Soil nutrient status was examined in some detail in alley cropping experiments at IITA (Kang *et al.*, 1985). For example, Kang *et al.*, (1981a) studied the effectiveness of *Leuceana leucocephala* (Lam.) prunings as a source of nitrogen for maize in field and pot trials and found that the prunings significantly increased the N uptake of seedlings and the N percentage in ear leaves of maize. Kang *et al.*, (1981b) also examined an alley crop of maize and *Leuceana* over a three year period at IITA; they found that when the leuceana prunings were removed, there was a reduction in extractable soil P, K and Mg, but total soil N decreased very little. More recent studies at IITA indicate that as much as 193 Kg N ha⁻¹ per season can be released by root turnover in *Leucaena* (Smucker *et al.*, 1992), representing a considerable proportion of the total N fixed and taken up by the trees. However, despite the superior ability of agroforestry systems to retain nutrients relative to many annual cropping systems, no agricultural system in which a harvestable product is removed can be truly sustainable unless a proportion of the material removed is returned in the form of a nutrient-rich input (Sanchez *et al.*, 1985).

A high proportion of nutrients are concentrated in the surface horizons of the soil (Young, 1976) therefore, fertility is substantially reduced when these layers are removed by wind and water erosion. Erosion may be reduced in agroforestry systems because the presence of tree roots may increase infiltration rates through radial growth and consequent improvements in subsoil porosity when deeper roots decompose (Sanchez *et al.*, 1985). The maintenance of canopy cover throughout the year may limit water erosion by reducing the kinetic energy of rainfall reaching the ground (Brady, 1984), and may also reduce wind erosion during dry periods by decreasing the windspeed at ground level (Jones, 1992).

Some soil types, such as Alfisols, are particularly prone to erosion due to their poor structural stability at the surface (Vijayalakshmi, 1987). The addition of soil organic

matter to such soils improves physical properties both directly (by increasing aggregate stability) and indirectly (by increasing biological activity), thereby increasing infiltration rates and reducing runoff and erosion (Belsky *et al.*, 1989). Schroth *et al.* (1992) studied nutrient release from branches and leaves of pigeonpea applied as a mulch and found that after 6-7 weeks all macro-nutrients except Ca had been released. They concluded that, in order to minimise nutrient losses, mulch should be applied in small quantities as required by the crop. Similarly, Sur *et al.* (1992) found that the effectiveness of mulch in improving soil fertility is highly dependent on the rate and mode of application. However, despite the obvious benefits of mulching, it is unlikely to be widely adopted by farmers in the SAT, due to the acute shortage of fodder.

1.4 PRODUCTIVITY AND RESOURCE UTILISATION OF INTERCROPPING AND AGROFORESTRY SYSTEMS

Productivity is determined by the quantity of a specified resource that is captured and the efficiency with which it is converted to dry matter. Complementarity of resource use can occur in mixed cropping systems, such that the component species make their major demand on resources at different times (temporal complementarity), or make more efficient use of resources at specific points in time (spatial complementarity; Willey, 1979b). In practice, there is considerable interaction between these two types of complementarity.

Complementarity of resource use is responsible for the yield advantage observed in some intercropping systems relative to the corresponding sole crops grown at their optimum populations (Willey, 1979a). Various methods for assessing such yield advantages have been developed for intercropping systems. The land equivalent ratio (LER; Willey, 1985) gives an index of the relative area of land planted under sole crops that is required to produce the same yield, and in the same species proportions, as the intercrop. The area-time equivalency ratio (Hiebsch and McCollum, 1987) is an adaptation of LER that takes into account the land that is left unused after harvesting the shorter duration sole crop. The concept of the crop

performance ratio (CPR) (Harris *et al.*, 1987; Azam-Ali *et al.*, 1990) was devised to compare the biological performance of intercrops relative to their component sole crops; this concept is applicable to replacement series intercrops, in which a number of rows of one crop component are replaced by a second component.

1.4.1 Microclimatic modification of plant growth and development

The purpose of this section is to provide an introduction to the role of microclimatic variables in controlling growth and development, before examining the influence of limiting physical resources on productivity.

The relationship between growth and development and temperature

When water and nutrients are non-limiting, temperature is the major factor governing the rates of both vegetative and reproductive growth (Leong and Ong, 1983; Baker *et al.*, 1985; Squire, 1990). Temperature influences all biochemical reactions by affecting the kinetic energy of the reacting molecules and the tertiary structure of the enzymes that control them, thereby controlling plant growth (Sutcliffe, 1977). The rate of enzyme activity increases with temperature from a minimum inactive level to an optimum, but damage to the tertiary structure of the enzymes begins to occur above a species or genotype-dependent optimum temperature and activity declines (Sutcliffe, 1977).

Temperature exerts a major effect on resource capture through its influence on the rates of leaf initiation and growth and leaf duration. Dry matter partitioning is also affected by the influence of temperature on the rate of primordial initiation and the period over which initiation occurs (Milthorpe and Moorby, 1979). In some crops, yield may increase as temperature decreases because the duration of dry matter accumulation in the harvestable storage organ is increased even though gross photosynthesis is reduced (Monteith, 1977). For example, the optimum temperature for pod yield in groundnut is considerably lower than that for developmental processes (Ong, 1984).

Dry matter conversion coefficients are also affected by temperature because of its effect on the balance between respiration and photosynthesis. This is most easily understood in terms of the concepts of growth and maintenance respiration introduced by McCree (1970). Growth respiration can be defined as the cost in metabolic terms of converting the products of photosynthesis to structural, cytoplasmic or storage compounds (Evans, 1980). As a crop ages, an increasing proportion of gross photosynthesis is used for the maintenance respiration required to replace structures that are being degraded. Unlike photosynthesis and growth respiration, maintenance respiration is highly temperature sensitive (Penning de Vries, 1972) and can be responsible for significant reductions in net photosynthesis with increasing temperature in mature crops.

Thermal time

Because the rate of developmental processes is strongly dependent on temperature, the concept of thermal time is often used in place of chronological time in phenological studies. The basic principle is that, for a given developmental process, the rate of the process increases linearly with temperature between a base value (T_b) and an optimum temperature (T_o). Above T_o , there is a linear decrease in developmental rate up to a maximum temperature (T_m), at which development ceases. In tropical conditions, where temperature frequently exceeds (T_o), thermal time (Θ) is often calculated from hourly leaf temperature values according to the following relation (Garcia-Huidobro *et al.*, 1982):

$$\Theta = t_1 (T_1 - T_b) + t_2 (T_m - T_2)K \quad \text{equation 1.1}$$

where t_1 represents periods when temperature (T_1) is below T_o and above T_b , t_2 represents periods when temperature (T_2) is above T_o and below T_m and K is a constant that describes the ratio of the linear relationship $T_o - T_b / T_m - T_o$.

This approach involving simple linear relations is adequate for most purposes, although non-linearities and the effects of other environmental variables have been

included in more complex models (e.g. Scaife *et al.*, 1987). Thermal durations for developmental processes have been established under controlled environment conditions for many crops including groundnut (Young *et al.*, 1979; Leong and Ong, 1983; Mohamed, 1984). The thermal time required for specific developmental events in field grown crops can be compared with the established thermal time requirements for the same event under controlled conditions to investigate the influence of environmental variables other than temperature.

Control of tissue temperature

The net radiation (R_n) received at a crop surface is expressed as (Dennett, 1984):

$$R_n = S(1-\alpha) + L_d - L_u \quad \text{equation 1.2}$$

where S is the solar radiation (both direct and diffuse) incident upon the crop surface, α is the reflection coefficient of the crop or soil surface and L_d and L_u are respectively the downward and upward fluxes of long wave radiation, which is received both from the atmosphere and nearby surfaces. The quantity of longwave radiation emitted by a surface is proportional to the fourth power of the absolute temperature and emissivity (Monteith, 1973).

Leaf temperature at any point in time is determined by the crop energy balance:

$$R_n - C - G - \lambda E = P + H \quad \text{equation 1.3}$$

where R_n is the net radiation (the net fluxes of short and long wave radiation), G is the flux of heat into the soil, λE is the flux of latent heat through evapotranspiration, P is the energy absorbed or released during chemical reactions, C is the sensible heat flux (by conduction or convection) into the air and H represents net physical storage by the canopy. Values of P are usually less than 5% of R_n (Jones, 1992). G is positive during much of the day, representing a loss of long wave radiation energy from the canopy, and negative at night. The value of G

may range from 2% of R_n in a dense canopy to 30% in an open or sparse canopy that shades the soil to a very limited extent (Squire, 1990).

Any imbalance in the energy equation affects the quantity of stored energy and therefore alters tissue temperature until changes in the sensible and/or latent heat fluxes act to restore the energy balance equilibrium and stabilise tissue temperature. Therefore, in the steady state when leaf temperature is constant, R_n will be zero. The canopy temperature is related to the sensible heat flux by the following relation:

$$C = [p c_p (T_c - T_a)] / r_h \quad \text{equation 1.4}$$

where p and c_p are respectively the density and specific heat capacity of the air and T_c and T_a represent the temperatures of the canopy and the atmosphere at a height h above the canopy. r_h is the resistance to radiative heat transfer, which is mainly dependent upon windspeed, although turbulence (random eddies) may be important in light winds, and is related to ΔE according to the relation:

$$\Delta E = [p c_p / \tau (v_i - v_a)] / r_s + r_b \quad \text{equation 1.5}$$

where τ is the psychrometric constant, v_i is the saturated vapour pressure at leaf temperature, v_a is the vapour pressure at height h above the canopy, r_s is the canopy diffusive resistance (determined by stomatal resistance and L) and r_b is the aerodynamic resistance to water vapour fluxes.

Most of the energy received at the surface of a well watered crop is lost as latent heat (ΔE) when windspeed is relatively high ($>$ approximately 2.5 m s^{-1}). If wind speed decreases (increasing r_h and r_b) and T_c is above T_a , T_c will tend to increase provided that there can be no further increase in ΔE and there is no change in stomatal conductance; C may then increase to re-establish the energy balance equilibrium. In practice, the effect of environmental changes on the energy balance is often more complex due to interactions between the environmental factors affecting sensible and latent heat loss and the ratio between them. For example, if

r_s is the main limiting factor for ΔE , a decrease in air saturation deficit resulting from a reduction in air temperature may reduce r_s , producing a subsequent increase in ΔE and a reduction in T_c .

The value of R_n for a specific quantity of incoming radiation depends upon several factors that affect surface temperature, including stomatal resistance, windspeed and saturation deficit (Biscoe *et al.*, 1975). For this reason, a net radiation value that is independent of surface temperature is often defined. This is known as the isothermal net radiation, and is defined as the net radiation that would be received by an identical surface in an identical environment if it were at air temperature (Jones, 1992). This term is useful when predicting the effect of a given environmental change on T_c .

1.4.2 Light

This section describes the basic principles of light interception and utilisation by crops before proceeding to a review of research into the relationship between improved light utilisation and productivity in intercropping and agroforestry systems.

Incident radiation

Seasonal mean fluxes of total incoming solar radiation at the canopy surface (0.4 - 3.0 μm) in the tropics vary from 12 MJ $\text{m}^2 \text{d}^{-1}$ in cloudy upland regions to 24 MJ $\text{m}^2 \text{d}^{-1}$ under clear conditions (Squire, 1990). Approximately half is photosynthetically active radiation (PAR) within range 0.390 to 0.715 μm (390 - 715 nm), which is slightly wider than the visible spectrum; the proportion of PAR within the incident radiation varies little either diurnally or seasonally (Monteith, 1973; Monteith *et al.*, 1981). Other discrete parts of the solar spectrum have specific roles in controlling growth and development through photomorphogenic and phototropic processes (Fitter and Hay, 1981). For example, far red radiation (0.7 - 0.8 μm) has a crucial role in photomorphogenesis through the phytochrome system (Kendrick and Kronenberg, 1994).

Potential productivity

PAR provides the energy necessary for photosynthesis, which ultimately determines the growth and productivity of crop and other species. When water is not limiting, the biomass production of crops is dependent on the quantity of light that is intercepted and the efficiency with which it is used to produce photosynthate, according to the following equation:

$$W = Sfet \quad \text{equation 1.6}$$

where W is the total dry matter (TDM) of the crop (g m^{-2}), S is the mean total solar daily radiation (MJ m^{-2}), f is the seasonal mean fractional interception of S , e is the efficiency with which intercepted radiation is converted into dry matter (g MJ^{-1}) and t is the duration of the canopy in days. The maximum productivity of species using the C3 photosynthetic pathway is $35\text{--}40 \text{ g m}^{-2} \text{ d}^{-1}$, whilst species with the C4 pathway have corresponding maximum rates of $50 - 55 \text{ g m}^{-2} \text{ d}^{-1}$ (Squire, 1990). It is rare for productivity to approach these potential limits due to numerous limiting factors such as assimilate availability or damage by pest and diseases.

Canopy development and light interception

The quantity of radiation intercepted is dependent on the rate of canopy development, its size and duration (Squire, 1990). In general, crops with longer life cycles such as cassava, or perennials such as oil palm, have a slower rate of canopy development than shorter duration crops such as C4 cereals and C3 legumes, although their seasonal mean fractional interception will be considerably higher due to their greater duration. Although population density may affect fractional interception prior to canopy closure, it has little effect on seasonal f values over a wide range of populations. For instance, Bell *et al.* (1987) found that seasonal mean fractional interception of groundnut increased by a factor of only 1.3 over a population range of 9 - 60 plants m^{-2} .

The canopy is often described in terms of its leaf area index (L), which provides a measure of the green leaf area per unit of ground area. For species in which stems and other organs form a significant proportion of the photosynthetically active material, such as cereals, green area index (GAI) may be more appropriate. The quantity of radiation intercepted is dependent on L or GAI and other aspects of the canopy, such as leaf geometry and arrangement. The effects of these aspects of canopy architecture on radiation interception may be expressed in terms of an extinction coefficient (K) which describes the attenuation of radiation transmitted through a canopy (Monsi and Saeki, 1953):

$$f = 1 - \exp(-KL) \quad \text{equation 1.7}$$

where f represents fractional interception and K is the extinction coefficient characteristic of a particular species or genotype. Fractional interception is the difference between the radiation incident upon the crop and the quantities reflected from the canopy surface or transmitted through it. Fractional interception may be measured either as total shortwave solar radiation using solarimeter tubes or alternatively as PAR using quantum sensors or filtered solarimeters.

The relationship described in equation 1.7 is based on the assumption that the canopy is homogeneous, with a random distribution of foliage and complete ground cover. K remains stable over a wide range of environmental conditions, although it is not entirely independent of canopy age. Crops whose leaves overlap greatly or have an erect habit (such as most cereals) have low K values (typically 0.30 - 0.45 for total shortwave radiation), whereas those with horizontal or evenly distributed leaves may have K values of up to approximately 0.8.

Light quality

The solar radiation reaching vegetation comprises direct radiation from the sun and diffuse radiation that has been scattered by cloud, dust, water vapour and other atmospheric constituents. Radiation is scattered by gaseous components and small

particles in the atmosphere in inverse proportion to its wavelength, thereby increasing the blue content of diffuse radiation (Fitter and Hay, 1981). Scattering increases with the path length of direct solar radiation through the atmosphere, and so diffuse radiation predominates at sunrise and sunset, or under cloudy conditions. Approximately two thirds of diffuse radiation is PAR, as compared with one third of direct radiation. However, PAR comprises approximately half of the total incident shortwave radiation at all times because, as the intensity of direct radiation decreases thereby lowering the PAR flux in this form, the proportion of PAR received as diffuse radiation increases (Monteith, 1977). Even on a clear day, diffuse radiation contributes 10 - 30% of the total solar shortwave receipts (Fitter and Hay, 1981). Szeicz (1974) found in a series of measurements at Cambridge that diffuse radiation generally made up more than half of the total solar radiation.

Radiation may penetrate plant canopies as transmitted radiation, unintercepted direct or diffuse radiation, or as reflected radiation from vegetative or reproductive organs. Radiation transmitted through green tissues will have been altered in terms of spectral quality (Allen *et al.*, 1979). Leaves transmit or reflect a small proportion of the visible wavelengths around 0.55 μm (hence their green colour), but otherwise absorb the majority of PAR. Solar radiation above 0.7 μm is mainly transmitted. Consequently there is a progressive depletion of PAR and an enrichment in the far red wavelengths within the canopy. For example, Sinclair and Lemon (1976) compared the ratios of 730/660 nm radiation with increasing depth in a maize canopy and found ratios of up to 20:1 at low solar elevations.

The relationship between the PAR flux density and CO_2 assimilation is normally an asymptotic curve. During the photochemical stages of photosynthesis, adenosine triphosphate (ATP) and reduced nicotinamide adenine dinucleotide phosphate (NADPH) are produced, while in the dark reactions the ATP and NADPH are used to reduce carbon dioxide to carbohydrate and regenerate the primary carbon dioxide acceptor ribulose biphosphate (RuBP) carboxylase. An alternative primary CO_2 acceptor, phosphoenolpyruvate (PEP) carboxylase, is utilised in plants with the C4 and CAM photosynthetic pathways. When water is non-limiting, photosynthesis is

rate-limited by the photochemical processes at low irradiance, and by the supply of carbon dioxide at high irradiance (Milthorpe and Moorby, 1979). The leaves of C3 crops tend to become light saturated at approximately half incident solar radiation (approximately 200-400 W m⁻²). However, it is unusual for C4 crops to become light saturated because PEP carboxylase has a much higher affinity for CO₂ than RuBP carboxylase and a high concentration gradient for CO₂ is maintained between the sub-stomatal cavities and the surrounding air (Fitter and Hay, 1981).

Light conversion coefficients

For a given quantity of intercepted radiation, the net rate of biomass accumulation (gross CO₂ assimilation minus respiration losses) may be expressed in terms of the light conversion coefficient (e). For many crops, net biomass accumulated is linearly related to intercepted radiation in the absence of drought or other stress factors, at least during vegetative growth (e.g. Sinclair and Horie, 1989). In determinate species, e tends to decline after flowering when new leaves are no longer being produced, whereas in indeterminate species the linear relationship may be maintained for much longer. The highest e values of approximately 4.2 g MJ⁻¹ of intercepted PAR during vegetative growth are achieved by the C4 cereals, whereas the maximum achieved by C3 crops is approximately 2.5 g MJ⁻¹ (Squire, 1990).

The value of e for a given species is often conservative when nutrient and water supplies are non-limiting and in the absence of pests and diseases (e.g. Monteith and Elston, 1983; Muchow, Robertson and Pengally, 1993). However, crop management and environmental conditions may have a major influence. For example, Ong and Monteith (1985) found that e may be reduced at very high solar irradiances in pearl millet, while Squire (1990) reported that e was reduced under conditions of high saturation deficit in a range of crops including groundnut and pearl millet. Several authors have concluded that e is dependent on temperature (Squire *et al.*, 1984; Kiniry *et al.*, 1989); Andrade *et al.* (1993) observed a close relationship between e and mean temperature during the vegetative phase of maize grown under field conditions. There is strong evidence that e may be increased by shade in some

C3 crops; for example, Stirling *et al.* (1990) demonstrated that e was increased by shading in groundnut, probably because the shaded leaves experienced radiation flux densities below their photosynthetic light saturation point, whilst the unshaded leaves were light saturated and their photosynthetic rate was limited by the supply of carbon dioxide.

Light interception and utilisation in intercropping

Several examples of temporal complementarity in light use have been reported, mostly involving mixtures of fast growing C4 cereals with a longer duration C3 crops. Much of this work has been conducted at ICRISAT; for example, maize/pigeonpea intercrops were studied by Sivakumar and Virmani (1980b), sorghum/ pigeonpea by Natarajan and Willey (1980a) and millet/pigeonpea by Rao and Willey (1983). These studies suggest that temporal complementarity results from the combination of an increase in fractional light interception relative to the sole stand of the legume prior to the cereal harvest and an increase in the canopy duration relative to the sole cereal crop. The short duration component develops rapidly and suffers little competition from the slower developing, long duration component. Typically in this type of system, there is a decrease in light interception when the short duration crop is harvested, after which the long duration component recovers from any competition that it previously experienced. The greater canopy duration usually increases the seasonal f value, despite the sharp decline in interception when the short duration component is harvested. If the short duration component is harvested during the vegetative phase of the longer duration crop, the yield of the latter is little affected and harvest index may be substantially increased. However, Keating and Carberry (1993) reanalysed data from a number of experiments in which there was an apparent increase in overall f and suggested that, in many cases, sole stands of the long duration component intercepted more light during the season than the intercrop. They also pointed out that, in some instances, resource use by intercrops should be compared with two consecutive short duration crops. For example, although Natarajan and Willey (1980b) found that total seasonal light interception was increased by using a sorghum/pigeonpea intercrop as compared to

the corresponding sole crops, it may be possible to grow two consecutive sorghum crops on deep Vertisols in India, which would be more productive than the intercrop.

In some studies, an increase in seasonal light interception has been reported which is insufficient to account for the apparent intercrop advantage in terms of total dry matter production and yield. For example, Willey *et al.* (1986), working with 1:3 and 1:5 row arrangements of pigeonpea:groundnut, reported an increase in total seasonal interception of 15 % relative to the sole pigeonpea. As the light conversion coefficients were similar in all treatments, the increase in the light interception was insufficient to explain the 48 % increase in TDM and the 58 % increase in grain yield (the groundnut and pigeonpea achieved 76 and 72 % of the sole crop yields respectively). This could be partly explained by the fact that the harvest indices of the intercropped pigeonpea were higher than in the sole crop. However, most of the discrepancy was probably attributable to the fact that the intercrop yield was expressed relative to that of the sole pigeonpea. This overestimated the intercrop advantage because this approach assumes that resource capture is linearly related to the population of plants in the sole crop, when in fact most species exhibit a curvilinear relationship (Ong and Black, 1994). Thus, plants can often achieve similar resource capture and yield over a wide range of population densities. The expected productivity of intercrop components, when expressed in terms of their sown proportion relative to the sole crop, is therefore often underestimated, resulting in overestimation of the intercrop advantage.

Canopy architecture and planting arrangement exert major effects on light interception and utilisation, and differences in these attributes may result in spatial complementarity within intercrops. For example, if the intercrop has a higher L than the corresponding sole crops with no change in K , then radiation interception should be increased. The K values for intercrops may well differ from those for sole crops but, as discussed by Keating and Carberry (1993), there is little experimental evidence to support this suggestion. For example, Wallace *et al.* (1990) found that the light extinction coefficient for a maize/sugarcane intercrop was intermediate

between the values for the corresponding sole crops.

Spatial complementarity in light interception only occurs if one crop component can attain maximum yield without achieving full ground cover. In general, sole stands planted at high populations can achieve a high L and almost complete light interception (Keating and Carberry, 1993). Thus, in many cases where it appears that there is spatial complementarity, this is because the sole crop used for comparison was not grown at its optimum population density. Spatial complementarity can occur when there is another limiting resource which restricts interception by the sole crop components but, if the species concerned compete strongly for the limiting resource, the intercrop advantage is lost (Willey, 1979).

Intercrop systems often combine C4 crops with high e values such as maize and sorghum with C3 legumes such as groundnut. However, there will only be an advantage over the sole C4 crop if there is an increase in overall light interception or in the e value of the canopy as a whole. As mentioned above, there is some evidence that the e value for some tropical C3 crops may be increased by partial shading.

There have been few studies in which light interception by the components of intercropping or agroforestry systems have been successfully separated. However, Marshall and Willey (1983) were able to partition light interception in a pearl millet/groundnut intercrop by placing quantum sensors above and below the canopy of each component in the sole and intercrop systems. The intercrop advantage was expressed in terms of the land equivalent ratio (LER). Although there was little increase in light interception by the intercrop as compared with the sole crops on a unit area basis, the LER of 1.31 could be largely explained by an increase in the light conversion coefficient for the intercropped groundnut of 46 %.

Little information is available concerning light interception by the components of agroforestry systems as related to productivity. Corlett (1989) examined light interception and dry matter production in a leucaena/pearl millet alley cropping

system in India, using solarimeter tubes placed both above and below the tree and millet canopies. The agroforestry system was more productive than the sole stands, largely due to an increase in light interception. Millet yield was reduced in the agroforestry system primarily because of shading and, although there was some increase in e , this was insufficient to compensate for the reduction in intercepted radiation. This system is an example of one-way complementarity, in which the leucaena was clearly the dominant component within the system.

Although intercropping and agroforestry clearly provide the opportunity to design systems that utilise light (and other resources) more efficiently, the numerous variables affecting light utilisation in mixed plant communities make it difficult to obtain a mechanistic understanding of the processes involved. It is wrong to assume that the results of resource use studies involving crops grown as sole stands will necessarily be relevant to mixed cropping systems. Major difficulties may be encountered, not only in partitioning light use between intercrop components, but also in determining actual advantages in resource use relative to sole crops. Consequently, there is little experimental evidence to confirm the role of increased light utilisation in the improved productivity of intercropping or agroforestry systems.

1.4.3 Water

Although the above discussion of light utilisation assumes that there were no other limiting factors, water is, in practice, the most commonly limiting natural resource for crop productivity in the SAT (Virmani *et al.*, 1978). This section presents the underlying theory and associated experimental evidence to show that agroforestry systems offer the potential for greater productivity than annual cropping systems in the SAT by increasing the proportion of annual rainfall that is used for transpiration, and hence biomass accumulation. The budget of water input, utilisation and loss in cropping systems can be described by the water balance summarised below:

$$Et = P - Es \pm \Delta M - D - I - R \quad \text{equation 1.8}$$

where E_t , P and E_s represent transpiration, precipitation and soil surface evaporation, ΔM is the change in stored soil moisture content and D , I and R denote deep drainage, canopy interception loss and runoff.

Transpiration is strongly affected by the other components of the water balance because it depends on the water left after losses resulting from soil evaporation, runoff and canopy interception. The addition of trees to a cropping system may increase the quantity of water available for productive use by reducing these losses (Wallace, 1995). The perennial component is also able to extract water from below the relatively shallow rooting zone of the annual crop, and can utilise off-season rainfall (Ong *et al.*, 1991b). In order to explain the tree/crop interactions involved, it is appropriate to examine each component of the water balance which may affect the proportion of rainfall available for transpiration.

Rainfall interception

Interception losses by the crop canopy reduce the effective rainfall available for use by the crop and tree components. Some of rainfall intercepted by the crop canopy evaporates, whilst the remainder eventually reaches the soil by running down the stem or dripping from the leaves. The quantity of rainfall lost by interception depends upon the intensity and duration of rainfall events and canopy characteristics (Wallace, 1995). There are few experimental data concerning the magnitude of interception losses in agroforestry systems, but models have been developed and tested for dense forest canopies (Rutter, 1975; Gash, 1979). The latest adaptations of these models for the sparse tree cover typical of agroforestry systems indicate that interception losses by the tree component are likely to be less than 5 % of rainfall (Wallace, 1995). Interception losses in agroforestry systems may significantly reduce effective rainfall in the short term, but these losses are likely to be outweighed by the long term advantages associated with other components of the water balance (cf. Neumann *et al.*, 1987).

Runoff

When rainfall is received at the soil surface more rapidly than it can infiltrate into the soil, it is lost as runoff. Alfisols have a relatively low water storage capacity and structural stability, which leads to low infiltration rates and tends to result in substantial runoff losses. Studies at ICRISAT have shown that on average 26 % of the annual rainfall is lost through runoff from Alfisols under the traditional farming systems practised in the region (El-Swaify *et al.*, 1987). Runoff not only reduces the quantity of water available for plant growth but also causes soil erosion, which removes the surface fertile layers of soil and reduces its structural stability.

There are still very few data available concerning runoff and erosion in agroforestry systems (Wiersum, 1991), but runoff is generally most effectively controlled in systems that maintain a good ground cover of crops and/or surface litter (Wiersum, 1991). The presence of vegetation reduces runoff as compared to bare soil both directly, by decreasing the kinetic energy of the rain reaching the soil, and indirectly, by reducing surface crusting and improving the hydraulic properties of the soil (Wallace, 1995). Agroforestry systems may reduce runoff losses by providing at least partial vegetative cover throughout the year, whilst the beneficial influence of the perennial component on soil physical properties may also improve infiltration whilst annual crops are present (cf. Sanchez *et al.*, 1985). Certain intercrop and agroforestry systems may also provide material for mulching, a technique that is widely used to reduce runoff and associated soil erosion in the tropics (Wallace, 1995).

Deep drainage

Under certain circumstances water that enters the soil, but is not taken up by roots, may be lost from the profile by deep percolation or drainage. Reduction of deep drainage may be an important mechanism enabling agroforestry systems to increase water capture as compared with sole crops because the tree component is able to utilise water that is beyond the rooting depth of annual species (Huda and Ong,

1989). In addition, the trees will continue to extract water from the profile after the annual component has been harvested, increasing total water use.

Snaydon and Harris (1981) stated that the differing root extraction zones of the component species of intercrops was an important potential mechanism for complementarity in resource use. However, experimental evidence suggests that this is not necessarily the case. Morris and Garrity (1993) described a study by Jena and Misra (1988) of the water balance of an annual pigeonpea/ rice (*Oryza sativa*) system in which it was found that 1.4 mm of water d⁻¹ drained through the 1 m rooting depth of sole rice, whereas sole pigeonpea removed 2.5 mm d⁻¹ from below the 1 m plane. Drainage below the 1 m plane in the intercrop was similar to the sole crop of rice, an effect attributed to the suppression of the pigeonpea growth by competition with the rice.

The few data available concerning the root distribution of trees in agroforestry systems (e.g. Dhyani *et al.*, 1990; Rao *et al.*, 1993) generally indicate that, although the tap and lateral roots penetrate deep into the soil profile, numerous roots are found near the surface, and thus extensive competition between the tree and crop species is to be expected. However, recent studies at ICRAF suggest that some tree species such as *Grevillea robusta* are predominantly deep rooting and abstract most of their water from depth (Howard *et al.*, 1995).

Soil surface evaporation

Evaporation from the soil surface is an important component of the water balance in the arid and semi arid tropics (Campbell *et al.* 1988). For example, Wallace (1991) found that soil evaporation accounted for 15 - 70 % of total evaporation from a sugar cane/maize intercrop in Mauritius. Evaporation from the soil surface can be described in two distinct phases. During the first, the soil is sufficiently wet for evaporation to occur at the potential rate and is limited mainly by incident radiation. As most soil surface evaporation occurs during this first phase of drying (Wallace, 1995), tree/crop arrangements that reduce the quantity of solar radiation reaching the

soil surface should significantly reduce evaporative losses. During the second stage, the surface water content falls below a threshold level at which the rate of evaporation becomes dependent upon soil hydraulic properties (Phillip, 1957). Models have been developed to calculate soil evaporation (e.g. Ritchie, 1972; Reddy, 1983; Squire *et al.*, 1984), but most experimental data come from intercropping studies where the sum of soil surface evaporation and transpiration have been recorded (e.g. Morris and Garrity, 1993).

The relationship between transpiration and productivity

Productivity may be related to the quantity of water used for transpiration and the dry matter production per unit of water transpired as follows:

$$W = \epsilon_w Et \quad \text{equation 1.9}$$

where W represents total dry matter production, Et denotes the total quantity of water transpired and ϵ_w is the dry matter production per unit of water transpired; the latter term is often known as the water use ratio. Reported seasonal water use ratios for rainfed C3 crops in the warm SAT and sub-tropics are 1.2-3.3 g kg⁻¹ and for C4 crops are 3.3-6.7 g kg⁻¹ (Squire, 1990).

When water is freely available, the total quantity of water transpired depends mainly upon leaf area index and canopy duration (Squire, 1990). Under these circumstances, dry matter production depends on irradiance, temperature and the duration and extent of stomatal opening, and is maximised by cropping systems that develop and maintain a full canopy cover for the longest period possible. In practice, water is usually the major limiting factor for productivity, and transpiration per unit leaf area is controlled by interactions between the plant and microclimatic conditions which act to optimise the photosynthetic rate and water use ratio of the crop involved (Jones, 1992). ϵ_w is inversely proportional to atmospheric saturation deficit (or more

precisely leaf to air vapour pressure difference), and for a given species the product of ϵ_w and saturation deficit is generally conservative (Tanner and Sinclair, 1983).

Vapour pressure difference (VPD) influences the energy balance of vegetation canopies, as shown in equation 1.5. Thus, for a crop with a plentiful water supply and specified values of r_s and r_b , a decrease in v_a will tend to increase ΔE . In practice, stomatal conductance and VPD are usually the major determinants of transpiration per unit leaf area (Bidinger, 1978). Any increase in ΔE will tend to reduce water use ratio, although stomatal functioning acts together with leaf metabolism to optimise both photosynthetic rate and ϵ_w . The relation between the water loss (E_t) and CO_2 assimilation rate (A) for a single leaf can be described as:

$$A/E_t = (C_a - C_i)/R(v_i - v_a) \quad \text{equation 1.10}$$

where C_a is the CO_2 concentration at height h above the leaf, C_i is the internal CO_2 concentration within the leaf, and R is the ratio of the diffusion resistances to CO_2 and water vapour. When the leaf and air are at the same temperature:

$$A/E_t \propto 1/D \quad \text{equation 1.11}$$

where D is the saturation deficit at height h (assuming that intercellular air spaces within the leaf are saturated with water vapour).

Because E_t and ϵ_w are both affected by many factors other than D , it is difficult to quantify the effect of VPD on crop growth, although Monteith (1986) developed a linear relation to describe the effect of VPD on the net rate of CO_2 assimilation. This is based on the principle that there is a lower threshold VPD (VPD_o) below which there is no restriction on photosynthesis, and an upper threshold (VPD_m) above which photosynthesis ceases. For mean daytime VPD values between VPD_o and VPD_m, the net carbon assimilation rate (A_n) can be represented as:

$$A_n = A_m [1 - (VPD - \text{VPD}_o)/(\text{VPD}_m - \text{VPD}_o)] \quad \text{equation 1.12}$$

where A_m is the maximum net carbon assimilation rate. A vapour pressure deficit factor (Z) can be used as an indicator of the degree of the impact of VPD on crop growth.

$$Z = 1 - [(VPD - VPD_o)/(VPD_m - VPD_o)] \quad \text{equation 1.13}$$

If the leaf and air are identical, D can be substituted for VPD. However, when leaf temperature is above air temperature (which often occurs during the day), the actual vapour pressure difference between the leaf and air should be calculated. Comparison of Z values are only valid if other factors such as soil moisture content remain constant because VPD tends to have a greater influence on crop growth if the plants are subject to drought or other forms of stress.

Mechanisms involved in stomatal responses to changes in saturation deficit

Stomatal aperture and carbon assimilation are affected by many environmental factors and the interactions between them; these variables include radiation, temperature and leaf and soil water status (cf. Jarvis and Mansfield, 1981; Ziegler *et al.*, 1987; Weyers, 1990). A direct response of stomata to changes in VPD was first demonstrated by Lange (1971), and it is now generally accepted that the stomata of numerous species respond directly to increases in VPD by closing at least partially, although the nature and mechanism of the response is variable. Prior to the work of Cowan (1977), a feedback response, whereby any increase in E_t reduced leaf water potential and induced stomatal closure, was believed to be the main mechanism. However, Farquhar (1978) produced the first mathematical model to demonstrate a feedforward response, the fundamental requirement being that the stomata may respond to changes in atmospheric conditions prior to any detectable change in bulk leaf water status. For some considerable time it was widely believed that the stomata were able to control the fluxes of water vapour and other gases between the leaf and atmosphere (Meidner and Mansfield, 1968). However, stomatal conductance is dependent on the rates of both transpiration and photosynthesis and it is therefore difficult to establish to what extent the stomata are controlling these

processes or are being controlled by them (Jarvis and Mansfield, 1981). In particular, there is increasing evidence of a non-stomatal contribution to photosynthetic inhibition with increasing VPD, and methods for quantifying this effect have been developed in laboratory studies (e.g. Jones, 1984; Guehl and Assenac, 1986). These studies were based on the fact that, when some species were exposed to increasing VPD, there was an increase in intercellular CO₂ concentration whilst the CO₂ assimilation rate (A) decreased, indicating that the reduction in A resulted largely from mesophyll limitations (Farquhar and Sharkey, 1982).

On the basis of the above information, it is possible that shading by the tree component of agroforestry systems may increase the ϵ_w values of understorey crops by reducing the VPD that they experience. Such an interactive effect might increase overall productivity due to spatial complementarity. However, although temporal complementarity of water use is apparent in intercropping systems, there is no experimental evidence of spatial complementarity from intercropping or agroforestry research (Morris and Garrity, 1993).

1.4.4 Nutrients

Nitrogen fixation, nutrient cycling from depth and mulching (Section 1.3) are important factors in determining nutrient availability and tree/crop interactions in agroforestry systems, but experimental evidence to support many of the hypothesis regarding soil improvements is extremely limited. Similarly, very few data are available concerning the mechanisms underlying competition for, or complementarity of, nutrient use in agroforestry systems (Ong, 1995), partly because it is difficult to distinguish between the effects of nutrient and water availability.

1.5 BIOPHYSICAL RESEARCH NEEDS IN AGROFORESTRY FOR THE SAT

Formalised agroforestry research is relatively new, and it is clear that there is a need to improve the understanding of the mechanisms responsible for yield advantages and

increased sustainability. Without this information, it is extremely difficult to identify the most biologically appropriate tree/crop combinations and management practices for a given environment. Much of the current information concerning resource utilisation is drawn from intercropping, but the major differences in root distribution and function between trees and crops mean that the principles of resource capture established in intercropping systems cannot necessarily be applied to agroforestry (Ong and Black, 1994). There have been few detailed studies of productivity and resource use in agroforestry systems in the semi-arid tropics. Agroforestry research at ICRISAT began in 1984 with the examination of alley cropping systems developed for the humid tropics, to determine their suitability for the SAT. The majority of these systems proved inappropriate for the SAT because of severe below-ground competition (Ong *et al.*, 1991a; Malik and Sharma, 1990). For example, Rao *et al.* (1991) assessed the productivity of various agroforestry systems on Alfisols at ICRISAT Center and concluded that alley cropping *Leucaena leucocephala* with annual crops conferred no advantage in terms of either biological productivity or economic returns, as compared to block planting sole crops of both components on shallow Alfisols. Rao *et al.* (1991) found no evidence of biological complementarity, suggesting that further studies of agroforestry systems using tree species that are less competitive with annual crops than leucaena are required.

1.6 THE EXPERIMENTAL SYSTEM

1.6.1 Pigeonpea

Pigeonpea (*Cajanus cajan* (L.) Millspaugh.) (commonly known as red gram in India) is the only cultivated food crop within the Cajaninae subtribe of the Phaseoleae (van der Maesen, 1990). Although pigeonpea probably originated in peninsular India, and the Indian sub-continent now accounts for 90 % of the World production, it is also cultivated in South East Asia, Africa and the Americas and is grown in many countries as a minor backyard crop (Nene and Sheila, 1990).

Pigeonpea ranks sixth in terms of area and production relative to other grain legumes

such as beans, peas and chickpeas, but has a far greater diversity of uses (Nene and Sheila, 1990). The main use in India is for human food, mainly in the form of dhal (dry, dehulled split seed used for cooking), although the green pods are also popular. In addition, the crushed dry seed husks and pod wall are commonly used for animal feed, the green leaves for fodder and the woody stems as fuelwood and building material (Nene and Sheila, 1990).

Willey *et al.* (1981) gave a comprehensive review of the place of pigeonpea in traditional cropping systems in India. About 90 % is grown in dryland areas as mixed crops or intercrops (Aiyer, 1949). Traditional cultivars are harvested after 180-280 d, but may be left to regrow and be browsed by animals. Pigeonpea is commonly intercropped with cereals (e.g. sorghum, pearl millet or maize) which provides greater stability of productivity than sole crops under rainfed conditions (Singh and Subba Reddy, 1988). During the past 25 years, breeders have developed a large number of short-duration, large seeded, high yielding cultivars suitable for sole cropping under high levels of management (Saxena and Sharma, 1990), and these can sometimes be grown before a post-rainy season crop of wheat in India. Some researchers claim that the deep rooting characteristics of pigeonpea allow it to recycle nutrients absorbed at depth to the surface horizons (Johansen, 1990), but this has not been confirmed. Using the ^{15}N isotope dilution method, it was estimated that 90 % of the N in medium duration pigeonpea grown as a sole crop on a Vertisol was derived from fixation (Kumar Rao *et al.*, 1987).

Germination is hypogeal and the growth rate of the seedlings is relatively slow (Sheldrake and Narayanan, 1979). The low initial growth rate of pigeonpea relative to many other crops is well recognised (Rachie and Roberts, 1974; Sheldrake and Narayanan, 1979; Willey *et al.*, 1981; Muchow, 1985b; Whiteman *et al.*, 1985), and this combined with apparent tolerance of low radiation, is a beneficial attribute for intercropping. Pigeonpea has little effect on companion crops, but can respond as soon as they are harvested (Sheldrake and Narayanan, 1979; Trenbath, 1980). Pigeonpea exhibits a quantitative short day flowering response (Troedson *et al.*, 1990) and most genotypes will flower in daylengths between 10.1 and 11.5 h

(Spence and Williams, 1972). However, pigeonpea is adapted to a wide range of environments and cropping systems and there is therefore extensive variation in daylength and temperature responses between genotypes. Pigeonpea produces numerous flowers which can be self or cross pollinated, but only about 10 % of these set pods (Pathak, 1970; Sheldrake *et al.*, 1979). The number of pods per plant is strongly dependent on assimilation during early pod growth (Thirathon *et al.*, 1987). Seeds mature 38-40 d after fertilisation, which occurs on the same day as pollination (Narayanan and Sheldrake, 1975). A proportion of the carbon assimilated during pod growth is diverted to the stems and other storage organs (Rawson and Constable, 1981), probably because of the intrinsically perennial nature of the plant (Sheldrake and Narayanan, 1979). Harvest index (HI) varies from 10 - 52 % (Lawn and Troedson, 1990) depending on genotype, environment and agronomic management.

An important attribute of pigeonpea for the SAT is its ability to withstand drought as a result of its deep rooting habit, which includes the development of a strong tap root (Rachie and Roberts, 1974; Sheldrake and Narayanan, 1979; Whiteman *et al.*, 1985), combined with many other drought tolerance strategies (cf. Muchow, 1985; Flower and Ludlow, 1987; Troedson *et al.* 1990). Pigeonpea is generally unresponsive to fertilisers (Morton, 1976; Edwards, 1981) and is able to tolerate a broad pH range (Edwards, 1981), but is sensitive to salinity (Keating and Fisher, 1985), waterlogging (Chauhan, 1987) and frost. Susceptibility to fusarium wilt, rhizoctonia stem rot and sterility mosaic disease have been a major constraint to the widespread adoption of perennial pigeonpea, but a number of genotypes with resistance to these diseases and good agronomic traits have been developed at ICRISAT (Daniel and Ong, 1990). The cultivar chosen for this study (ICP 8094) is a semi-spreading perennial type, with combined resistance to wilt and sterility mosaic virus, which matures in approximately 250 days at ICRISAT and has grain yields comparable to the medium duration types (e.g. ICP-1).

Pigeonpea productivity in relation to requirements for grain, fodder and fuel in rural India

A survey involving six villages in rural Andhra Pradesh showed that 65 % of households grow pigeonpea grain for home consumption only (Ryan *et al.*, 1984). The protein content of pigeonpea grain (21 %) compares well with other grain legumes (Nene and Sheila, 1990), and a survey of diets in rural villages in semi-arid regions of India (Bidinger and Nag, 1981) found that the average per capita consumption of pigeonpea grain (usually in the form of dahl) was 35-40 g d⁻¹. This constituted 10 % of their protein and 5 % of their energy intake. If surplus grain was available it could be sold at the local markets for approximately 15 rupees kg⁻¹ (Ranganathan, 1993), about 20 % less than the market value of groundnut pods.

Approximately 50 % of the dry matter not attributable to grain is suitable for firewood or building material. The former is the more important use, and some farmers sow pigeonpea for the wood it produces rather than grain (Faris *et al.*, 1990). In many rural areas, firewood and cow dung cakes are gathered for domestic use, and a limited proportion of the fuel requirements are purchased. A variable proportion of the daily household energy requirements are met by firewood, depending on the availability and ability to purchase or gather other fuels such as cow dung, kerosene and coal. In a detailed study of the energy requirements of a village in Andhra Pradesh, Dendukuri and Mittal (1993) found that the most commonly used fuels for cooking included *Prosopis* species, pigeonpea and dried branches of citrus trees; when fuelwood was scarce, crop residues were burnt. The heat value of pigeonpea wood is relatively high, being approximately half that of coal or kerosene (Jain *et al.*, 1987). The mean annual household consumption of firewood and crop residues were respectively 1.4 and 1.0 t. Electricity, kerosene and castor oil were used mainly for lighting, and the total energy consumption of these commercial energy sources was less than one tenth of the non-commercial sources. These findings were similar to other studies in India. For example, Shah (1987) reported a study involving 25 families in Gujarat in which the basic annual requirement for fuelwood was 1.44 t for a family of six. The growth of perennial

pigeonpea potentially provides the opportunity to meet a higher proportion of the fuelwood requirements within the village, thereby reducing the need to collect wood from forests and burn valuable crop residues and animal manure.

Approximately 50 % of the remaining yield is suitable for fodder (Akinola and Whiteman, 1975) and has a local market value of 0.25-0.50 rupees kg⁻¹ (Sharma, pers. comm.). There is limited information on the intake and digestibility of pigeonpea compared with other sources of fodder, although studies in Hawaii (Henke *et al.*, 1940) indicated that weight gain in cattle was greater when they were fed on pigeonpea rather than grass. Topps (1992) concluded that the value of leguminous shrubs and trees as a rich source of protein for livestock in the tropics had been underestimated, and that in nutritional terms, pigeonpea fodder compares favourably with other species in this group. No data are available concerning fodder productivity by pigeonpea in traditional systems in India because the majority of the medium and long duration cultivars are grown as annuals in intercropping systems, mainly for grain (Ali, 1990). In traditional systems in Andhra Pradesh, cattle are often allowed to graze freely on pigeonpea once its pods and other crops have been harvested (Faris *et al.*, 1990). A major potential benefit of pigeonpea cultivars which can be grown successfully as perennials in semi-arid regions is the provision of fodder from regular harvests throughout the dry season, when alternative sources of animal feed are scarce.

1.6.2 Groundnut

Groundnut (*Arachis hypogaea* L.) is an indeterminate legume originating from South America and is a member of the Papilionaceae, a family that is invariably geocarpic (mature their fruits underground) but shows considerable variation in other characteristics (Ashley, 1984). Groundnut is widely distributed over a range of environmental conditions between latitudes 40 °S and 40°N. It requires light, neutral or alkaline soils, with at least 450 mm of available water during the growing season. The crop is usually confined to lowland areas, grows most successfully within the temperature range 25 - 35 °C and is not able to withstand frost (Ashley, 1984).

About 90 % of the World production of groundnut is in developing countries. Groundnut accounts for more than half of all tropical grain legume production and, due to its relative drought tolerance, is a particularly important crop in semi-arid regions where potential evaporation exceeds precipitation for 5-10 months of the year (Virmani *et al.*, 1978). Thus, 67 % of the total annual production Worldwide is within the SAT (Gibbons, 1981) and over 7 million hectares are cultivated annually in India (Reddy, 1988).

The major use of groundnut is as a source of cooking oil (Cummins, 1986). Groundnut oil is the second most important global source of vegetable oil (Gill and Vear, 1980) and is widely used in the production of salad oils, margarines, soaps and lubricants. The oilcake (protein residues after extraction of the oil) is widely used as an animal feed and also to some extent in human foods. The whole nuts are eaten throughout the World in various raw, salted and roasted forms. The high protein (23 %) and energy content of the seed (23 MJ g⁻¹; FAO, 1981) make it a valuable contribution to the human diet. Although groundnut is predominantly grown as a cash crop, there may be great benefit in promoting and facilitating its use for home consumption in areas of the SAT where food shortages and nutritional problems are common (Cummins, 1986).

In the SAT, groundnut is usually planted following the first significant monsoon rains, and takes about seven days to emerge. The root system consists of a tap root with numerous lateral roots on which nitrogen fixing nodules form. At the seedling stage, root growth predominates until the roots reach a depth of approximately 30 cm; thereafter the rate of canopy development increases rapidly (Ketring *et al.*, 1982).

Flowering is indeterminate and commences 20-30 days after emergence. Flowers are self-fertilised in the morning and wilt quickly, and 5-7 days later the base of the fertilised ovary forms a gynophore or peg which elongates geotropically towards the soil. After 8-12 days the peg reaches its final position about 5 cm below the soil surface, with the ovary tip pointing away from the tap root. The presence of

moisture and calcium enhances gynophore presentation and fruit formation (Slack *et al.*, 1972). Full-sized fruits are present 14-21 days after the peg has penetrated the soil and the shells harden after 21-28 days (Ashley, 1984). Many of the flowers produced on the later nodes do not form pegs, and often only one flower in an inflorescence does so (Reddy, 1988). Most of the pods that form are produced from the earliest flowers closest to ground level, as these have the best supply of assimilates (Duncan *et al.*, 1978). Pod yields may reach 2.9 t ha⁻¹ in the USA, but in the SAT, where groundnut is also an important cash crop, the average yield is only 0.8 t ha⁻¹ (Gibbons, 1986). Constraints on production usually result from a combination of drought, disease and pest damage.

The groundnut cultivar chosen for this study was the semi-branching genotype, Kadiri-3 (formerly known as Robut 33-1), which is successful and relatively high yielding in the SAT. Kadiri-3 exhibits rapid root extension and canopy expansion and has a high water extraction capacity. It also has the benefit of a relatively high dry matter production to water use ratio (ODA, 1987). However, Kadiri-3 suffers the disadvantage in dry years that flowering is sensitive to drought.

1.6.3 Aims and objectives

The aim of this work was to obtain a mechanistic understanding of the relationship between productivity and resource utilisation in perennial pigeonpea/groundnut agroforestry systems established on Alfisols in the SAT. The specific objectives were to:

1. Determine the influence of the spatial arrangement of pigeonpea on resource use and productivity by comparing an alley-cropping system, in which the planting arrangement was similar to the traditional annual pigeonpea/groundnut intercrops grown in Andhra Pradesh, with a system in which the pigeonpea was planted in a dispersed pattern at the same population.

2. Quantify and partition water use and calculate water use ratios for the tree and crop components in each of the agroforestry and sole systems and establish a soil water balance;
3. Quantify and partition light use and calculate light conversion coefficients for the tree and crop components in each treatment;
4. Examine microclimatic modifications in the agroforestry systems and establish their effects on groundnut growth, development and yield;
5. Determine the relative importance of the major limiting factors for productivity in each of the agroforestry systems and sole crops.

Chapter 2: MATERIALS AND METHODS

2.1 EXPERIMENTAL SITE AND DESIGN

2.1.1 Introduction

Fieldwork was carried out at the International Crop Research Institute for the Semi Arid Tropics (ICRISAT), near Hyderabad, Andhra Pradesh, India (18°N, 78°E; altitude 545 m). The area forms part of the relatively high and flat lands of the Deccan Plateau, which is divided between the states of Karnataka, Maharashtra and Andhra Pradesh and is largely surrounded by coastal plains.

The climate at Hyderabad is typical of the semi-arid regions of India. The mean annual temperature is greater than 18 °C, mean daily insolation is in the range 15-25 MJ m⁻² and rainfall exceeds potential evapotranspiration for only 2 to 4.5 months of the year. There are three distinct seasons. The rainy season (Kharif) extending from June to October has a mean maximum temperature of approximately 29 °C. The majority of unirrigated crops are confined to this period, during which approximately 80% of the mean annual rainfall (780 mm) is received. The remaining 20% of the annual rainfall generally occurs in the post rainy season, between October and January. However, rainfall is highly erratic, as indicated by a study of data extending over a period of 77 years at Hyderabad which showed considerable seasonal variation and annual totals ranging from 320 mm (1972) to 1400 mm (1917; Virmani *et al.*, 1978). The dry summer season has a mean maximum temperature of 40 °C. Mean daily saturation deficits are generally of the order of 1.0-1.5 kPa in the rainy season, rise to 2-3 kPa in the post-rainy season, and may reach to 3-4 kPa in the dry season (Virmani *et al.*, 1978; Ong *et al.*, 1991c).

The experimental site was located on an Alfisol soil on ICRISAT field number RP15. This field was mechanically levelled for large experiments shortly after ICRISAT was established in 1971. As a result, the horizons differ from typical Patancheru series Alfisols which comprise light reddish brown soils derived from

pink granites, and are classified according to the USDA Soil Taxonomy (1975) as belonging to the fine loamy mixed isohyperthermic family of Udic Rhodustalf. Alfisols typically have a 15-25 cm thick A horizon, with a loamy sand to sandy loam texture and a 65 - 80 cm thick Bt horizon with a sandy clay loam to sandy clay texture. They are generally well drained with moderate permeability, and may have well defined gravel and weathered rock fragments within the B horizon. Their available water-holding capacity is intermediate (60 - 100 mm) and the organic content is low, leading to poor structural stability (El-Swaify *et al.*, 1987).

2.1.2 Field history

In 1987, leuceana (*Leuceana leucocephala* Lam.) and sunflower (*Helianthus annuus* L.) were grown in field RP15. When this trial was concluded, the field was deep-ploughed, and large tree roots were removed to reclaim the site for annual crop studies. During the 1988 rainy season, pearl millet (*Pennisetum glaucum* L.) was grown, followed by irrigated sorghum (*Sorghum bicolor* L.) in the post-rainy season. Relatively low yields were obtained in both years, which were attributed to a zinc deficiency (J.R. Burford, pers. comm.). Zinc sulphate (40 kg ha⁻¹) and diammonium phosphate (DAP, 100 kg ha⁻¹) were applied in May 1989.

2.1.3 Experimental design

The experimental site was highly appropriate for a randomised block design (RBD) experiment and there was clear justification for creating four blocks. The land had previously been divided into two separate fields of similar size covering the Eastern and Western portions of the site. These areas had not been treated identically in previous years, and drainage was poorer on the Western side. In addition, there was a slight North to South gradient. A plan of the experimental layout is shown in Figure 2.1 and statistical analysis appropriate to this type of experimental design is discussed in Section 2.2.3.

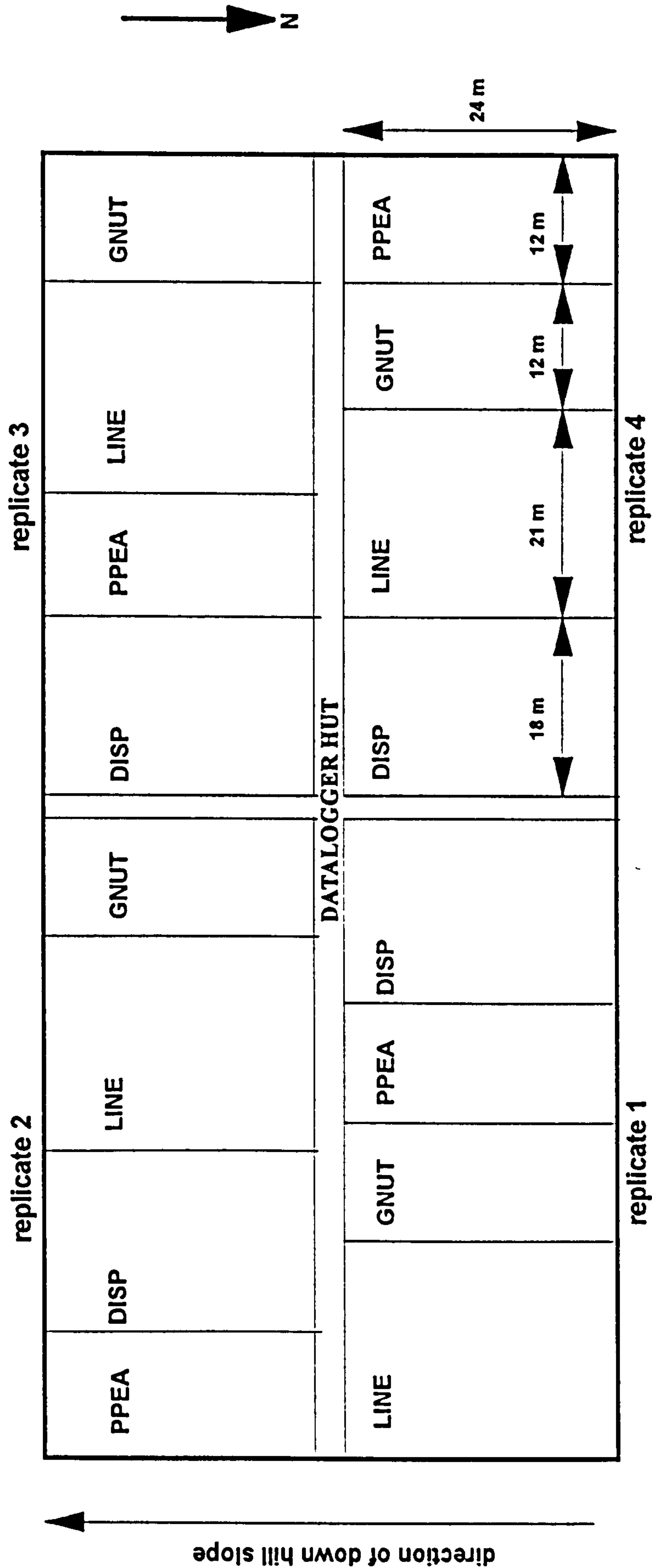


Figure 2.1: Plan of experimental layout. PPEA, GNUT, DISP and LINE represent the sole pigeonpea, sole groundnut, dispersed planted pigeonpea/groundnut and line planted pigeonpea/groundnut plots respectively. Plot sizes are shown to scale.

Four treatments were imposed. The intention was to grow sole pigeonpea and sole groundnut at their optimum populations, and to compare these sole crops with two addition series intercrops, a 'line planted' treatment in which pigeonpea was grown in wide alleys with groundnut rows between, and a 'dispersed planted' treatment in which pigeonpea was grown in a regular dispersed arrangement (1.8 x 1.2 m) with groundnut rows planted between the pigeonpea. Details of plot size, plant population and spacing for each of the four treatments are given in Table 2.1.

The experimental area (0.6 ha) accommodated a randomised block design (RBD) containing four treatments with four replicates (Fig. 2.1). Plot size was sufficient to accommodate the large quantity of permanent monitoring equipment required, whilst providing areas away from the border strips (areas around the margins of each plot not used for data collection) for destructive sampling. In order to comply with the experimental objectives, the minimum spacing between pigeonpea rows in the line planting was 4 m because this was the spacing adopted by farmers in the region. A minimum of four pigeonpea rows was required in the line planting to allow a single border row of pigeonpea on either side of the area within which measurements and destructive samples were to be taken.

2.1.4 Field preparation

Drainage was an important consideration because field RP15 is low-lying relative to the surrounding land, has a slight North to South gradient and a small lake a short distance from the Southern perimeter. Existing drains around the field were cleared and additional 1 m deep trenches were dug along the North, East and West perimeters to divert runoff water from higher lying fields. In June 1989, prior to measuring and marking the experimental plots, the field was disced and harrowed to create a uniform seed bed.

Table 2.1: Plot size, plant population, and spacing for each of the four treatments examined in 1989 and 1990

	Sole Pigeonpea		Sole Groundnut	Line Planting	Dispersed Planting
Plot size (m)	12 x 24		12 x 24	21 x 24	18 x 24
Pigeonpea population (plants m ⁻²)	1989	8.88		0.45	0.45
	1990	0.44			
Pigeonpea plant spacing (m)	1989	0.15 x 0.75		0.37 x 5.40	1.20 x 1.80
	1990	1.5 x 1.5			
Maximum number of pigeonpea plants plot ⁻¹	1989	2560		236	195
	1990	128			
Groundnut population (plants m ⁻²)			33.33	33.33	33.3
Groundnut plant spacing (m)			0.10 x 0.30	0.10 x 0.30	0.10 x 0.30
Maximum number of groundnut plants plot ⁻¹			9600	16800	14400

2.1.5 Planting and crop establishment

Groundnut seed (cv. Kadiri 3) was obtained from ICRISAT 1988 stocks; its 100 seed weight was 200 g. The seed was visually checked to ensure that it was free from pest and disease damage before planting. On July 2 1989, a cub tractor was used to open furrows to a depth of 5 cm and the groundnut seed was planted by hand. The seeds were placed in a continuous line and the seedlings were thinned after germination to provide the required 10 cm intra-row spacing. To minimise soil drying, planting took place as the furrows were opened and the seeds were covered immediately.

Pigeonpea seed (cv. ICP 8094) from 1988 ICRISAT seed stocks was hand-planted at a depth of 5 cm on July 3 1989. The position of each pigeonpea row was indicated with tape secured by wooden pegs. Coloured markers were placed at appropriate intervals on the tape to indicate the position of individual trees in the line and dispersed plantings. The pigeonpea seeds were planted at least 5 cm from the groundnut rows. In the dispersed planting this sometimes necessitated a slight deviation (less than 5 cm) from the planned 1.8 m inter-row spacing. Seed was planted closely within rows in the sole pigeonpea plots and then thinned to produce the required 0.15 m intra-row spacing after germination. The rows of both groundnut and pigeonpea were sown in an East - West direction to reduce shading of the groundnut by pigeonpea rows at sunrise and sunset. In the line planting there were 18 rows of groundnut between each pigeonpea row, whereas in the dispersed planting there were six groundnut rows between pigeonpea rows.

By July 10 1989, groundnut emergence had reached 50 % (Table 2.2), much lower than expected by eight days after sowing (8 DAS). As there had been very little rain during this period, a light sprinkler irrigation was applied for one hour and all work in RP15 was suspended until full emergence to avoid damage to the crop. 50% emergence of pigeonpea was recorded on July 9 1989 in all plots. Heavy rainfall (118 mm) on July 16 and 17 caused damage to a large number of the seedlings in the sole pigeonpea plot of replicate 4 (Fig. 2.1) because of runoff from

Table 2.2: Biological measurements and observations for groundnut

	Date	Julian Day	Days After Sowing
1989			
Planting	July 2	183	
50% emergence	July 10	191	8
50% flowering	August 8	219	36
Harvest	October 29	302	119
Growth analysis	10 day intervals between August 1 and October 10	213 - 283	30 - 100
1990			
Planting	July 19	200	
50% emergence	July 26	207	7
50% flowering	August 23	235	35
Harvest	November 7	311	111
Growth analysis	10 day intervals between August 18 and October 27	230 - 300	30 to 100

neighbouring fields. The majority of uprooted seedlings were successfully replanted, but where this was not successful additional seed was sown; these plants were excluded from measurements during 1989.

Population counts for both species were carried out in all plots on August 2 1989. For the groundnut, the numbers of plants were counted in 20 randomly selected 1 m row lengths in each plot. The counts revealed that the established groundnut population was approximately 85 % of the optimum of 33.3 plants m². All pigeonpea plants were counted in each replicate of the line and dispersed planted treatments. In the sole pigeonpea plots, five of the 32 rows were selected at random and the total number of plants per row was recorded. At that stage there were no missing pigeonpea plants in the line and dispersed plots and very few in the sole plots, with the exception of the water-damaged area in replicate 4.

In 1990, the groundnut was planted in a similar arrangement to that described for 1989, although the presence of established pigeonpea plants made it necessary to open furrows by hand. As previous studies at ICRISAT had indicated that the optimum population for perennial pigeonpea in the second year of growth was approximately 0.5 plants m² (Ong, pers. comm.), the sole pigeonpea population was reduced to 0.44 plants m² on June 1 1990. This was as close to the population in the line and dispersed planted treatments (0.45 plants m²) as could be achieved within the existing plant spacing. Alternate pigeonpea rows and plants within rows were removed to increase the spacing from 0.15 x 0.75 m to 1.5 x 1.5 m.

2.1.6 Pest and disease control

Pest and disease monitoring and control was undertaken by staff in the Farm Developments and Operations Unit at ICRISAT Center. In both 1989 and 1990, three common fungal diseases were apparent in groundnut; early leaf spot (*Cercospora arachidicola* Hori), late leaf spot (*Phaeoisariopsis personata* Berk. and Curt.) and rust disease (caused by *Puccinia arachidis* Speg.). The incidence of early

and late leaf spot was greater in 1990, probably because these diseases are soil-borne and therefore tend to be more prevalent when groundnut is grown in consecutive years on the same land, although the wetter conditions in 1990 may also have favoured disease development. No chemical control methods were used, but all crop debris was removed after harvest to reduce the build up of fungal pathogens.

Pigeonpea cultivar ICP 8094 is resistant to the two most important diseases affecting pigeonpea in the Indian subcontinent (Daniel and Ong, 1990), namely the soil-borne fusarium wilt (*Fusarium udum* Butler) and sterility mosaic disease, which is transmitted by the mite vector *Aceria cajani* (Reddy *et al.*, 1990). The crop was affected by the pod borer *Helicoverpa armigera* (Hub.), which is the most important insect pest of pigeonpea in Southern and Central India (Reed and Lateef, 1990). The larvae of this insect may affect up to 80 % of the pods, causing substantial yield reductions (Daniel, 1989). Several pesticides recommended for control of *Helicoverpa* were applied between flowering and harvest in 1989 and 1990 (Table 2.3) using a hand-operated knapsack sprayer. The proportion of pods damaged by *Helicoverpa* was recorded at final harvest.

The numerous species of weeds present on the experimental site (*Cyperus rotundus* was particularly abundant) necessitated the use of various control methods to avoid substantial yield loss. Before planting in 1989, a mixture of Prometryn (to control broad leaved weeds) and Fluchloralin (to control grass weeds) was applied (Table 2.3) using a knapsack sprayer. It was also necessary to carry out several hand-weeding operations during the experiment.

2.2 GROWTH ANALYSIS.

2.2.1 Groundnut

In 1989 and 1990, routine growth analysis was carried out for groundnut at 10 day intervals between 30 - 100 DAS in all four replicates. The sampling procedure was designed to allow the growth and development of the sole crop to be compared with

Table 2.3: Pest and weed control measures, 1989-1991 (a.i. denotes active ingredient)

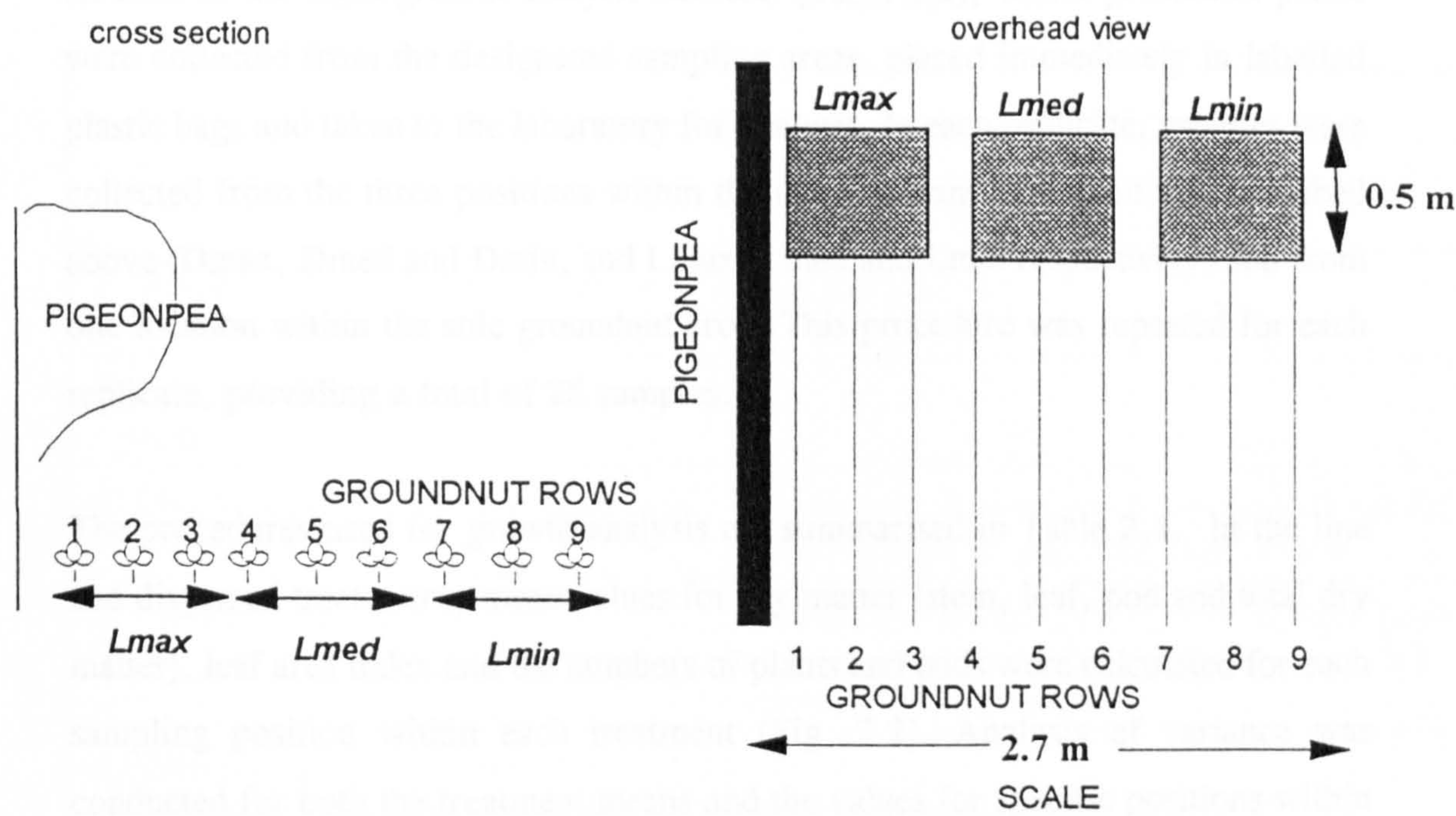
Date	Weed control	Chemical control of <i>Helicoverpa armigera</i> on pigeonpea
1989-1990		
July 4	Fluchloralin and Prometryn (both at 1 kg a.i. ha ⁻¹) July 4 1989	
July 19 - 22	hand-weeding of all plots	
September 8	hand-weeding of all plots	
October 26	hand-weeding of all plots	
November 1	hand-weeding of all plots	
December 2		Carbaryl (3 kg a.i. ha ⁻¹)
December 18		Lannate (2 kg a.i. ha ⁻¹)
December 27		Nucravon (1 kg a.i. ha ⁻¹)
1990-1991		
April 26		Thiodan (2 kg a.i. ha ⁻¹)
June 15	mechanical weeding with rotovator plus hand weeding	
August 20	hand-weeding of all plots	
October 4	hand-weeding of sole pigeonpea plots	
November 17		Nucravon (1 kg a.i. ha ⁻¹)
December 15		Ekalux (2kg a.i. ha ⁻¹)
January 2		Thiodan (2 kg a.i. ha ⁻¹)

the intercropped groundnut. In addition to the comparison of treatment mean values, the relationship between groundnut growth and proximity to adjacent pigeonpea plants was investigated in the line and dispersed treatments.

In the sole groundnut plots, areas were randomly selected for growth analysis, leaving a 2 m wide boundary (measured from the edge of the plots and any instrumentation) around the area from which plants were sampled. On each of the eight sampling dates, plants were removed from 0.5 m lengths of three neighbouring rows to provide a sampling area of 0.5 m². Consecutive samples were taken from the same rows, leaving a 1 m guard area between samples. The total area sampled before final harvest was less than 2 % of the entire plot area, leaving sufficient space for the permanent instrumentation and the destructive measurements at final harvest.

Three sampling sites were selected for groundnut grown in each of the intercrops (Fig. 2.2) to represent areas of high (Dmax and Lmax), medium (Dmed and Lmed) and low (Dmin and Lmin) competition with the pigeonpea. As there were 18 rows of groundnut within each pigeonpea alley in the line planting, nine rows extending from the edge to the centre of the alley were sampled as being representative of the entire system. The sampling area of 0.5 m² for individual harvests was achieved by harvesting 0.5 m lengths of three neighbouring rows, as in the sole crop. The three groundnut sampling sites in the dispersed planting (Dmax, Dmed and Dmin) were also chosen so that the mean would be representative of the entire system. This was achieved by removing plants from an area that spanned the entire range of distances between adjacent pigeonpea plants (Fig. 2.2). Other sampling patterns might have established more clearly the trends of interspecific competition between the pigeonpea and groundnut, but would have been more complex and time-consuming to harvest and might have introduced difficulties in estimating system productivity. Samples Dmax, Dmed and Dmin each comprised a single 0.6 m row length. On consecutive sampling dates, measurement of the 0.6 m row length sampled for each position commenced at the adjacent pigeonpea plant in the same row.

(a) Line planting



(b) Dispersed planting

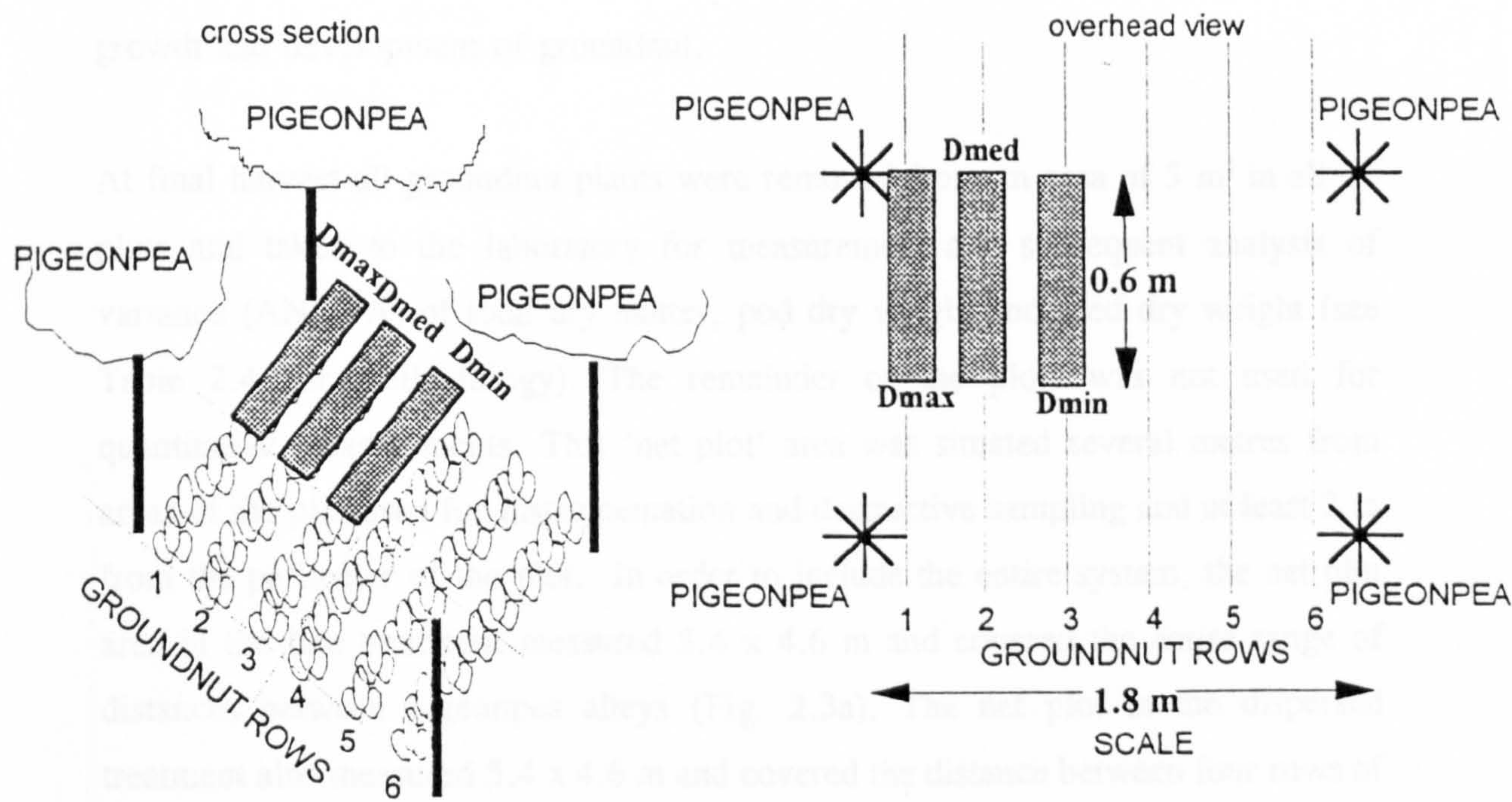


Figure 2.2: Sampling locations (hatched areas) for groundnut growth analysis in a) the line and b) the dispersed plantings of pigeonpea.

At each of the eight growth analysis harvests (Table 2.2), whole groundnut plants were collected from the designated sampling areas, placed immediately in labelled plastic bags and taken to the laboratory for analysis. In each replicate, samples were collected from the three positions within the dispersed and line plantings described above (Dmax, Dmed and Dmin, and Lmax, Lmed and Lmin respectively) and from one location within the sole groundnut crop. This procedure was repeated for each replicate, providing a total of 28 samples.

The procedures used for growth analysis are summarised in Table 2.4. In the line and dispersed treatments, mean values for dry matter (stem, leaf, pod and total dry matter), leaf area index and the numbers of plants and pods were calculated for each sampling position within each treatment (Fig. 2.2). Analysis of variance was conducted for both the treatment means and the values for specific positions within treatments. The treatment means were used to compare the overall productivity and dry matter partitioning of groundnut in the sole, line and dispersed treatments, whilst the variation between sampling locations within the line and dispersed treatments was used to assess the influence of proximity to the nearest pigeonpea plants on the growth and development of groundnut.

At final harvest all groundnut plants were removed from an area of 5 m² in all 12 plots and taken to the laboratory for measurement and subsequent analysis of variance (ANOVA) of total dry matter, pod dry weight and seed dry weight (see Table 2.4 for methodology). The remainder of the plots was not used for quantitative measurements. This 'net plot' area was situated several metres from areas of the plot used for instrumentation and destructive sampling and at least 2 m from the perimeter of the plot. In order to include the entire system, the net plot area in the line treatment measured 5.4 x 4.6 m and covered the entire range of distances between pigeonpea alleys (Fig. 2.3a). The net plot in the dispersed treatment also measured 5.4 x 4.6 m and covered the distance between four rows of pigeonpea (Fig. 2.3b).

Table 2.4: Summary of groundnut growth analysis procedures, 1989-1990.

Task	Method
1. Preparing samples	Washed each of the 28 samples to remove soil; surface water allowed to evaporate
2. Measuring total fresh weight (g) for each of the 28 samples	Electronic balance
3. Counting plant number (NOP) in each sample	
4. Division of each plant into stem, pods, flowers and leaves	Stems, pods, flowers and leaves for each sample placed in separate paper bags and labelled
5. Counting pod number	Counted and recorded the number of small pods < 1 cm in length (NSPOD) and large pods > 1 cm (NLPOD) separately
6. Determining leaf area index (L): (i) Measurement of total leaf fresh weight (TLFW(g)) (ii) Measurement of the leaf area (Ls (m ²)) of 100 g sub-sample of leaves from each sample (or total leaf area if less than 100 g of leaves) (iii) Calculation of the total leaf area (La (m ²)) for each sample (iv) Calculation of L (the green leaf area per unit ground area)	(i) Electronic balance (ii) LICOR 3100 Leaf Area Meter (iii) $La = (TLFW/100) \times Ls$ equation 2.1 (iv) $L = La/Ga$ where Ga is the ground area from which the sample was taken (0.5 m ² for the line and sole crop samples and 0.21 m ² for the dispersed treatment samples)
7. Recording dry matter in stems (SDWT), large pods (LPDWT), small pods (SPDWT) and leaves (LDWT). (LDWT = leaf dry weight of 100 g sub-sample + remaining leaf dry weight)	All samples oven-dried at 80 °C; weight recorded using an electronic balance
8. Calculation of total dry matter production (TDM)	$TDM = SDWT + LDWT + LPDWT + SPDWT$
9. Conversion of SDWT, LDWT, SPDWT, LPDWT, LPDWT+SPDWT, TDM, NSPOD, NLPOD, NLPOD+NSPOD and NOP into values per m ² of land area	$x \text{ m}^{-2} = x/Ga$ where x = the variable concerned
10. Analysis of variance for variables listed in point 9 above and for L	GENSTAT or SPSSPC+ statistical packages were used (Table 2.7)

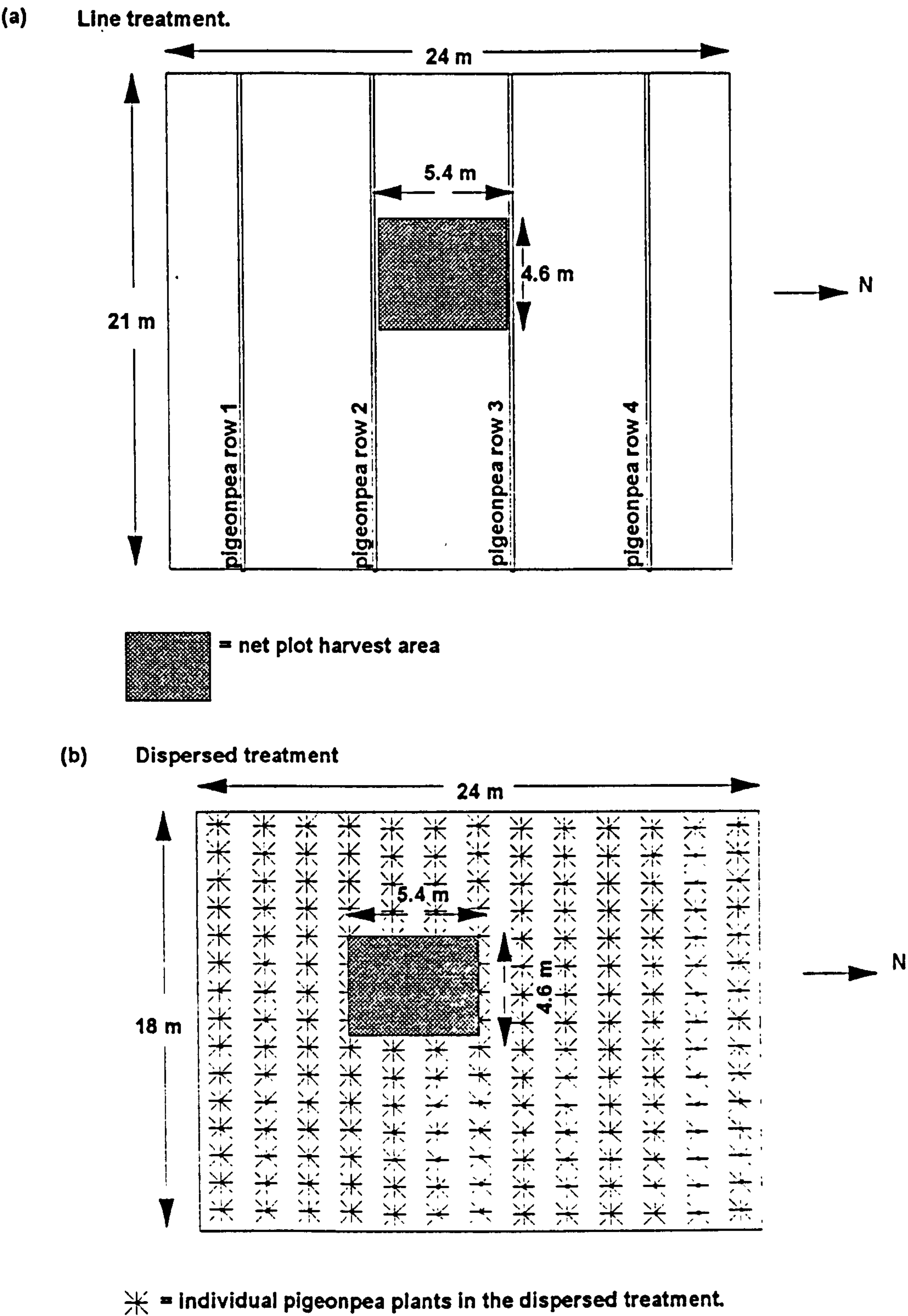


Figure 2.3: Position of net plot harvests of groundnut in relation to pigeonpea; the diagrams show the plots viewed from above and are drawn to scale.

2.2.2 Pigeonpea

It was not possible to conduct frequent growth analysis for pigeonpea since, although the overall plot size was large, undisturbed areas were required for micrometeorological measurements, neutron probe access tubes and net plot areas for groundnut and pigeonpea harvest. In the line arrangement, only pigeonpea rows 2 and 3 (Fig. 2.3) were used for biological and physical measurements and rows 1 and 4 were left as border rows. In the sole and dispersed treatments, 2 m wide border areas were left around the perimeter of the plots and each of the instrumentation sites within plots. Destructive samples were taken on five occasions over the two year experimental period (Table 2.5). Three of these samples were taken at the time of grain or fodder harvests (31/1/90, 8/8/90 and 25/1/91) when a sub-sample of five plants was taken from the net plot harvest (indicated in Table 2.6). For the analyses conducted on October 30 1989 and December 12 1990, five plants were randomly selected from a single pigeonpea row close to the edge of the plot.

The methods used in the growth analysis of pigeonpea are summarised in Table 2.6. The net plot area for grain and fodder harvests amounted to 1.25 % of the plant population of the sole pigeonpea before the population was reduced to 0.5 plants m² on June 1 1990 and 12.5 % thereafter. Net plot harvests amounted to 15 and 8 % respectively of the plants in the line and dispersed treatments. On each occasion, the plants were cut at a height of 0.5 m above ground level. In May 1991, plants in the net plot area were cut at ground level and the total accumulated dry matter in the stem portion up to a height of 0.5 m was measured.

The density of the mainstem was estimated for the five plants in each sub-sample at the first grain harvest on January 31 1990. A 10 cm portion of the mainstem (extending from 50 to 60 cm above ground level) was removed from each plant and stem diameter (d) was measured at the centre of each segment. The stem sections were then placed in separate labelled bags and oven-dried at 80 °C for 48 h before

Table 2.5: Biological measurements and observations for pigeonpea, 1989-1991

	Date	Julian Day	Days after Sowing Pigeonpea
1989-1990			
Planting	July 3	184	
Destructive sampling for growth analysis	October 30	303	113
Measurement of mainstem height, stem diameter (at 50 cm height) and number of primary branches	September 26	269	79
	October 9	282	92
	October 18	291	101
	November 16	320	130
	December 13	347	157
	January 30	30	205
1990-1991			
Grain and fodder harvest 1	January 31	31	206
Fodder cut 1	April 16	106	281
Fodder cut 2	May 22	142	317
Population of sole pigeonpea reduced to 0.5 plants m ⁻²	June 1	152	327
Fodder cut 3	August 8	220	395
Destructive sampling to estimate L in line and dispersed treatments	December 12	346	521
Measurement of main stem height	August 7	219	394
	September 30	273	448
	November 20	324	499
	January 30	30	570
Measurement of main stem diameter at 50 cm	September 30	273	448
	November 20	324	499
	April 6	96	636
Grain and fodder harvest 2	January 25	25	565
Pigeonpea plants cut to ground level	April 3	93	633

Table 2.6: Summary of growth analysis procedures for pigeonpea 1989-1991

Task	Procedure		
Harvesting pigeonpea plants from net plot area (except for October 30 1989 and December 12 1990 when only five plants per plot were removed) for the line, sole and dispersed treatments in each of the four replicates	Trees cut at a height of 50 cm above ground level and removed from plot.		
	TREATMENT	NET PLOT SIZE	NUMBER OF TREES IN NET PLOT
	sole	6 x 6 m	32 (16 after June 1 1990)
	line	14 m row length from rows 2 or 3 (Fig. 2.3)	36
	dispersed	6 x 6 m	15
Recording total sample fresh weight (NTFWT)	Measured in the field using a spring balance and supporting tripod		
Removing five trees from each sample to record dry matter partitioning and L	Five trees from each net plot harvest selected at random, placed in labelled bags and taken to the laboratory		
Recording total fresh weight (TFWT) of five plant sub-sample	Measured using a spring balance		
Preparing the sub-sample	Each five plant sample divided into stems, leaves (fodder cuts only) and pods		
Calculation of L	Method as summarised in Table 2.4. The ground area from which the sample was taken (Ga) was 10 m ² for the line and dispersed plantings, 0.56 m ² for the sole crop prior to June 1 1990 and 10 m ² thereafter		
Examination of pods	Mean number of pods per plant (NPOD) and total number of damaged pods per sample (NDPOD) were counted		
Measurement of the dry weight of stems (SDWT), leaves (TLDWT) and pods (PDWT)	Samples oven-dried at 80 °C for 48 h; dry weight (g) measured using an electronic balance		
Calculation of total dry matter (TDM) per sample	$\text{TDM} = \text{TLDWT} + \text{SDWT} + \text{PDWT}.$ For the net plot total harvest $\text{NTDM} = (\text{TDM}/\text{TFWT}) \text{NTFWT}$		
ANOVA of TDM, LDWT, SDWT, PDWT, NPOD, NDPOD and L	GENSTAT and SPSSPC+ statistical packages were used as summarised in Table 2.7		

their dry weights (SDM (g)) were recorded. The density of the stem (Ω (g cm⁻³) was calculated as follows:

$$\Omega = \text{SDM} / [\pi(d/2)^2] 10 \quad \text{equation 2.3}$$

2.2.2.1 Routine non-destructive measurements

The height and stem diameter of pigeonpea plants were regularly monitored in all replicates of each treatment throughout the experiment (Table 2.5). The height of ten randomly selected plants per plot was measured from ground level to the tip of the mainstem using a 2.5 m rule, while stem diameter 15 cm above the ground was measured with metal callipers. Forty plants per plot were randomly selected for stem diameter measurements in each of the four replicates. A larger number of trees was assessed for stem diameter because this information was required to select plants for heat balance measurements of sap flux (Section 2.3.2.1).

The total number of pigeonpea plants in each plot was counted at the time of the grain harvests and also in June 1990 and March 1991 to assess percentage mortality.

2.2.2.2 Pigeonpea root studies

The root system of pigeonpea consists of a deep woody tap root with well developed lateral roots close to the soil surface (Reddy, 1990). Under certain circumstances, pigeonpea roots have been observed to penetrate to depths exceeding 2 m, although most roots are confined to the top 60 cm of the profile (Sheldrake and Narayanan, 1979; Natarajan and Willey, 1980). There appears to be a relationship between growth habit and root distribution, with the result that bushy cultivars such as ICP 8094 produce shallower, more spreading root systems than tall compact varieties such as ICP 7035 (Pathak, 1970). However, these previous investigations have been confined to the first year of growth, whereas the current study provided the opportunity for a detailed examination of root distribution after 18 months of

growth.

The major objective of these studies was to compare the root distribution of pigeonpea within the line and dispersed treatments. Unfortunately, it was not possible to include the sole pigeonpea because of the limited time available. The root studies facilitated a quantitative assessment of the proportion of the soil profile that was being exploited for water. A deep and extensive root system is necessary when perennial genotypes are grown in the semi-arid tropics to maximise the potential for extracting stored soil moisture and surviving the long dry season. The greater above-ground productivity of the dispersed pigeonpea led to the expectation of a more extensive root system than in the line-planted treatment.

In agroforestry systems, the distribution of tree roots has major implications for below-ground competition with the annual crop component. In this experiment a trend of decreasing groundnut productivity with increasing proximity to pigeonpea was observed (Section 3.2.2). Examination of the distribution of pigeonpea roots within the groundnut rooting zone was expected to provide an indication of the importance of below-ground competition to this phenomenon. However, the information obtained should be treated with some caution since the studies of pigeonpea root distribution were carried out approximately one month after groundnut harvest on November 7 1990, during which period its root distribution may have altered to some extent. For instance, root growth is known to continue during the reproductive phase in pigeonpea; indeed, Sheldrake and Narayanan (1979) reported a doubling of total root length after the onset of flowering.

The soil profiles also provided visual information on the effect of local variations in soil properties on root distribution. Soil properties such as bulk density, moisture content, aeration and nutrient availability may all exert a considerable influence on root growth. For example, dense or compacted layers can slow or halt root expansion, while drying soil may cause a decrease in lateral root extension near the surface, and an increase deeper in the profile (Lawn and Troedson, 1990). Root studies also provide important information for the design of future experiments. For

example, the degree of lateral root extension should be taken into consideration when planning trials, since it is essential that agroforestry experiments should provide sufficiently large plots and boundary areas to ensure that the root systems of trees in specific treatments do not affect neighbouring plots (cf. Hauser, 1993).

Root studies were carried out during December 1990 using the profile wall method described by Böhm (1979). The number and position of trenches for root distribution studies were constrained by the need to minimise damage to the rest of the experimental area. Soil trenches were dug in the line and dispersed treatments of replicate 1 (cf. Fig. 2.1). These plots were located on the extreme Western and Eastern sides of their respective replicate blocks, and could be accessed without causing damage to the remainder of the experimental area. A mechanical digger was used to form trenches of 3 m long x 2.2 m height x 2.5 m wide, perpendicular to the pigeonpea rows. In the line treatment, the trench extended from approximately 20 cm to the South of pigeonpea row 2 (Fig. 2.3) to the midpoint between rows 2 and 3. In the dispersed treatment, the trench extended across two pigeonpea rows and approximately 60 cm on either side. The soil profile closest to the trees in both treatments was smoothed to provide a vertical face using hand tools and plumb lines. Just before root counting commenced, a hand-held sprayer was used to remove a layer of soil approximately 3-5 mm deep and expose the roots (Plate 4).

A rectangular wooden frame of 2.7 x 2.0 m was constructed and string was used to form a 10 x 10 cm square grid within it. The squares within the grid were numbered and the grid was attached to the soil profile so that roots within it could be counted to a depth of 2 m. In the line treatment, the grid was placed so that it extended to the midpoint between pigeonpea rows 2 and 3; this area was selected so that the root distribution examined would be representative of the entire root system. In the dispersed treatment, the grid extended across two pigeonpea rows and 45 cm to either side. Once the frame was securely attached, the number of exposed root ends in each grid square was recorded. In order to minimise excavation, the existing trenches were extended into the plot to produce 'replicate' profile wall sites. Root

distribution in four profile walls was examined for both the line and dispersed treatments.

2.2.3 Statistical analysis of growth analysis results

Standard analysis of variance (ANOVA) for randomised block design experiments (cf. Mead and Curnow, 1983) was carried out. The residual variances of total dry matter were calculated for all plots and were found to be independent and normally distributed, confirming that the blocking design shown in Fig. 2.1 was appropriate.

When several similar measurements were made within individual plots (for example, the main stem height of twenty trees in each plot) additional subdivisions of the sum of squares (ss) were used. A valid analysis involving these subdivisions was ensured by checking that the total set of comparison ss added up to the treatment ss.

Before comparing differences between specific treatment means, the significance of the overall difference between treatments was examined by calculating the F-values (treatment mean square/error mean square) for a given ANOVA; the probability that this value could have been obtained due to random variation alone was determined from the F distribution using the appropriate number of degrees of freedom. Having calculated the standard error of the difference between treatment means (SED), the Student's t distribution was used in order to determine the probability that any two treatment mean values could have come from the same population. The levels of significance used for all statistical tests were 5 %, 1 % and 0.1 %, and are represented by *, ** and *** respectively.

This basic ANOVA methodology was used to test for significant treatment differences on each of the growth analysis dates. Although these individual analyses were valid, it should be noted that significant results obtained over a period of time from the same experiment are not as meaningful as they would have been from

different experiments (Langton, 1989). In addition, there was no test for interactions between treatments and time.

Linear regression analysis was also used to investigate the relationship between two growth analysis parameters on occasions, for example groundnut pod dry weight and pod number. Having fitted the line by means of the least squares method, 95 % confidence intervals for the slope of the true relationship and individual mean values for the dependent variable (y axis) were calculated.

2.3 WATER BALANCE MEASUREMENTS

An attempt was made to quantify the major components of the water balance (equation 1.8) in order to investigate the influence of the tree component in increasing the proportion of rainfall available for transpiration and to compare water use in the line and dispersed treatments. As there were insufficient resources available to monitor all components of the water balance throughout the experimental period, monitoring of precipitation, transpiration by pigeonpea and ΔM were given priority. Fortunately, estimates of E_t (Section 4.2.1.2) and E_s (Section 4.2.4) for groundnut could be obtained from growth analysis and micrometeorological data.

Productivity may also be improved in agroforestry or intercropping systems by an increase in the efficiency of water utilisation relative to the sole crops (Section 1.4.3). The transpiration and growth analysis data were therefore used to determine the water use ratios of the tree and crop components. The causes of any treatment differences were investigated using concurrent micrometeorological data.

2.3.1 Precipitation

At ICRISAT Center, total daily rainfall is routinely recorded at the meteorological station (several km West of field RP15) and also using numerous standard rain gauges in the field experimental area; this is important due to the large spatial

variation in rainfall across the site. Two of the standard raingauges were situated close to RP15, one approximately 100 m from the North East boundary and the second a similar distance from the North West boundary. The mean daily rainfall for RP15 was calculated as the mean of these two gauges.

2.3.2 Transpiration

Until recently, it has not been possible to measure the transpiration of undisturbed trees growing in the field routinely, accurately and non-invasively (Ong *et al.*, 1995). There have therefore been very few field studies of agroforestry systems in which transpiration by the tree and crop components has been separated, or even where total water use has been determined. Recent technical advances have now made this type of measurement possible and these were applied in this study. In addition, transpiration data were examined in relation to concurrent micrometeorological conditions to establish the nature of relationships between them. This type of information helps to determine the contribution of changes in water use to the overall differences in productivity between treatments and to understand the mechanisms involved.

2.3.2.1 *Pigeonpea*

The two most commonly used methods for measuring transpiration from small trees or large annual crop plants are the heat pulse and heat balance techniques. Huber (1932) introduced the heat pulse technique, in which the sap flow velocity in plant stems is calculated from the time required for a discrete input of heat to travel from its source to sensors (thermocouples or thermistors) placed further downstream in the flow path. This technique has been utilised, assessed and modified by many researchers (e.g. Marshall, 1958; Swanson *et al.*, 1981; Cohen *et al.*, 1981). The difficulties involved in determining the conducting area of xylem have resulted in the technique being used more frequently for comparative rather than absolute studies of sap flux (Ong *et al.*, 1995). Recent developments have overcome many of the calibration difficulties (Swanson, 1994), but the technique still requires skill

and expertise to install and operate successfully.

The heat balance technique introduced by Vieweg and Ziegler (1960) has also been adopted and adapted by many workers. This method involves the calculation of sap flux through measurement of the balance of heat fluxes into and out of a section of stem. Heat balance methods have an almost instantaneous response time and are sensitive to relatively small changes in flow rate. Developments of this technique by Cermak (1984) and others have involved a heat input to a section of stem which was continuously adjusted to maintain a constant temperature gradient between the heated section and an unheated section of stem below. The amount of heat required to maintain this temperature difference is dependent on sap flux. These methods frequently involve the insertion of electrodes into the stem to heat the sap and often have the disadvantage that they do not measure conductive losses directly (Ishida *et al.*, 1991). An alternative design provides a constant heat input to the stem and the sap flux is calculated directly from the temperature gradients (Sakuratani, 1981; Baker and van Bavel, 1987). In these systems, a heating element is wrapped around the stem surface, but because there is no control over stem temperature there is a possibility of damage. The heat balance technique described by Ishida *et al.* (1991) was designed to overcome the main disadvantages of the two approaches described above by controlling stem temperature and measuring conductive heat losses directly. It is also relatively inexpensive and easy to install, and is capable of measuring transpiration rates in the range 20-700 g h⁻¹ in both woody species and large herbaceous crop plants with an error of ± 8 %.

A heat balance technique based on the design of Ishida *et al.* (1991) but modified as described by Khan and Ong (1995) was used to monitor sap flux in pigeonpea in RP15 between November 1989 and March 1991 (Fig. 2.4). This method was calibrated for perennial pigeonpea by simultaneously recording the weight of pigeonpea plants grown in pots (sealed to avoid water loss from the bottom of the pot or the soil surface and placed on 30 kg Mettler balances) and sap flux measured with the heat balance equipment. The heat balance approach was found to overestimate actual transpiration by approximately 5 % (Ong *et al.*, unpublished).

Theory of heat balance method.

The energy balance of the system illustrated in Figure 2.4 can be described as:

$$C \, dT_h/dt = Q_h - Q_r - Q_u - Q_d - Q_c \quad \text{equation 2.4}$$

where C is the heat capacity of the stem ($J \, K^{-1}$), Q_r is the radial heat loss through the styrofoam (K), Q_u and Q_d are the conductive heat losses upstream and downstream respectively, Q_c convective heat loss, T_h temperature of the heater surface and Q_h the heater input. Q_h was calculated from Joules law using the voltage applied (V) and the heater resistance (R):

$$Q_h = V^2/R \quad \text{equation 2.5}$$

The radial heat flux was calculated from (Carslaw and Jaeger, 1959) as:

$$Q_r = 2\pi k_r (T_h - T_o) L / \ln(r_1/r_2) \quad \text{equation 2.6}$$

where k_r is the thermal conductivity of the styrofoam (assumed to be $0.005 \, W \, m^{-1} \, K^{-1}$), T_h is the temperature at the heater surface, T_o is the ambient temperature of the stem below the heater unit, r_1 and r_2 are the radii of the stem and the insulation material and L is the length over which heat is dissipated.

The heat losses due to conduction were calculated as:

$$Q_u = A \, k_w (T_h - T_u)/d_u \quad \text{equation 2.7}$$

and

$$Q_d = A \, k_w (T_h - T_d)/d_d \quad \text{equation 2.8}$$

where A is the cross-sectional area of the stem, K_w is the thermal conductivity of the wood ($0.76 \, W \, m^{-1} \, K^{-1}$; Swanson and Whitfield, 1981) and d_u and d_d are the

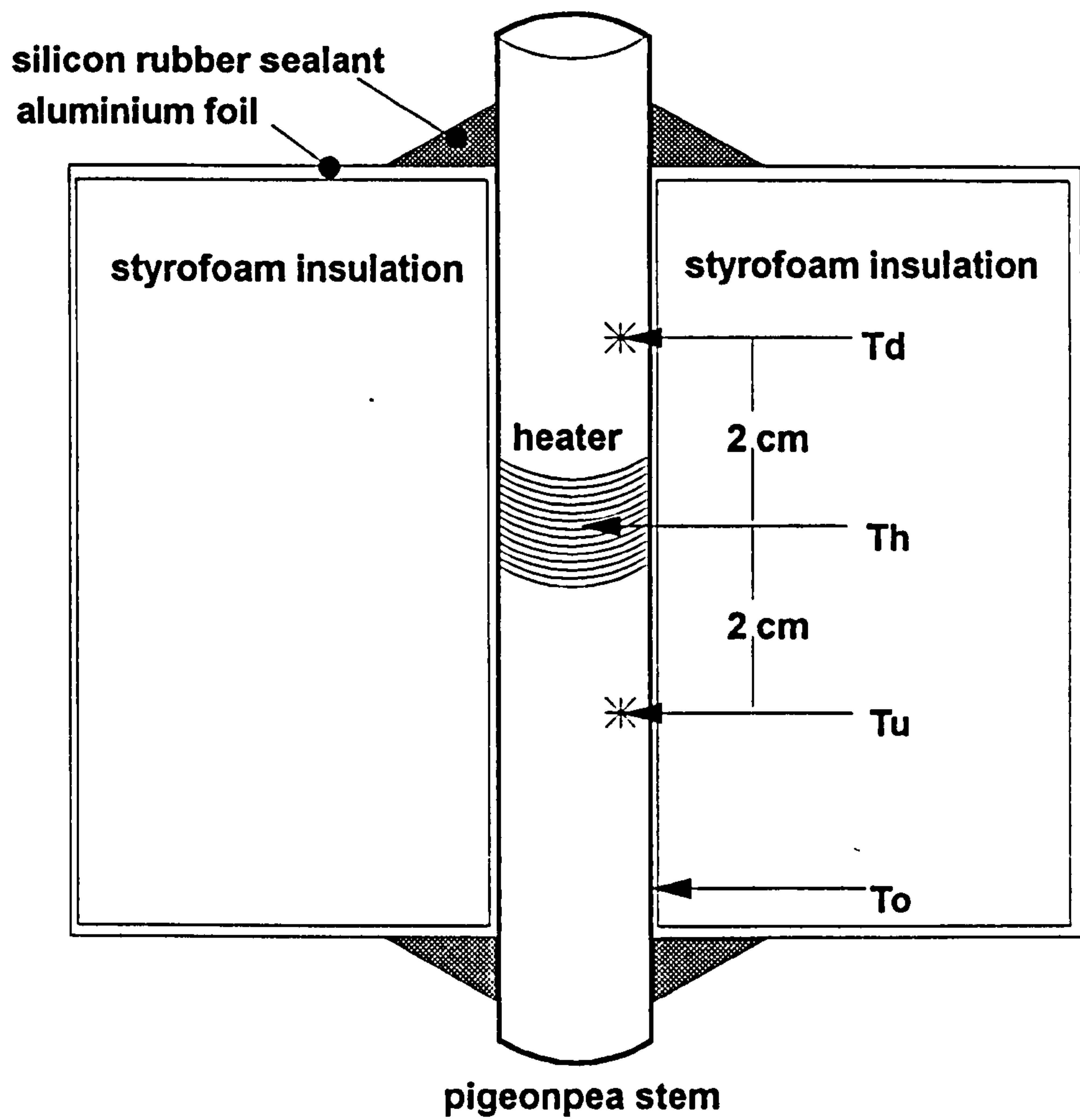


Figure 2.4: Heat balance equipment, showing relative positions of the heater and thermocouples (T_h , T_d , T_u and T_o).

distances between the heater thermocouple and the upstream and downstream thermocouples respectively.

The convective heat loss can be represented as:

$$Q_c = C_w J_w (T_u - T_d) \quad \text{equation 2.9}$$

where C_w is the specific thermal capacity of water ($4.18 \text{ J g}^{-1} \text{ K}^{-1}$) and J_w is the water flux (g s^{-1}) through the stem.

Because the heat input is continuously adjusted to maintain steady state conditions, Q_c can be calculated and the equation solved for J_w . When the known heat losses Q_r , Q_u and Q_d are deducted from the heat input Q_h , the remaining heat loss must be due to convection (Q_c) such that:

$$J_w = (Q_h - Q_r - Q_u - Q_d) / [C_w (T_d - T_u)] \quad \text{equation 2.10}$$

During the day, conductive and radial heat losses are small relative to convection and so Q_r , Q_u and Q_d may be ignored and an approximate value for J_w calculated by combining equations 2.8 and 2.10:

$$J_w = V^2 / [C_w R (T_u - T_d)] \quad \text{equation 2.11}$$

Ong and Khan (unpublished) calculated transpiration using both equations 2.10 and 2.11 and found the latter provided satisfactory estimates of daytime transpiration. This simplified calculation was used to estimate transpiration from pigeonpea plants.

It is important to obtain correct average values of xylem fluid temperature since any overestimation of $T_u - T_d$ will result in underestimation of J_w . In stems with separate vascular bundles there may be considerable variation in the radial temperature profile (Ishida *et al.*, 1991). However, because the woody stems of established pigeonpea plants possess continuous rings of xylem tissue (Bisen and Sheldrake, 1981),

insertion of thermocouples into the xylem should provide reliable estimates of $T_u - T_d$.

Heat balance measurements of J_w may not always agree with the actual transpiration rate. For example, during the early part of the day, transpiration exceeds absorption and so the quantity of water stored in plant tissue declines. During this period, the true rate of transpiration exceeds J_w , whilst the situation is reversed later in the day. Although these effects influence instantaneous measurements of transpiration, the totals obtained over daily or weekly periods often agree closely with the true transpiration rate (Ong *et al.*, 1995). However, in large woody species, the effects of changes in the quantity of stored water may persist over periods of days or weeks during drying or wetting cycles.

Practical application

The heater coil comprised a 92.6 cm length of 36 gauge Teflon-coated wire with a resistance of 15 ohms which was wound closely around the stem of a pigeonpea plant and fixed in position using insulation tape. The heater was powered by an 8 V battery using a control circuit and a thermocouple was taped to its surface (Fig. 2.4). Small holes were drilled into the xylem, 2 cm above and below the heater, and thermocouples T_u and T_d were inserted into these. When stem diameter exceeded 20 mm, the distance between T_h and T_u and T_d was increased to equal stem diameter. The thermocouple cables were wrapped once around the stem to minimise conduction of heat down the lead wires. A fourth thermocouple (T_o) was taped to the stem surface 5 cm below the heater. All thermocouples were connected to a CR 21X datalogger (Campbell Scientific, Logan, USA). The datalogger was programmed to read the thermocouple temperatures, control the heater input and compute and display the transpiration rate (Ong and Khan, 1995). Three plants could be monitored using one CR21X datalogger; the heater inputs were controlled by three relay circuits that maintained T_h 5 °C above the control thermocouple (T_o). This ensured that the heat input into the stem Q_h (W) was balanced by the heat fluxes out of the heated stem segment. The entire installation was insulated with

styrofoam cut to provide a close fit and attached with insulation tape; this was then covered with aluminium foil. The purpose of the insulation was to avoid any additional heat input from incident radiation and minimise radial heat exchange. The insulation was sealed onto the stem using a quick-setting silicon rubber to prevent water penetration. Errors in temperature measurement were minimised by shading the apparatus.

The method described by Ishida *et al.* (1991) differed in several respects from that described above. For example, in their system T_h was maintained 2.5 to 3.0 °C above T_u , conductive heat losses were calculated and thermocouple (T_o) was placed on the outside of the insulating material to estimate Q_r (equation 2.6), rather than on the stem surface under the insulating sheath.

As there were only two dataloggers available, sap flux measurements were confined to the line and dispersed treatments; unfortunately the sole pigeonpea could not also be monitored for purposes of comparison. Trees were selected for measurement on the basis that their mainstem diameter and hence presumed sap flux was modal for the plot concerned (Section 2.2.2.1), and that no side branches were present below 40 cm. Because three trees were connected to a single datalogger, these were selected in close proximity to minimise the length of the cable-runs for the thermocouples and heater. The heat balance equipment was moved to a further group of three trees, selected as described above, at 21 d intervals to avoid damage to the stem by the heater coil as stem diameter increased due to continued growth.

2.3.2.2 *Groundnut*

A Delta-T Mark II Automatic Diffusion Porometer was used to measure the diffusive resistance of groundnut leaves. These values may be used to estimate transpiration from a crop canopy if leaf area index, the leaf to air vapour pressure difference and boundary layer resistance are measured at the same time (Azam-Ali, 1983). Transpiration per unit ground area E_g ($\text{g m}^{-2} \text{s}^{-1}$) for a layer of foliage can be

represented as:

$$E_i = L (v_i - v_a)/(r_i - r_b) \quad \text{equation 2.12}$$

where L is the leaf area index of the layer, v_i is the saturated vapour pressure at leaf temperature (g m^{-3}), v_a is the vapour pressure of the surrounding air (g m^{-3}), r_i is the mean leaf diffusive resistance (s m^{-1}) and r_b is the mean boundary layer resistance (s m^{-1}). Transpiration from the entire canopy can then be estimated by summing the values for each layer measured.

Diffusion porometers operate on the principle that transpiration by the enclosed tissue humidifies a small cup temporarily attached to the leaf surface. Delta-T porometers pass air through a silica gel reservoir periodically so that humidity within the cup cycles automatically around a pre-set point. The time taken for transpiration by the enclosed leaf to increase humidity within the cup to the set level is indicated as a digital count. The counts are converted to diffusive resistances by using calibration curves constructed using a calibration plate containing known diffusive resistances. Full details of the porometer specifications are given in the manufacturer's manual.

The porometer was placed in a shaded position in the field 15 minutes before each set of readings were commenced and allowed to cycle with the calibration plate in position until the readings stabilised. A damp paper pad (moistened with distilled water at ambient temperature) was placed onto the flat side of the calibration plate and covered with waterproof tape. The pump rate was adjusted so that the air within the cup dried to the set point rapidly (approximately 2 s), but not so fast that drying beyond the set point occurred. Count rates for each resistance on the calibration plate were recorded, starting with the highest and waiting for the count to stabilise for each position. The calibration plate resistances values were corrected for variations in ambient temperature, as indicated in the manufacturer's manual, and a calibration curve plotted. This process was repeated for each set of measurements throughout the day.

One of the objectives of the measurements in 1989 was to determine diurnal patterns of leaf diffusive resistance in groundnut from 30 DAS onwards, in order to calculate transpiration. Unfortunately, repeated failure of the porometer pump and lack of a replacement severely limited the number of days on which measurements could be made.

On each sampling date, measurements were made at 0900, 1100, 1300, 1500 and 1700 IST. However, measurements frequently had to be abandoned due to rain, since it is crucial that the leaf surface is completely dry if accurate values are to be obtained. For this reason, no measurements were attempted before 0900 and any rain during the course of the day usually resulted in no further observations being made.

Because of the difficulties encountered, porometer measurements were confined to individual leaves of five randomly selected plants in replicates 1 and 2 of the sole groundnut treatment in 1989. Although it is usual to divide the groundnut canopy into upper and lower levels and to calculate mean values for canopy diffusive resistance (Azam-Ali, 1983), many of the older leaves in the lower part of the canopy had developed symptoms of foliar disease (Section 2.1.6) and so the canopy was considered as a single layer. Measurements were made on both the adaxial and abaxial surfaces of young fully expanded leaves, avoiding the midrib. The sensor head was shaded during and between measurements to avoid heating and maintain the difference between the cup and leaf temperatures $< 1^{\circ}\text{C}$ since the count rate is increased by about 16 % per $^{\circ}\text{C}$ if cup temperature exceeds leaf temperature at high humidity.

A porometer was not available in 1990 until the groundnut reached 70 DAS. Intensive measurements were then made between 70-80 DAS to establish whether there was any systematic variation in diffusive resistance in groundnut in relation to distance from the pigeonpea. In the dispersed planting, diffusive resistance was measured for five healthy fully expanded leaves in rows Dmax, Dmed and Dmin (Fig. 2.2). In the line treatment, three leaves were measured in each of the shaded rows 1, 2 and 3 (comprising Lmax, Fig. 2.2) and each of the unshaded rows 4, 5

and 6 (Lmed). Measurements were made around midday, when the diffusive resistance would be expected to be at its lowest point in the diurnal cycle. The data obtained were again limited by rainfall and an ongoing fault with the porometer pump. On several occasions, the technique described by Azam-Ali (1983) was used to estimate boundary layer resistance using artificial leaves made from blotting paper.

Wet and dry bulb temperatures (T_w and T_d respectively) at the surface of the groundnut canopy were measured using aspirated psychrometers placed permanently in the plots (Section 2.6.3). Instantaneous readings were obtained directly from the CR7 datalogger (Campbell Scientific, Logan, USA) and the values converted to atmospheric vapour pressure (v_a) using standard tables, according to the relationship:

$$v_a = v_{sw} - \tau (T_d - T_w) \quad \text{equation 2.13}$$

where τ is the psychrometric constant (66 Pa °C⁻¹ at sea level for a ventilated psychrometer) and v_{sw} is the saturated vapour pressure (Pa) at the wet bulb temperature. The conversion factor required for use in equation 2.13 is 217 g m⁻³ = 1 kPa.

2.3.3 Stored soil moisture

Until about 40 years ago, soil moisture measurements relied mainly on gravimetric methods (Squire *et al.*, 1981). However, the potential for a neutron logging method for measuring the water content of soil was established during the 1950s (Greacen, 1981). The technique is based on the fact that fast neutrons emitted by a radioactive source are slowed down by the presence of water. The slow neutrons can be detected and a count displayed which is directly related to the soil water content. Measurements are made by lowering a probe containing the neutron source down a series of access holes in the soil profile and taking readings at specific depths. As neutron probe methods provide estimates of soil moisture integrated over large soil volumes over extended periods, the technique is much less labour intensive than

traditional gravimetric sampling for large or long term experiments. Troxler (Troxler Electronic Laboratories Inc., North Carolina, USA) neutron probe soil moisture meters were used in the present study to monitor the use of stored soil moisture in each of the cropping systems examined.

Hydrogen nuclei are largely responsible for slowing the fast neutrons emitted by the probe. The assumption is that the majority of hydrogen nuclei will be associated with water molecules in most soils but, because soils contain varying quantities of other hydrogen-containing compounds, careful calibration is required for individual soils. The factory calibration is based on an 'ideal soil' without neutron-absorbing elements or other hydrogen-containing compounds (Troxler, Depth Moisture Gauge, manufacturer's manual, 1983).

The neutron moisture meter (neutron probe) used in this study was a Troxler model 3330. Because neutrons are unstable when free and decay with a half life of about 13 minutes into an electron and a proton, they must be created by a nuclear transmutation process within the probe. As no radioactive element emits neutrons as a natural decay product, it is necessary to have two elements within the neutron source, the first to produce energetic particles by nuclear decay and the second to absorb these particles and produce neutrons by decay. The Troxler 3330 uses Americium-241 to produce alpha particles (accompanied by gamma radiation) and Beryllium-9 which absorbs the alpha particles and emits fast neutrons. The neutrons produced are moderated to thermal velocities by collisions with nuclei in the soil medium. Thermalisation is the process by which fast neutrons are slowed to a point where further collisions with hydrogen or other molecules will slow them no further. A proportion of the slow neutrons are back-scattered to the source and are detected by a Helium 3 tube that is insensitive to fast neutrons. Aluminium is used as the access tube material because it absorbs very few thermal neutrons and is durable in the field. The instrument is calibrated to determine the relationship between the number of slow neutrons detected and the water content of the soil in a specific location.

Measurements were taken on seven occasions in 1989-1990 and nine in 1990-1991 during the soil drying cycle between the end of the rains and the point in the dry season when no more water could be extracted from the profile. These data were intended to provide information regarding the quantity of water extracted by pigeonpea roots at various depths in the profile and the effect of different plant spacings. During the rainy season more frequent measurements would have been required to determine the amount of water removed from the profile between successive rainfall events as the soil was returned regularly to field capacity. In addition, a detailed study of the soil water balance during the rainy season would have required frequent measurements of interception losses, runoff, deep drainage and soil evaporation, which was impossible within the time available.

Neutron probe measurements were made at equivalent positions within treatments to the growth analysis samples and micrometeorological instrumentation (Fig. 2.5). In the line treatment, there were three tube positions; MLmax between groundnut rows 1 and 2, MLmed between groundnut rows 4 and 5 and MLmin between groundnut rows 7 and 8. This arrangement allowed the changes in stored soil moisture to be examined in relation to distance from the pigeonpea row and mean values for the entire system to be calculated. Two sets of access tubes were installed in each of the three replicates that contained micrometeorological instrumentation (Replicates 1, 3 and 4) to provide a total of eighteen tubes.

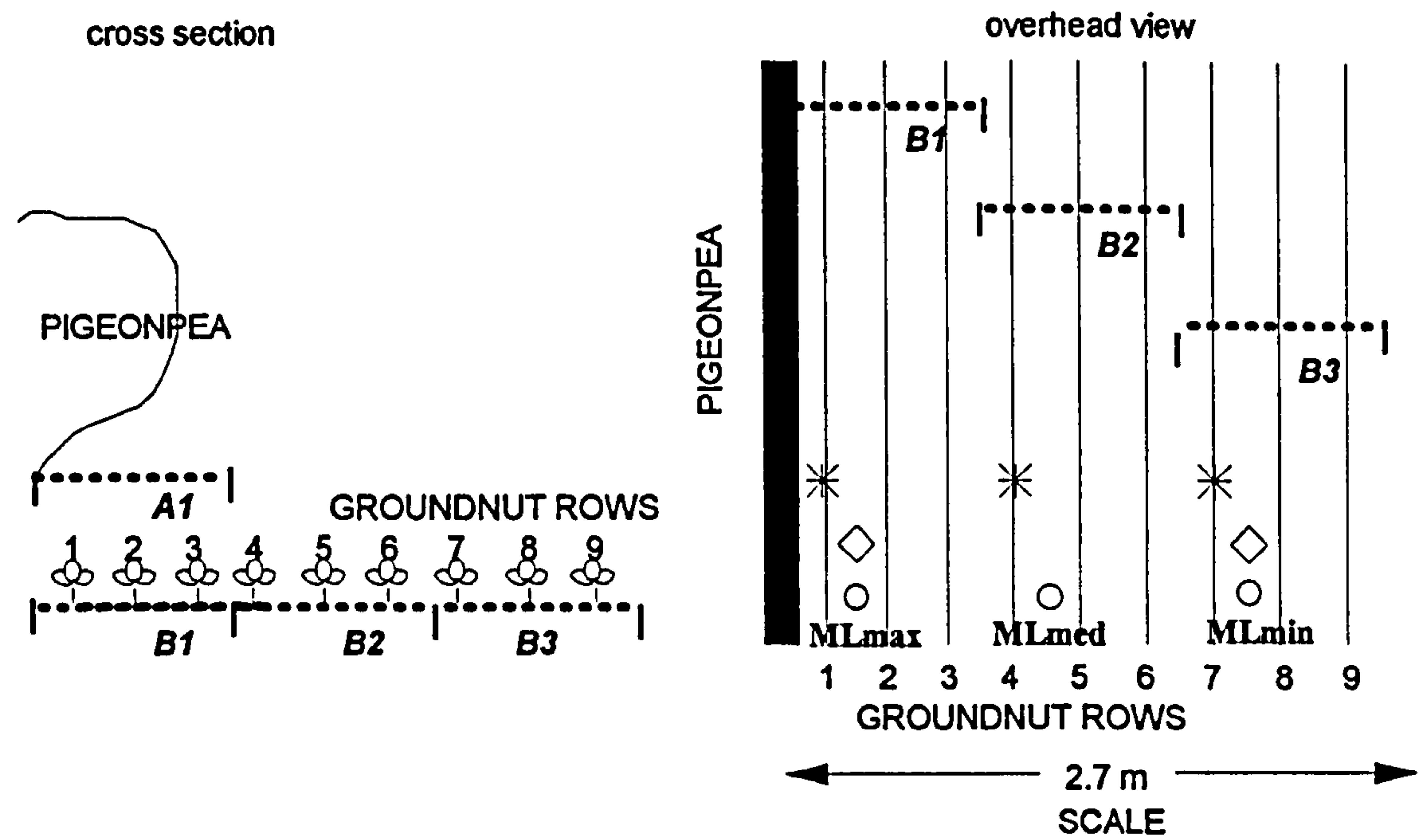
In the dispersed planting, three positions were selected to represent the full range of distances from individual pigeonpea plants (Fig. 2.5) so that the mean value for these three locations could be used to estimate stored soil moisture for the entire system. MDmax was situated 5 cm from the base of a pigeonpea plant, MDmin was located between groundnut rows 3 and 4, at the furthest possible point from the nearest pigeonpea plants (108 cm from each of a group of four plants), while MDmed was also located between groundnut rows 3 and 4, but mid-way between two pigeonpea plants in adjacent rows (90 cm from each plant). As in the line treatment, two sets of tubes were installed in Replicates 1, 3 and 4. In the sole groundnut plots, two access tubes were placed randomly in Replicates 1, 3 and 4,

whereas in the sole pigeonpea plots two access tubes were placed midway between adjacent plant rows in these three replicates. In all treatments, the access tubes were placed as close as possible to the micrometeorological equipment, whilst ensuring that the latter would not be disturbed during routine measurements.

The access tubes were first installed between 4-8 August 1989, but 13 tubes had to be replaced on 17 and 18 July 1990 due to pigeonpea mortality during the 1990 dry season. The access holes were prepared by driving corers of increasing length into the soil to a maximum depth of 1.5 m. A winch mechanism assured smooth removal of the corers and minimal disturbance to the surrounding soil. The 1.5 m depth was chosen to cover the maximum expected rooting zone of the pigeonpea during the first year of growth. A greater depth would have been ideal for 1990, but the stony nature of the soil below 1.5 m precluded installation to greater depths. The access tubes were prepared by cutting aluminium tubing into 170 cm lengths. One end of each tube was sealed with a tightly fitting wooden bung before being carefully installed into the prepared holes, ensuring that no gaps remained between the tube and surrounding soil. Water would have entered any gaps present around the access tubes, causing neutron probe measurements to be unrepresentative of the true moisture content. The tops the tubes were trimmed to project 10 cm from the soil surface and covered with metal caps to ensure that they remained clean and dry. Each of the 48 tubes was numbered and measurements taken in the same sequence on each sampling date.

Metal stops on the neutron probe cable determined the measurement depth at which measurements were taken. The stops were set so that the probe measurements were centred at 15 cm depth increments between 7.5 and 142.5 cm. The instrument was set to record data automatically for the desired number of depth readings and the values obtained were expressed as count ratio values against a standard. This standard was checked at the start of each set of measurements to allow for changes in probe sensitivity and reduce random count error to a minimum. Prior to taking the standard count, the instrument was allowed to stabilise in the field for 10 min with the probe locked within the body of the gauge. The POWER/TIME switch was

(a) Line planting



(b) Dispersed planting

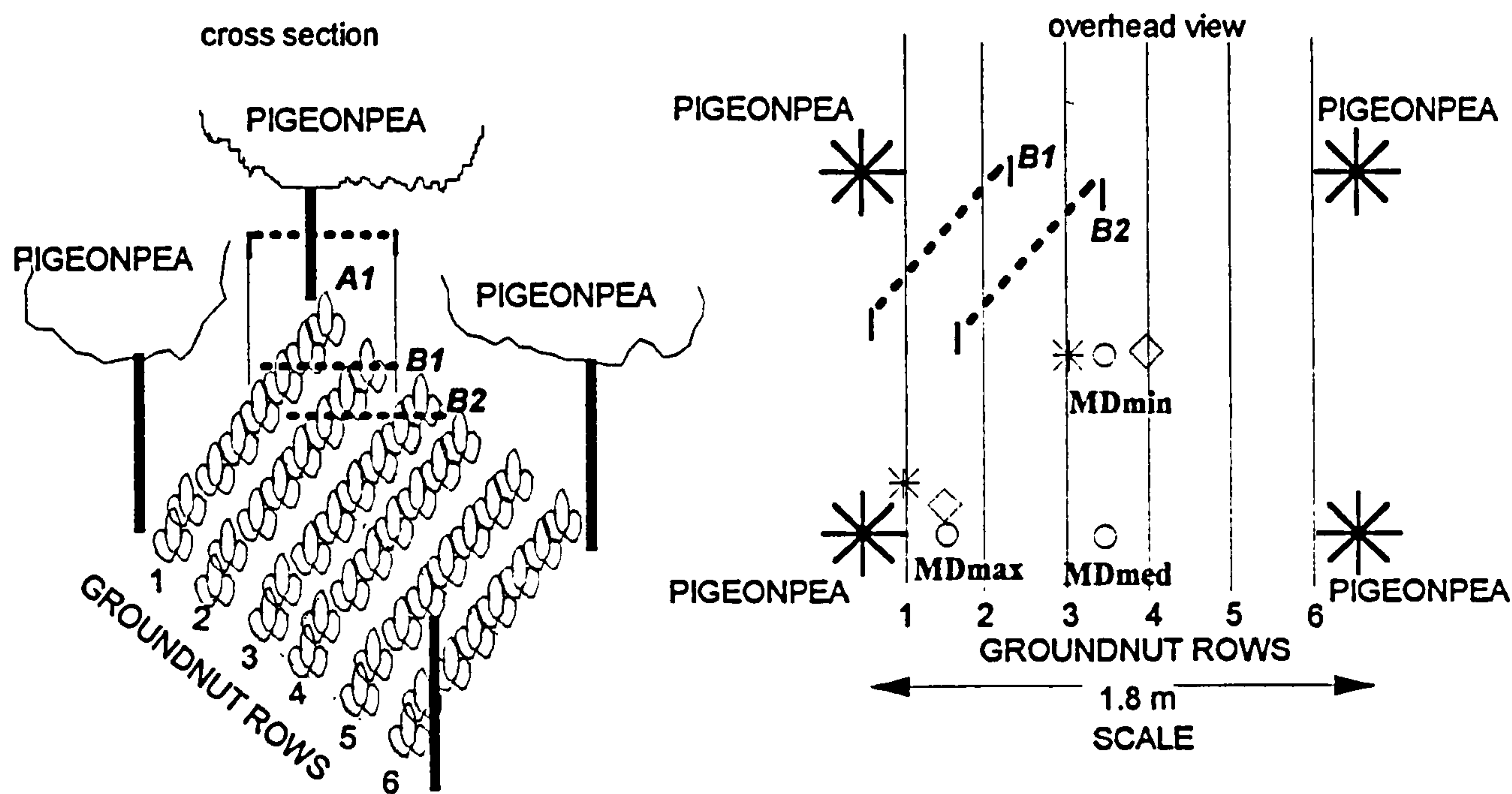


Figure 2.5: Location of the instrumentation in a) the line and b) the dispersed plantings of pigeonpea. \uparrow ----- \uparrow represents solarimeters, \circ neutron probe access tubes, \ast thermocouples (soil and leaf temperature) and \diamond psychrometers.

set at 4 min, the DISPLAY switch set to STD COUNT and the START button depressed. The standard count was then displayed and automatically stored. Since neutron probe measurements are only as accurate as the standard count, the procedure was repeated until a stable value was reached. A record was kept of standard counts over the entire experimental period since small changes may be expected, but larger or more sudden changes are indicative of defective procedures or instrumentation. The probe was then placed onto access tube number 1, unlocked and secured at the desired depth for the first reading. The POWER/TIME switch was set at 30 s and the START button depressed. At the end of this period the data were stored and the probe moved to the next depth. The probe was locked within the gauge body when moving between tubes. When the data from all 48 tubes had been collected, or if data collection was interrupted, the data were immediately downloaded onto the VAX mainframe computer system at ICRISAT. An ETA RS232-9 conductor cable was used to connect the computer terminal and neutron gauge, and the BAUD rates on both gauge and terminal were set at 300. Having created a file for data storage, the display switch was set to PRINT/CAL and the START button depressed. The DISPLAY switch was then set to count ratio and the START button pressed once again to initiate the transfer. Full operational details for the neutron moisture meter are given in the manufacturer's manual.

Accurate calibration of the neutron moisture meter is relatively difficult because the count rate for a given soil and depth depends not only on its volumetric water content, but also the quantity of hydrogen present in compounds other than free water, and on other soil properties such as bulk density. The instrument responds most strongly to soil properties close to the detector, which is an important consideration since most soils are not uniform (Bell, 1973; Greacen, 1981). Fortunately the soil in RP15 is relatively uniform and stone-free, allowing calibration and access tube installation to be carried out without undue difficulty.

The aim of the calibration process was to obtain paired neutron probe counts and gravimetric samples (from which volumetric water content was calculated) at 15 cm depth increments from 0 to 150 cm in RP15. As a range of values extending from

the percentage volumetric water at field capacity through to the permanent wilting percentage is ideal, the dry season is the most appropriate time to carry out the calibration. Calibration was carried out during the dry season of 1990 and repeated between January and April 1991.

Eight access tubes were installed for calibration purposes, two beside each of the replicates 1, 3 and 4 (Fig. 2.1). The tubes were placed approximately 2 m from the West boundary of replicate 1 and a similar distance from the East boundary of replicates 3 and 4. At each of the calibration locations, aluminium strips were hammered into the ground to form a rectangle 2 x 1 m in size, leaving a rim extending 20 cm above the soil surface. This enclosure allowed irrigation of the calibration area to be carried out more easily and ensured that it was not disturbed. The two access tubes were installed to a depth of 1.5 m, 2 m apart and 50 cm from the aluminium fence. The area within each of the aluminium fences was then flooded using a low pressure hose so that the soil profile was not disturbed. After three days, it was assumed that the soil had drained to field capacity, and the first set of readings was taken at 15 cm depth increments in each of the six calibration tubes. At each of the three calibration sites, three sets of gravimetric samples were taken using a soil auger, sub-dividing the soil core into 15 cm depth increments. The gravimetric samples were taken at least 30 cm from the access tubes so that later probe readings were not disturbed. The radius of neutron probe measurement increases with decreasing moisture but does not normally exceed 28 cm. Each soil sample was immediately placed in labelled aluminium cans with tight-fitting lids to prevent moisture loss prior to weighing. After the fresh weight had been recorded, the cans were placed in an oven at 105°C for 48 h and the dry weight recorded. Gravimetric water content (G) was calculated as:

$$G = (C_{wet} - C_{dry})100 / (C_{dry} - C) \quad \text{equation 2.14}$$

where C is the weight of the empty can and C_{wet} and C_{dry} are the weights of the soil and can before and after drying.

The values obtained were converted to the corresponding volumetric percentage water contents by multiplying them by the bulk density of the soil at the depth in question. Bulk density was determined during 1990 at the same time as deep soil profiles (to 2 m) were being exposed for root studies. As the soil in RP15 proved to be relatively uniform across the experimental site, replicate samples taken from a single vertical soil profile were considered sufficient to estimate bulk density. A mechanical digger was used to expose a vertical soil face in the line planting treatment of replicate 2 on 17 and 18 January 1991 and the face was smoothed by hand. A small hand-held corer was used to remove six horizontal samples from the exposed face at 15 cm depth intervals from 7.5 to 142.5 cm below the soil surface. The cores were removed carefully to ensure that no soil was lost and placed immediately into aluminium cans. The corer produced samples 6 cm long and 5.5 cm in diameter. The air-tight cans were placed in an oven at 105 °C for 48 hours before weighing. Bulk density (BD) was calculated as:

$$BD = (C_{dy} - C)/v \quad \text{equation 2.15}$$

where C_{dy} is the mass of the can and soil after drying (g), C is the mass of the empty can (g) and v is the volume of the soil sample (142.5 cm³). The mean BD for all six samples at each sampling depth was used in subsequent calculations.

This calibration procedure provided an equation which could be used to convert count ratios to percentage soil moisture content for most of the soil profile. However, because the surface layer of most soils has a higher organic matter content than the rest of the profile, and since some neutrons escape to the atmosphere and reduce the count, measurements recorded by the neutron moisture meter for the surface horizon may be inaccurate unless appropriate corrections are made (Bell, 1973; Brenner, 1986). The loss of neutrons to the atmosphere is greater when the surface soil is dry, as was the case throughout the measurement period. To overcome this problem, soil samples were taken from the top 15 cm of the soil profile for gravimetric determination of soil water content whenever neutron probe

measurements were made. Two gravimetric samples were taken adjacent to each access tube and the mean value used. In the line planted and sole treatments, the samples were taken at the same distance from the pigeonpea row as the access tube in use, and at least 25 cm from the tube. In the dispersed planting, samples for MDmax (Fig. 2.5) were taken from within a 15 cm radius of the base of the tree, and the Mdmed and MDmin samples from within a 30 cm radius of the relevant access tube. The sample holes were refilled with equal quantities of top soil from outside the experimental site.

2.3.4 Runoff

Runoff plots were installed during the 1990 dry season in all four treatments of Replicate 2 (Fig. 2.1). This replicate was chosen because there was a slight North-South gradient in the field and the trenches associated with the runoff plots must be at the lower end of this; Replicate 2 was also the only one without micrometeorological instrumentation, and so interference with routine data collection in the more heavily instrumented replicates was avoided.

The length of the runoff plots in all ICRISAT trials was standardised so that quantitative comparisons could be made between experiments. The standard dimensions are 22 x 3 m, which is considered to provide a reasonable comparison with the average farmer's field in India. Runoff should only be measured in experimental plots when these are large enough for the water flow to attain velocities similar to those reached in a traditional field situation (Brenner, 1986).

Aluminium sheets were used to define the edges of the runoff plots; these were buried 1 m into the soil and projected 0.5 m above the soil surface to minimise the edge effect of the plots (Khan, pers. comm.). The water from the runoff plots was channelled into locally manufactured tipping buckets which released their contents into a trench running away from the experimental area when full. The tipping buckets were connected to a CR10 datalogger (Campbell Scientific Inc., Logan, USA). There was also a small collection area, so that rainfall that was insufficient

to make the buckets tip could be measured by hand.

The maximum rate of precipitation received at ICRISAT Center (approximately 150 mm h⁻¹) was multiplied by the runoff plot area (72 m²) to determine the maximum potential runoff (3 l s⁻¹). So that runoff could be measured at all possible rates, the volume of water collected before the bucket would tip was set at 3 l (assuming that the buckets took < 1 s to tip and return to their upright collection position). Each tip of a bucket was equivalent to a runoff of 0.04 mm from the 72 m² collection area.

The equipment was calibrated to determine the relationship between the number of bucket tips per unit time and the rate of runoff from the plot. This was achieved by providing a controlled water flow from metal drums placed at the opposite end of the plots to the tipping buckets, and recording the number of bucket tips for a range of known water flow rates from the drums.

An automatic raingauge (Texas Electronics TE525), which was activated by rainfall events greater than 0.5 mm, caused the datalogger to scan the buckets and record the number of tips per minute from each. The scanning and recording process continued for 1 h after each rainfall event. Data obtained from each rainfall event were downloaded onto cassette tape and transferred to the ICRISAT mainframe VAX computer through an RS232 interface.

2.4 LIGHT INTERCEPTION MEASUREMENTS

2.4.1 Introduction

The potential of mixed cropping systems for improving crop productivity through increased interception and more efficient use of incident radiation was reviewed in Section 1.4.2. However, experimental data demonstrating the realisation of this potential are limited, particularly for agroforestry systems. A major contributory factor is the difficulty not only of partitioning light use between intercrop

components, but also of determining the actual advantage in resource use relative to the sole crops (Keating and Carberry, 1993; Ong and Black, 1994; Azam-Ali, 1995). In addition, the numerous variables affecting light utilisation in mixed crop communities make it difficult to obtain a mechanistic understanding of the processes involved.

Intensive measurements of light interception by the pigeonpea and groundnut components of all treatments were carried out throughout the experiment. The major aims were to establish radiation interception and conversion coefficients for the components of each system, examine their relative contribution to observed effects on growth and productivity, and investigate any interactions between light interception and concurrent micrometeorological conditions.

2.4.2 Solarimeter measurements

The concept of measuring the radiation profiles within plant canopies was first introduced by Isobe (1962) and later developed by Szeicz *et al.* (1964), who used copper plated constantan wire to produce thermopiles (with a light sensitive surface area of approximately 0.02 x 0.86 m), which were placed in a glass tube. When a temperature difference exists between thermopile junctions, a voltage is created that is proportional to the number of junctions and the temperature difference. In solarimeter tubes, the temperature difference occurs between black and white painted areas which provide hot and cold junctions respectively, since both receive the same radiant energy flux but are subject to differential heating. Tube solarimeters tend to provide less accurate measurements than flat solarimeters because they do not obey Lambert's Cosine Law (Jones, 1992). Because the sensitivity of tube solarimeters depends on the angle of incidence of incoming radiation, they are usually used to provide interception data rather than an absolute measure of irradiance. Radiation interception is obtained by measuring the ratio of the irradiances recorded by solarimeters mounted above and below the canopy (Monteith *et al.* 1981). Standard tube solarimeters measure irradiance in all wavelengths transmitted by glass (0.4 to 3 μm), although they may be fitted with filters (e.g. Kodak Wratten 88) that only

transmit infra-red radiation (0.75 to 3.0 μm). By comparing the values for filtered and unfiltered tubes, the energy received between the 0.40 - 0.75 μm waveband (which is slightly wider than the photosynthetically active spectrum (PAR) of 0.390 - 0.714 μm) can be determined by difference (Palmer, 1980).

Unfiltered tube solarimeters of the type described by Green and Deuchar (1985) were manufactured at ICRISAT and fifty were installed immediately after the groundnut was planted in July 1989, and data were recorded from July 21. These solarimeter measurements enabled light interception by both the individual crop components and the entire cropping system to be examined. In addition, cumulative values for light interception could be studied in relation to dry matter accumulation and transpiration.

All tubes were checked to ensure that their output for a given irradiance was constant before connecting them to a CR7 datalogger (Campbell Scientific, Logan, USA) located in a hut in the centre of the experimental site (Fig. 2.1). On 20 July 1989, two of the tubes were calibrated against a Kipp solarimeter to determine the conversion factor required to convert their millivoltage output into intercepted radiation expressed in units of W m^{-2} . This calibration was repeated on 7 August 1990. The remaining 48 tubes were cross-calibrated against simultaneous readings from the 'control' tubes to determine individual correction factors, which were entered into a BASIC computer programme to calculate percentage light interception

from the values recorded by the datalogger according to the following relation:

$$f = 100 [1 - (T_x.CF)/T_c] \quad \text{equation 2.16}$$

where T_x represents the radiation recorded by solarimeters below the crop canopy, CF is the calibration factor and T_c is the incident radiation recorded by the control tube.

In the line planting, the solarimeter tubes were placed perpendicular to the pigeonpea

rows in Replicates 1, 3 and 4. Each 90 cm tube spanned three groundnut rows (Plate 5) and the use of three adjacent tubes allowed half the distance between adjacent pigeonpea rows to be monitored (B1 spanned rows 1-3, B2 rows 4-6 and B3 rows 7-9). The mean values for radiation interception at these three tube positions provided an estimate of total interception for the treatment as a whole, while the values for the individual sampling positions enabled the spatial variation in interception to be established. The N-S orientation of the tubes minimised measurements errors early and late in the day when solar angle is large. As the East-West pigeonpea row orientation would have caused more radiation to be received by solarimeters placed to the South of the row than those placed to the North, two sets of tubes were installed in each replicate, one to the North and the other to the South of the pigeonpea row. A single tube was placed above the groundnut canopy at position B1, at a height of 30 cm, to monitor light interception by the pigeonpea canopy. It was not possible to predict whether the pigeonpea would cause shading extending beyond groundnut rows 1-3 because the potential height and canopy radius of the pigeonpea were unknown. Ideally 'above groundnut' solarimeters would also have been placed at position Lmed to quantify any shading of groundnut rows 4-7 by the pigeonpea, but this was not possible due to the limited availability of both solarimeter tubes and datalogger channels.

In the dispersed planting, two 'below groundnut' solarimeter positions were used so that their mean interception values were representative of the system as a whole. This was achieved by placing the tubes at distances of 30 cm (tube B1) and 55 cm (tube B2) from a pigeonpea plant, oriented at an angle of 45° to the pigeonpea row (Plate 6), so that one quarter of the area between four pigeonpea trees was covered. One set of tubes was installed to the North and another to the South of the pigeonpea row. Above-groundnut tubes (A1) were installed 30 cm above each B1 tube, but unfortunately insufficient tubes were available to place 'above groundnut tubes' above position B2. Unlike the line treatment, this solarimeter arrangement did not facilitate detailed measurements of the relationship between radiation interception and distance from the pigeonpea row. Ideally, an array of light interception measurements arranged in a concentric pattern around individual pigeonpea trees, or

numerous point measurements between groups of four trees would have been made to achieve this objective.

In the sole groundnut, two tubes were randomly positioned at right angles to the crop rows in each replicate plot. The same arrangement was adopted for the sole pigeonpea in 1989, but in June 1990 (when the pigeonpea population was reduced) the two tubes were placed in a similar manner to the B1 tubes in the dispersed planting. The two reference tubes were placed on metal supports 3 m above ground level in the centre of the field between the four replicates. One of these was placed at the same angle as the tubes in the line treatment, and the second at the same angle to those in the dispersed treatment.

The tubes were cleaned daily and checked to ensure they were undamaged and remained horizontal after heavy rain. During the rainy season, some solarimeters were replaced because of condensation within the tubes or breakages. The replacement tubes were individually calibrated and the conversion programme for calculating light interception was altered accordingly.

The datalogger was powered by a 12 volt car battery which was replaced with a newly charged battery at three day intervals. Data were transferred from the datalogger to cassette tape at two day intervals. Occasional loss of data for individual instruments occurred because of damage to wires or connections, although a total failure of the datalogger on 16 August 1990 caused by an infestation of black ants resulted in the total loss of data over a three day period. Careless operation of a mechanical rotovator by a member of field support staff in June 1990 caused severe damage to the lead wires for the solarimeters and other micrometeorological instruments. Complete rewiring was required, an operation which was not completed until 3 August 1990, fourteen days after groundnut had been sown. Soil temperatures alone were recorded from groundnut emergence, using a Campbell 21X datalogger.

2.5 MICROMETEOROLOGICAL MEASUREMENTS

2.5.1 Introduction

The main purpose of the micrometeorological measurements was to determine the effects of pigeonpea on the microclimate experienced by the groundnut. The relationships between microclimatic conditions and groundnut growth and development have been studied in detail (e.g. ODA, 1987; Ong *et al.* 1991c) and this information provided a sound basis for examining the likely contribution of microclimatic factors to the observed treatment differences in light and water use, and the growth, development and productivity of groundnut.

2.5.2 Soil and leaf temperature

For soil temperature measurements, copper-constantan thermocouples were manufactured from 24 gauge wire and sealed with silicon rubber to prevent water penetration. These were placed at positions MDmax and MDlow in the dispersed planting and MLmax, MLmed and MLlow in the line planting (Fig. 2.5). Individual thermocouples were placed randomly in the sole groundnut plots, whilst in the sole pigeonpea they were located midway between pigeonpea rows prior to June 1990, and at an equivalent position to MDlow thereafter. In each treatment, a single set of thermocouples was placed at a depth of 5 cm. 36 gauge wire was used to construct leaf thermocouples, which were attached to the abaxial surface of young, healthy fully expanded groundnut leaves using plastic paperclips. The thermocouples were checked daily and moved to younger leaves when necessary. In the line treatment, leaves were monitored in groundnut rows 1, 4 and 7, whilst in the dispersed treatment, leaves at positions MDmin and MDmax were selected (Fig. 2.5). Leaf thermocouples were randomly placed in both the sole groundnut and sole pigeonpea plots.

Soil and leaf temperatures were monitored in replicates 1, 3 and 4 using a total of 42 thermocouples, connected to the same CR7 datalogger (Campbell Scientific) as the solarimeters. Measurements began on July 21 1989 and continued throughout most of the experimental period, as described in Section 2.6.2.

2.5.3 Saturation deficit

Aspirated psychrometers units, based on the design of Saffell (1981), were constructed at ICRISAT for measuring saturation deficit. These consisted of two copper-constantan thermocouples shielded within a foil-covered plastic tube; one thermocouple remained dry whilst the other was attached to a cotton wick which was kept moist from a reservoir of distilled water. The units were aspirated by a fan operating at a velocity of 3.5 m s^{-1} and powered by a 12 volt DC motor. Saturation deficit was calculated from the wet and dry thermocouple readings according to equation 2.13.

Aspirated psychrometers were placed at locations MLmax and MLmin in the line planting, and at MDmax and MDmin in the dispersed planting (Fig. 2.5), but were randomly positioned in the sole groundnut and pigeonpea plots. In all plots the psychrometers were located 40 cm above ground level, close to the surface of the groundnut crop. Psychrometers were placed in replicates 1, 3 and 4, providing a total of 18 units recording wet and dry temperature and requiring 36 channels on the CR7 datalogger. The units were examined daily to ensure that the fan was fully operational and the reservoir of distilled water was adequate, and the wicks were replaced at 14 d intervals. The orientation of the psychrometers was changed periodically to ensure that all units were similarly ventilated.

2.5.4 Windspeed

Cup anemometers (Met-one, Model O14A) were used to monitor horizontal wind velocity. As only four units were available, one was placed in each of the four

treatment plots of replicate 4. They were connected to the CR7 datalogger and monitored from July 21 1989. The anemometers were initially placed at a height of 0.5 m, but were periodically raised to correspond with the maximum canopy height.

Plate 4: Root profile studies in the dispersed treatment (December 1990)





Plate 5: Line treatment (August 1990)



Plate 6: Dispersed treatment (August 1990)



Chapter 3: GROWTH AND DEVELOPMENT

3.1 INTRODUCTION

The purpose of this chapter is to present the growth results, developmental observations and yield data, and to highlight the major treatment effects. This information will provide a basis for understanding the processes responsible for differences in overall productivity between treatments. The relationships between these biological observations, and the partitioning of physical resources and microclimate are examined in Chapter 4.

Detailed information was collected concerning canopy development, biomass accumulation and dry matter partitioning for the groundnut component of the line, dispersed and sole treatments. As described in Chapter 2 (Section 2.2), the positions for groundnut growth analysis samples were chosen to compare the effect of proximity to pigeonpea within a given treatment on growth and productivity, as well as overall treatment effects. In presenting the results for groundnut, leaf area index (L) is considered first, followed by the accumulation of total dry matter (TDM) and the partitioning of biomass to the pods. The data are expressed per unit ground area so that the treatments can be compared, even though the number of plants per sample may have varied. For each variable, the mean values for all treatments are compared initially, before considering the results for different sampling positions within the line and dispersed treatments.

Unfortunately, due to the relatively small plot size and the need to leave undisturbed areas for instrumentation and harvest, it was not possible to take regular destructive samples of pigeonpea. Although additional growth analysis would have been preferable, as the pigeonpea was the dominant component in the intercrop (cf. Chapter 1), the study of the effects of the pigeonpea on groundnut was of prime

importance. A series of non-destructive measurements complemented the limited growth analysis data for the pigeonpea and provided valuable information for examining productivity in relation to resource use.

Comparison of the growth and development of the sole groundnut crops in 1989 and 1990 indicated the extent to which the differences in the growth analysis results for the line and dispersed plantings between these two years might have been attributable to meteorological variables, rather than increasing competition from the pigeonpea component. Data from the ICRISAT weather station for mean daily shortwave radiation, rainfall, open pan evaporation and air temperature for the period between groundnut sowing and final harvest for 1989 and 1990 are shown in Figures 3.1 and 3.2 respectively. Rainfall, which is generally the most important factor influencing crop productivity in the semi-arid tropics, amounted to 823 mm in 1989 and 531 mm in 1990 between sowing and harvest of groundnut. However, the correlation between seasonal total rainfall and groundnut yields at ICRISAT is poor (Ong, 1986), since yield can be affected substantially by the distribution of rainfall (ODA, 1987; Stirling, 1988); this is discussed further in Chapter 4. The severity of disease damage is related to temperature and rainfall and may also vary from year to year, causing substantial effects on yield. Figure 3.3 shows meteorological data for the period extending from 50 days prior to groundnut planting in 1989 until groundnut planting in 1990 to indicate the extent of the annual climatic variation, and in particular the conditions experienced before the groundnut was planted in each year. Meteorological data for the period between groundnut sowing in 1990 and final harvest of the pigeonpea in 1991 are shown in Figure 3.4.

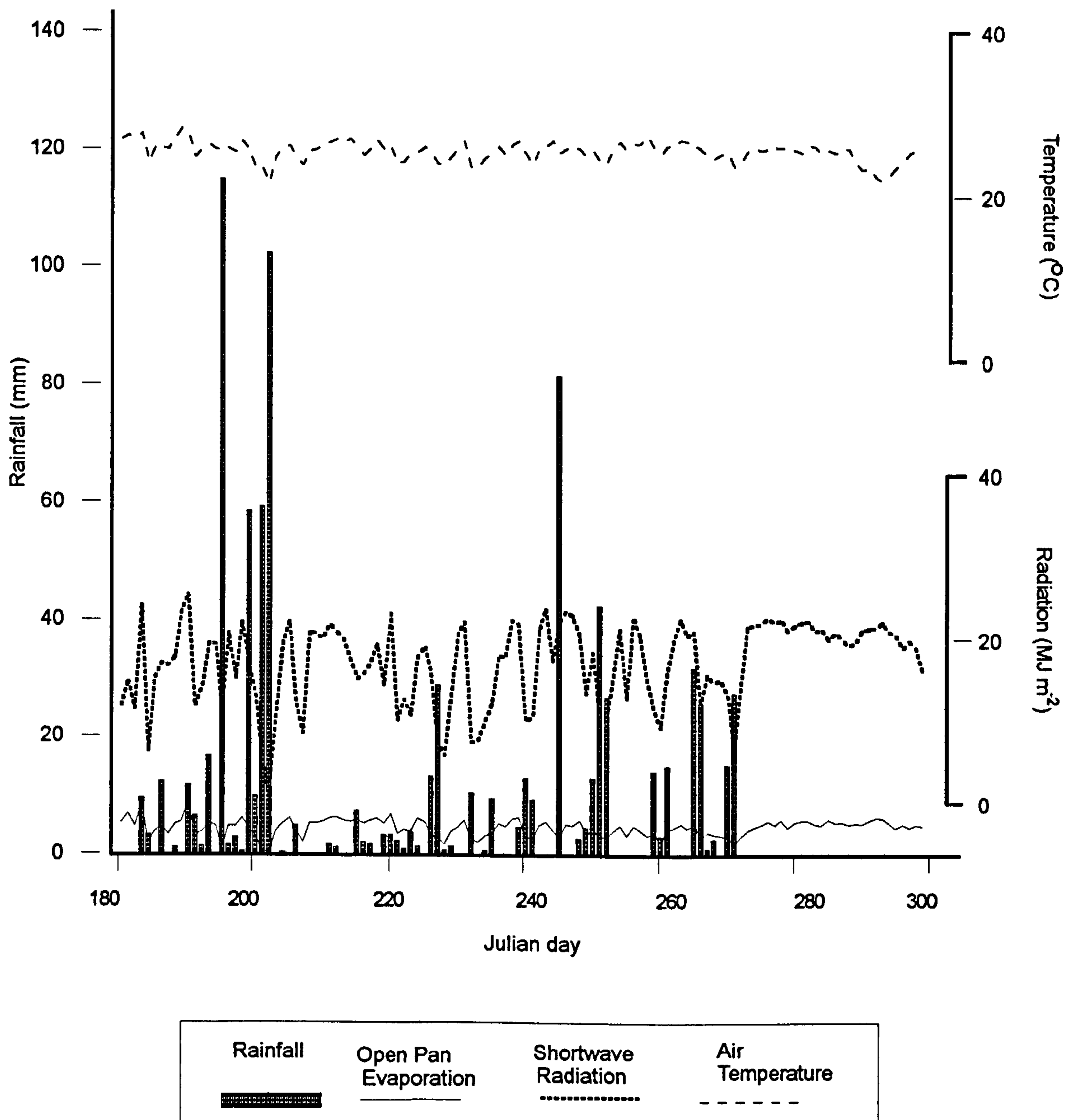


Figure 3.1: Daily mean values for climatic variables between groundnut sowing and harvest, 1989 (shortwave radiation includes 0.3-3.0 μm).

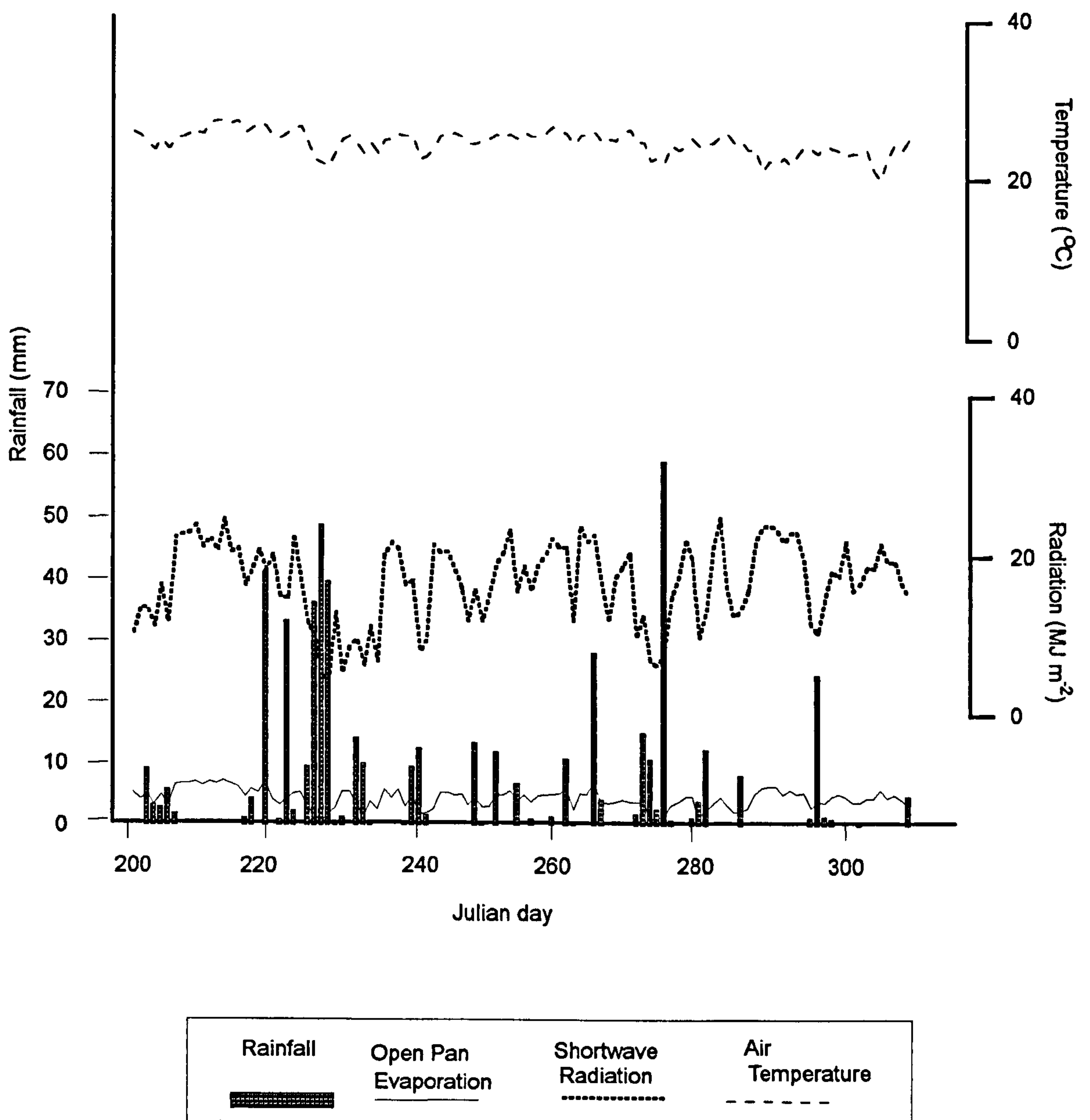


Figure 3.2: Daily mean values for climatic variables between groundnut sowing and harvest, 1990 (shortwave radiation includes 0.3-3.0 μm).

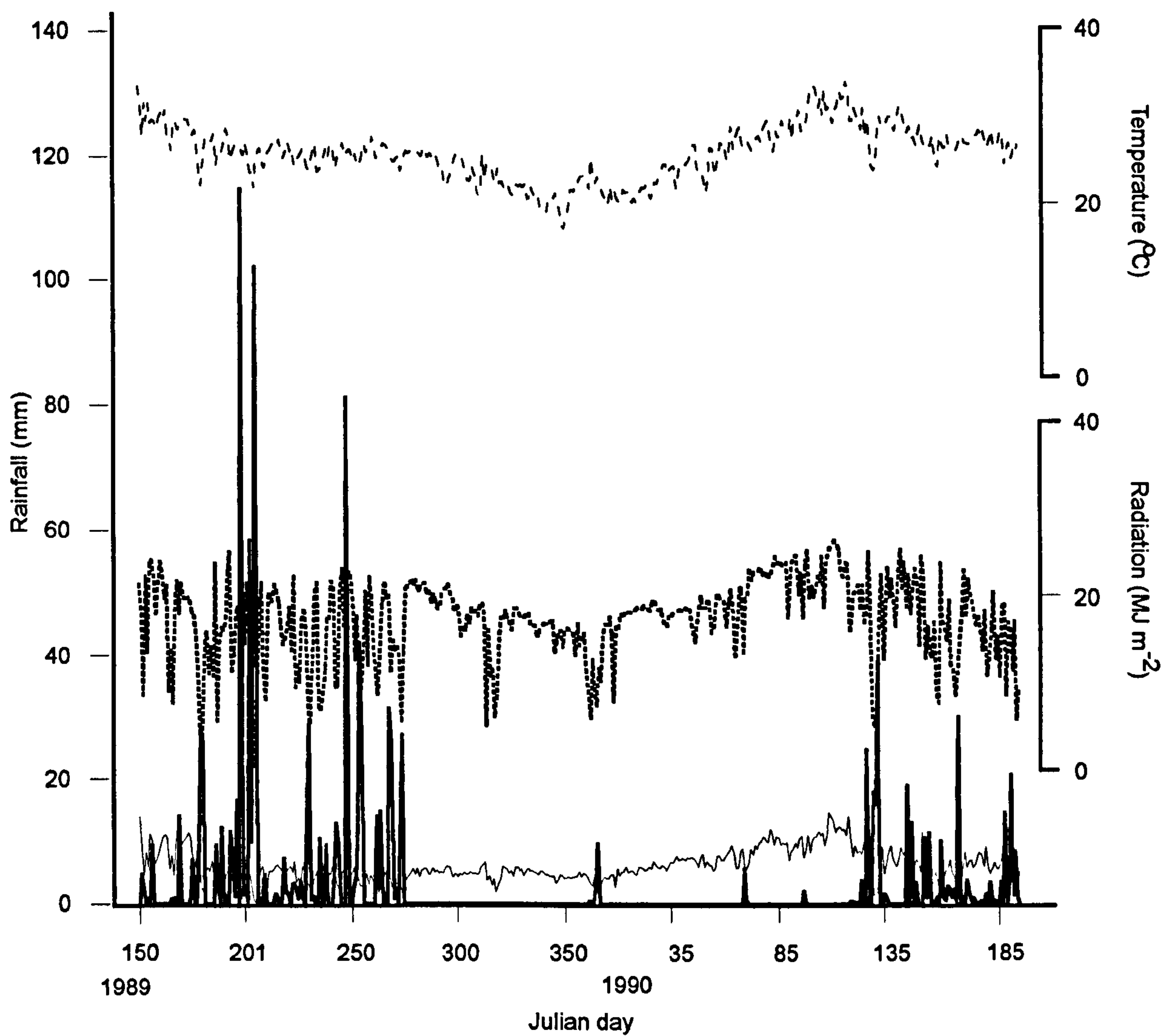


Figure 3.3: Daily mean values for climatic variables between May 30 1989 and July 18 1990 (solar radiation includes 0.3-3.0 μm).

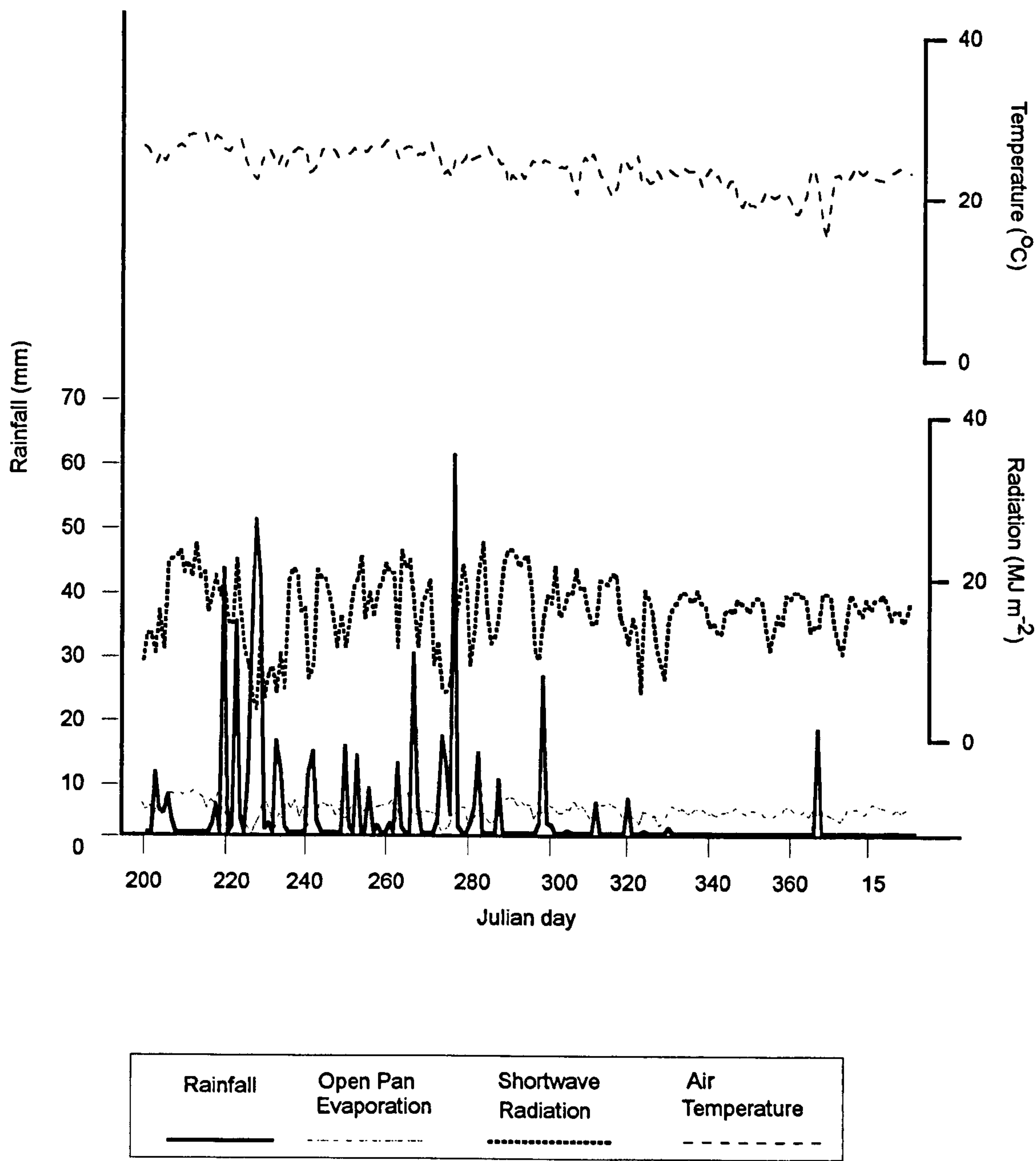


Figure 3.4: Daily mean values for climatic variables between July 19 1990 and January 25 1991 (solar radiation includes 0.3-3.0 μm).

3.2. GROUNDNUT GROWTH AND DEVELOPMENT - 1989

3.2.1 Leaf area index (L)

The timecourses for leaf area index in groundnut in 1989 are shown in Figure 3.5a for the sole, line and dispersed treatments. L increased from an initial value of approximately 0.6 at 30 DAS to maximum values at 70 DAS of 2.7, 2.5 and 2.6 for the sole, line and dispersed treatments respectively. During this period there were no significant differences between treatments (Table 3.1), and no consistent systematic differences. Between 70 and 80 DAS there was a slight decline in L in all treatments, followed by a rapid decrease between 80 - 100 DAS in the sole and dispersed treatments to final values at 100 DAS of 0.6 and 0.3 respectively. In the line planting, the period of rapidly decreasing L did not begin until 90 DAS but the rate of decline was more rapid than in the other two treatments, resulting in similar values for all treatments at 100 DAS (0.4 in the line treatment). At 90 DAS the L value for groundnut in the line planting was 2.0, significantly higher than in the sole ($p < 0.01$) and dispersed ($p < 0.001$) treatments.

Figures 3.5b and 3.5c show the seasonal timecourses of L for the various sampling positions within the line and dispersed treatments (cf. Fig. 2.2). The F values and effective standard error for comparing mean values for groundnut at each position are given in Table 3.2. The timecourses of L at each location followed a similar trend to the treatment means and there was little change in L according to proximity to the pigeonpea.

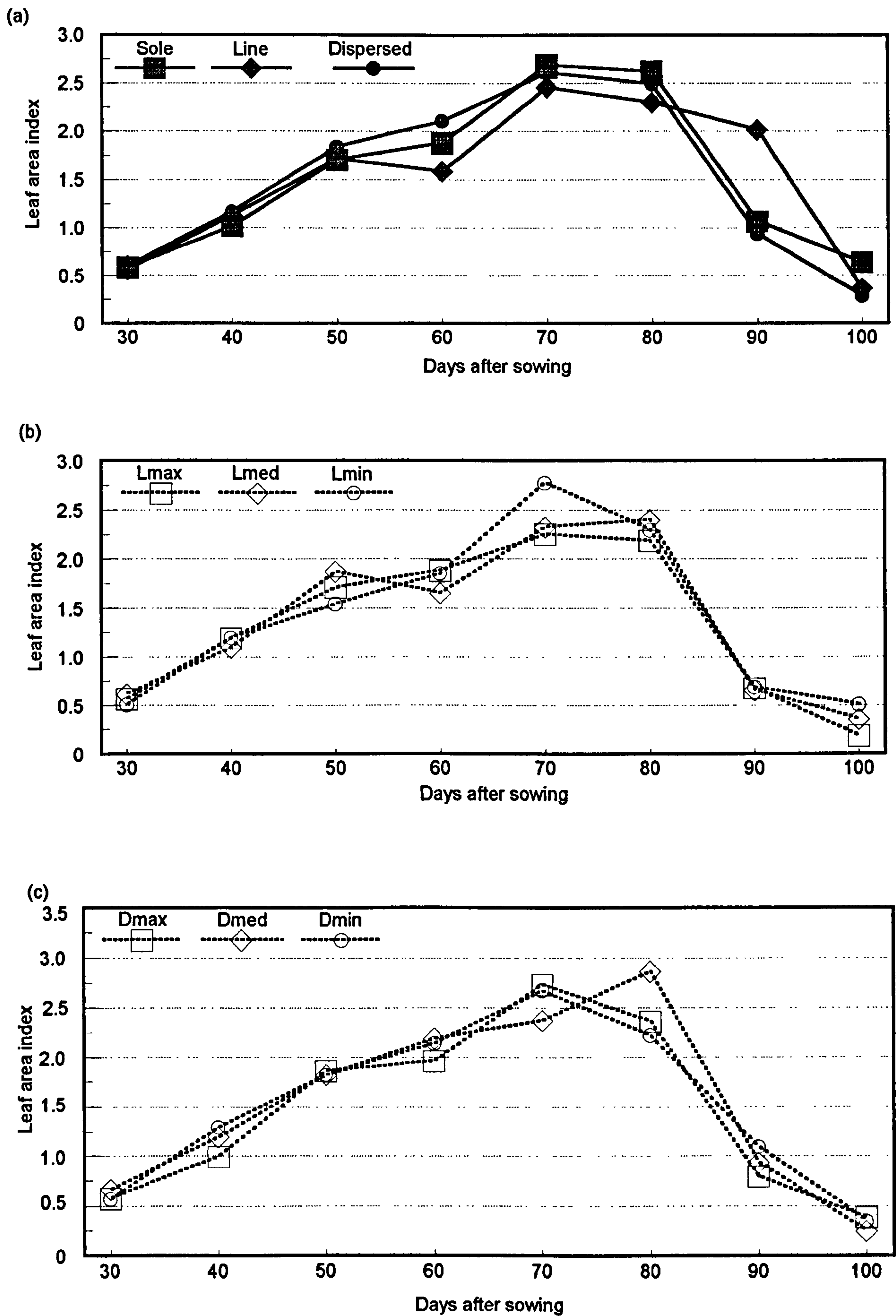


Figure 3.5: Leaf area index in groundnut, 1989: (a) treatment means, (b) sampling positions within the line treatment and (c) sampling positions within the dispersed treatment.

Table 3.1: Standard errors of differences (SED) for comparing treatment mean values of leaf area index (L) in groundnut, 1989. The value of t for which 5 % of the population lies outside the t distribution is 2.45 (6 d.f.)

	DAYS AFTER SOWING							
	30	40	50	60	70	80	90	100
SED	0.22	0.16	0.16	0.70	0.24	0.34	0.27	0.16

Table 3.2: Standard errors of differences (SED) for comparing treatment mean values of leaf area index (L) at various sampling positions in the line and dispersed treatments of groundnut, 1989. The value of t for which 5 % of the lies outside the range of the t distribution is 2.10 (18 d.f.)

	DAYS AFTER SOWING							
	30	40	50	60	70	80	90	100
SED	0.08	0.13	0.16	0.21	0.26	0.25	0.11	0.10

3.2.2 Total dry matter (TDM)

Figure 3.6a shows the seasonal mean timecourses for groundnut TDM in each treatment. All treatments exhibited a sigmoidal growth pattern, reaching maximum values at 80 DAS of 416.4, 364.9 and 433.3 g m² for the sole, line and dispersed treatments respectively. Although the maximum TDM for groundnut in the line planting was over 50 g m² less than in the other treatments, this difference was not significant (Table 3.3), due to a large variation between replicate samples on this date.

The maximum TDM was recorded at 80 DAS, ten days after L reached its maximum; TDM then declined rapidly between 80 and 100 DAS during the period of rapid leaf senescence and fall. TDM declined at a similar rate in all treatments between 80 and 90 DAS when values of 341.8, 353.6 and 274.6 g m² were recorded for the sole and dispersed and line treatments respectively. Between 90 and 100 DAS there was slight decline in TDM in the sole and line treatments to final values of 325.4 and 263.8 g m² respectively and much greater decline in the dispersed treatment to a final value of 247.9 g m². At 100 DAS the TDM of the sole groundnut was significantly greater ($p < 0.05$) than in the dispersed treatment.

Figures 3.6b and 3.6c show the timecourses for groundnut TDM at the various sampling locations in the line and dispersed treatments. In the line treatment, the positional samples followed similar timecourses to the treatment mean, although maximum TDM values were recorded for Lmin at 70 DAS (401.2 g m²), ten days earlier than Lmax and Lmed (326.3 and 384.2 g m² at 80 DAS). There was no significant difference in TDM for any of the positions at any point during the season (Table 3.4). In the dispersed treatment, the positional mean values for TDM differed little from the treatment means between 30 and 90 DAS and reached maximum values at 80 DAS of 421.4, 468.0 and 411.3 g m² at positions Dmax, Dmed and Dmin respectively. TDM values at positions Dmax and Dmed declined between 80 and 100 DAS to final values of 207.7 and 239.0 g m² respectively. However, there was only a slight decline in TDM at Dmin where the value recorded at 100 DAS

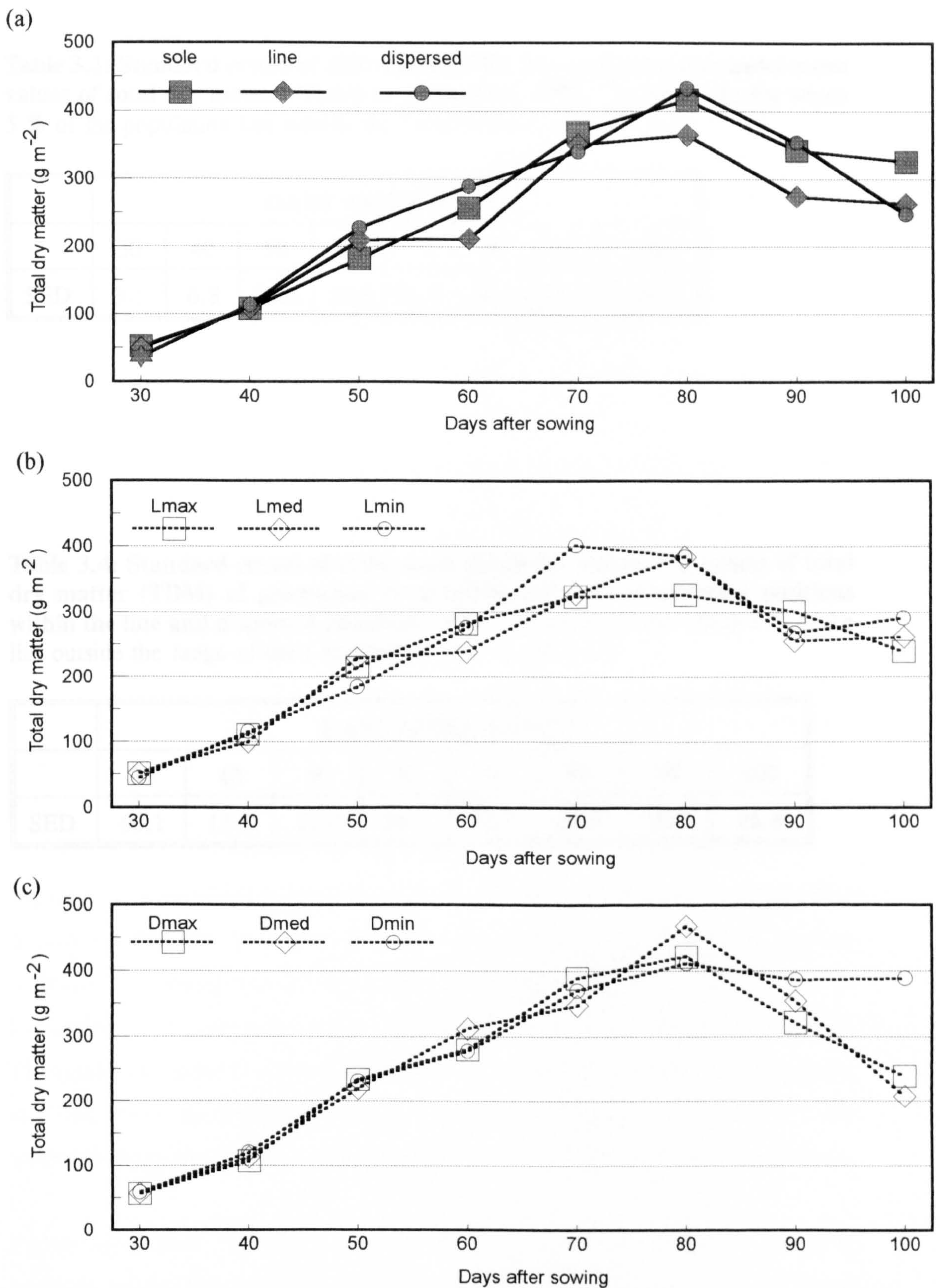


Figure 3.6: Total dry matter in groundnut, 1989: (a) treatment means; (b) sampling positions within the line treatment and (c) sampling positions within the dispersed treatment.

Table 3.3: Standard errors of differences (SED) for comparing treatment mean values of total dry matter (TDM) in groundnut, 1989. The value of t for which 5 % of the population lies outside the t distribution is 2.45 (6 d.f.)

	DAYS AFTER SOWING							
	30	40	50	60	70	80	90	100
SED	3.1	6.8	22.6	37.3	52.3	39.1	36.7	28.7

3.2.3 Pod dry weight

Pod dry weight was measured at 30, 40, 50, 60, 70, 80, 90 and 100 DAS. The mean values of pod dry weight for the line and dispersed plantings are given in Table 3.4. The values of SED for comparing treatment mean values of pod dry weight are given in Table 3.5.

Table 3.4: Standard errors of differences (SED) for comparing values of total dry matter (TDM) of groundnut recorded at the various sampling positions within the line and dispersed plantings, 1989. The value of t for which 5 % of the lies outside the range of the t distribution is 2.10 (18 d.f.)

	DAYS AFTER SOWING							
	30	40	50	60	70	80	90	100
SED	60.1	13.5	21.0	24.1	38.7	38.7	36.9	25.6

Figure 3.2 shows the mean values of pod dry weight at the various sampling positions within the line and dispersed plantings. There were no significant differences between positions, as between any two adjacent positions and the whole crop (Table 3.5). This is probably due to the plot size which had no significant effect on pod dry weight in 1989. The results presented in Figure 3.2 showed that there was no positional variation in TDM within the line plot, and it also appears that partitioning of the dry matter between the vegetative and reproductive organs was unaffected by position.

Figure 3.3 shows the mean values of pod dry weight at the various sampling positions within the dispersed planting. Groundnut in positions D1 and D2 exhibited significant patterns of pod dry weight similar to the mean values for the dispersed treatment. D1 and D2 reached maximum values of 91.1 and 92.8 g m⁻² at 90 DAS, before declining to 81.6 and 89.1 g m⁻² at 100 DAS.

(388.4 g m⁻²) was significantly greater than at positions Dmax ($p < 0.01$) and Dmed ($p < 0.001$). The final value for Dmin was also significantly greater than in the sole groundnut at 100 DAS ($p < 0.05$). However, as the mean value for the sole crop was significantly greater than at positions Dmax ($p < 0.05$) and Dmed ($P < 0.01$), there was no difference in the mean values for the sole and dispersed treatments at 100 DAS.

3.2.3 Pod dry weight

All three treatments showed an initial sigmoidal increase in mean pod dry weight (Fig. 3.7a). After an initial lag phase between 50 and 60 DAS, pod dry weight increased rapidly between 60 - 80 DAS; this was followed by a more gradual increase up to 90 DAS, when the dispersed planting reached its maximum value (100.3 g m⁻²), before declining to 82.2 g m⁻² at 100 DAS. In contrast, pod dry weights continued to increase up to 100 DAS in the sole and line treatments, when values of 102.8 and 83.1 g m⁻² respectively were recorded. Differences between the treatment means were not statistically significant on any of the sampling dates (Table 3.5).

Figure 3.7b shows that pod dry weights followed similar timecourses at all sampling positions within the line treatment; there were no significant differences between positions, or between any individual specific position and the sole crop (Table 3.6). Proximity to the pigeonpea also had no apparent effect on pod dry weight in 1989. The results presented in Section 3.2.2 showed that there was no positional variation in TDM within the line planting, and it also appears that partitioning of this dry matter between the vegetative and reproductive organs was unaffected by position.

Figure 3.7c shows the timecourses for pod dry weight at the various sampling positions within the dispersed planting. Groundnut at positions Dmax and Dmed exhibited sigmoidal patterns of pod dry weight similar to the mean values for the dispersed treatment. Dmax and Dmed reached maximum values of 95.1 and 92.8 g m⁻² respectively at 90 DAS, before declining to 63.6 and 59.1 g m⁻² at 100 DAS.

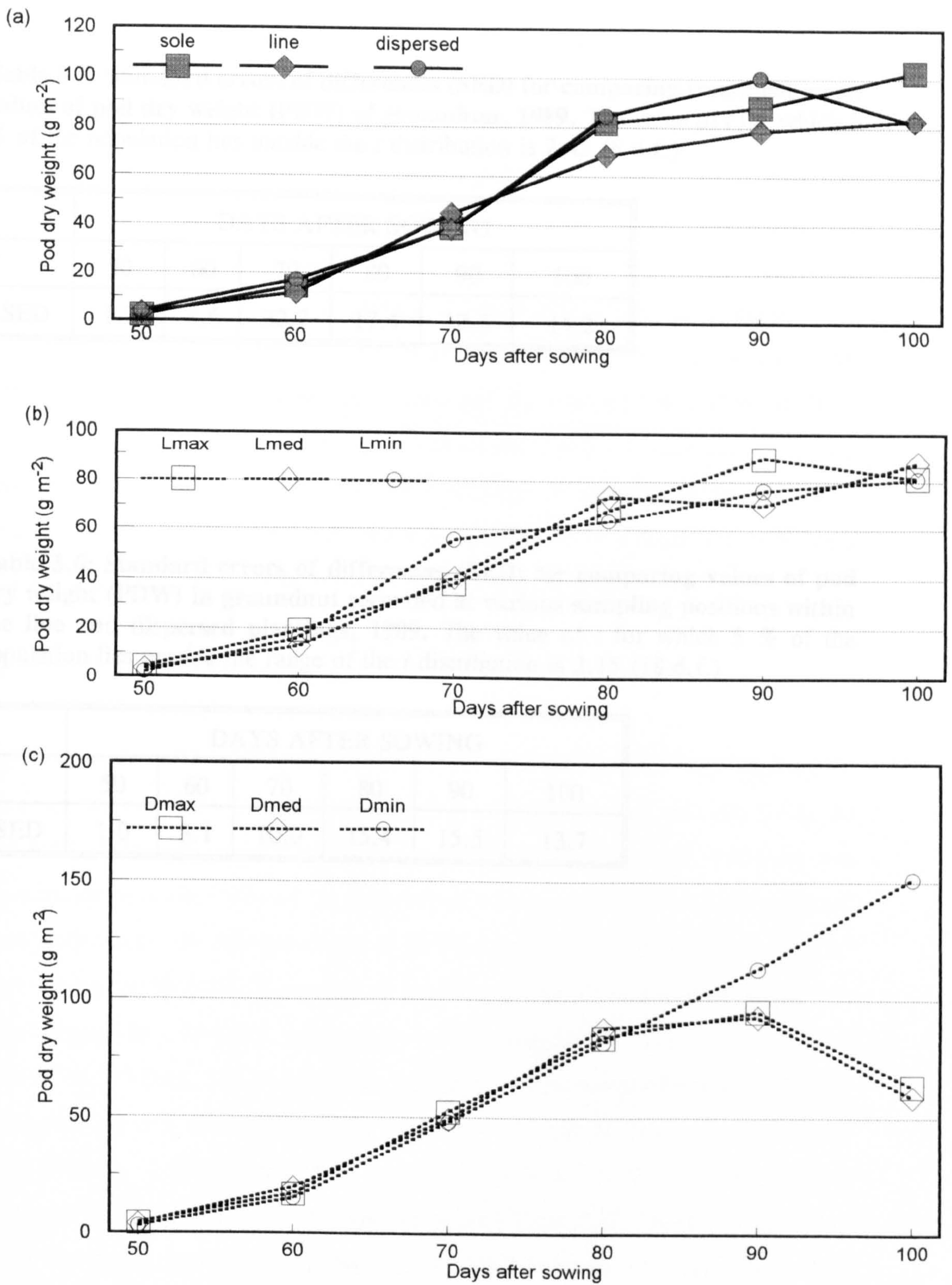


Figure 3.7: Pod dry weight in groundnut, 1989: (a) treatment means, (b) sampling positions in the line planting and (c) sampling positions in the dispersed planting.

Table 3.5: Standard errors of differences (SED) for comparing treatment mean values of pod dry weight (PDW) of groundnut, 1989. The value of t for which 5 % of the population lies outside the t distribution is 2.45 (6 d.f.)

	DAYS AFTER SOWING					
	50	60	70	80	90	100
SED	1.2	4.6	32.7	17.4	17.5	14.2

Table 3.6: Standard errors of differences (SED) for comparing values of pod dry weight (PDW) in groundnut recorded at various sampling positions within the line and dispersed plantings, 1989. The value of t for which 5 % of the population lies outside the range of the t distribution is 2.15 (18 d.f.)

	DAYS AFTER SOWING					
	50	60	70	80	90	100
SED	1.0	3.1	10.0	15.4	15.5	13.7

The rate of increase in pod dry weight at position Dmin was similar to that at Dmax and Dmed between 60 - 80 DAS, but then continued at this same rate until 100 DAS, to reach a final value of 151.1 g m⁻², significantly higher ($p < 0.001$) than at the other two sampling positions (Table 3.6). However, the mean values for the dispersed treatment were not significantly different from the other treatment means at 100 DAS because the values at Dmax and Dmed were lower than in the sole and line treatments; the magnitude of this difference was sufficient to offset the much higher value at Dmin. These results indicate that the relatively high TDM at Dmin at 100 DAS (Fig. 3.6c) was at least partly attributable to the greater quantity of dry matter present in the pods. This may have been due to a due to the initiation of a greater number of pods, the development of larger pods or a combination of these two factors; these possibilities are examined further in Section 3.2.4.

3.2.4 Pod number

Figure 3.8a shows the seasonal timecourses for total pod number in groundnut for each treatment between 50 DAS, when pods were first observed, and 100 DAS. At 100 DAS there were approximately 200 pods m⁻² in all treatments, but there was some variation in the shape of the timecourses between 30 - 100 DAS. 20 pods m⁻² were recorded for the sole groundnut at 30 DAS and a maximum of 223.0 pods m⁻² were present at 80 DAS. There was an apparent decline in pod number in the sole crop between 80 - 90 DAS, followed by a slight increase to a final value of 203.5 pods m⁻² at 100 DAS. The groundnut in the line treatment had produced considerably more pods per unit area than the sole treatment at 50 and 60 DAS, significantly so at 60 DAS ($p < 0.05$) when there were 113.0 pods m⁻² in the line treatment, as compared to 74.5 pods m⁻² in the sole treatment (Table 3.7). There was an almost linear increase in pod number in the line treatment between 50 - 70 DAS to reach 178.0 pods m⁻², followed by a more gradual increase between 80 - 100 DAS to a final value of 200.5 pods m⁻². The values for the dispersed treatment were similar to the line treatment for all harvests except 90 DAS, when the dispersed treatment

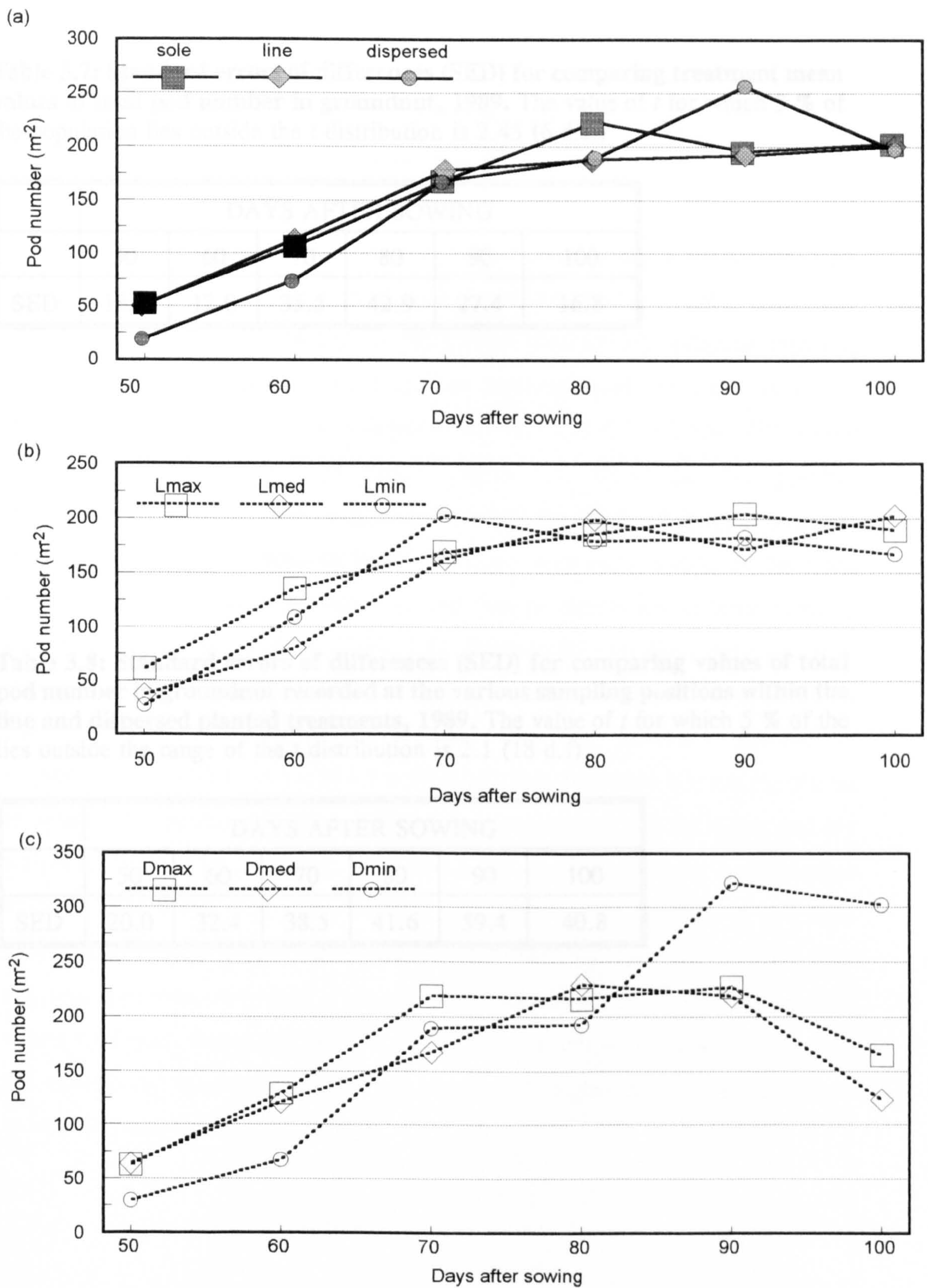


Figure 3.8: Number of groundnut pods, 1989: (a) treatment means, (b) sampling positions within the line treatment and (c) sampling positions within the dispersed treatment.

Table 3.7: Standard errors of differences (SED) for comparing treatment mean values of total pod number in groundnut, 1989. The value of t for which 5 % of the population lies outside the t distribution is 2.45 (6 d.f.)

	DAYS AFTER SOWING					
	50	60	70	80	90	100
SED	18.4	12.0	35.5	42.9	27.4	16.8

Table 3.8: Standard errors of differences (SED) for comparing values of total pod number in groundnut recorded at the various sampling positions within the line and dispersed planted treatments, 1989. The value of t for which 5 % of the lies outside the range of the t distribution is 2.1 (18 d.f)

	DAYS AFTER SOWING					
	50	60	70	80	90	100
SED	20.0	32.4	38.5	41.6	59.4	40.8

had many more pods (265.2 pods m⁻²) than the line and sole treatments (192.2 and 196.0 pods m⁻² respectively); although this difference was not significant, a similar trend was observed for pod dry weight (Fig. 3.7a).

Figure 3.8b shows total pod numbers for the various sampling positions within the line treatment. The values for all positions followed a similar timecourse to the mean values for the line treatment and the differences observed on particular sampling dates were not significant (Table 3.8). The maximum pod numbers recorded at positions Lmin, Lmed and Lmax respectively were 208.0 (70 DAS), 202.5 (100 DAS) and 204.5 pods m⁻² (90 DAS). Figure 3.8c shows the corresponding timecourses at the various sampling locations within the dispersed planting. Between 50 - 80 DAS, the pod numbers for all positions were again similar to the mean values for the dispersed treatment, and there was no significant variation between the various sampling positions (Table 3.8). Between 80 - 90 DAS there was little change in pod number at positions Dmax (216.6 at 80 DAS vs. 227.3 at 90 DAS) and Dmed (229.7 vs. 219.0). However, there was a large increase in pod number at Dmin (192.8 at 80 DAS vs. 322.5 at 90 DAS); this difference was not significant as compared to positions Dmax and Dmed, but does suggest that the higher pod dry weight recorded at 90 DAS (Fig. 3.7c) was partly due to an increase in the number of pods filled rather than being entirely attributable to an increase in pod size. Unfortunately, information concerning pod size was not collected in 1989. Pod numbers apparently decreased at all positions between 90-100 DAS, and the final values for Dmax, Dmed and Dmin at 100 DAS were 165.4, 123.8 and 302.3 pods m⁻² respectively; the value for Dmin was significantly higher than at positions Dmax ($p < 0.01$) and Dmed ($p < 0.001$).

3.3 GROUNDNUT GROWTH AND DEVELOPMENT - 1990

3.3.1 Leaf area index (L)

The sole and dispersed treatments showed similar patterns of leaf area development and decay (Fig. 3.9a) and reached maximum L values of 1.75 and 1.45 at 60 and 70 DAS respectively. The line treatment followed a similar pattern between 30 and 50 DAS but attained a maximum of 2.19 at 60 DAS, which was significantly greater than in the other treatments (Table 3.9; $p < 0.05$ and $p < 0.001$ for the sole and dispersed treatments respectively). Thereafter, L decreased rapidly from 60 DAS in the line and sole treatments and 70 DAS in the dispersed treatment as senescence and leaf fall occurred. These reductions in L preceded the corresponding reductions in TDM by 10 days in the line and sole plantings, and 20 days in the dispersed arrangement. In all treatments, L decreased by approximately 20% before any reduction in TDM was observed. By 100 DAS, L had fallen to 0.1 in the line and dispersed plantings and 0.3 in the sole crop. Severe attack by foliar disease organisms (rust - *Puccinia arachidis* and late leaf spot - *Phaeoisariopsis personata*) from approximately 60 DAS onwards may have contributed to the rapid decline in L in all treatments.

L was significantly higher in the sole groundnut than in the dispersed planting from 50 DAS onwards. This difference was greatest at 60 and 70 DAS when the L values for sole groundnut were 1.75 and 1.73 respectively, 27 and 19% greater than in the dispersed treatment ($p < 0.05$ and $p < 0.01$ for 60 and 70 DAS). L was significantly greater in line planted than in dispersed groundnut during the period of maximum L between 50 - 70 DAS, but not at other times. L was also significantly greater in the line treatment than in the sole groundnut at 60 DAS, but was significantly lower by 70 DAS due to rapid senescence. There was no significant difference in specific leaf area (g cm^{-2}) between treatments on any of the sampling dates (data not presented).

Figure 3.9b shows the timecourses of L at all sampling locations in the line

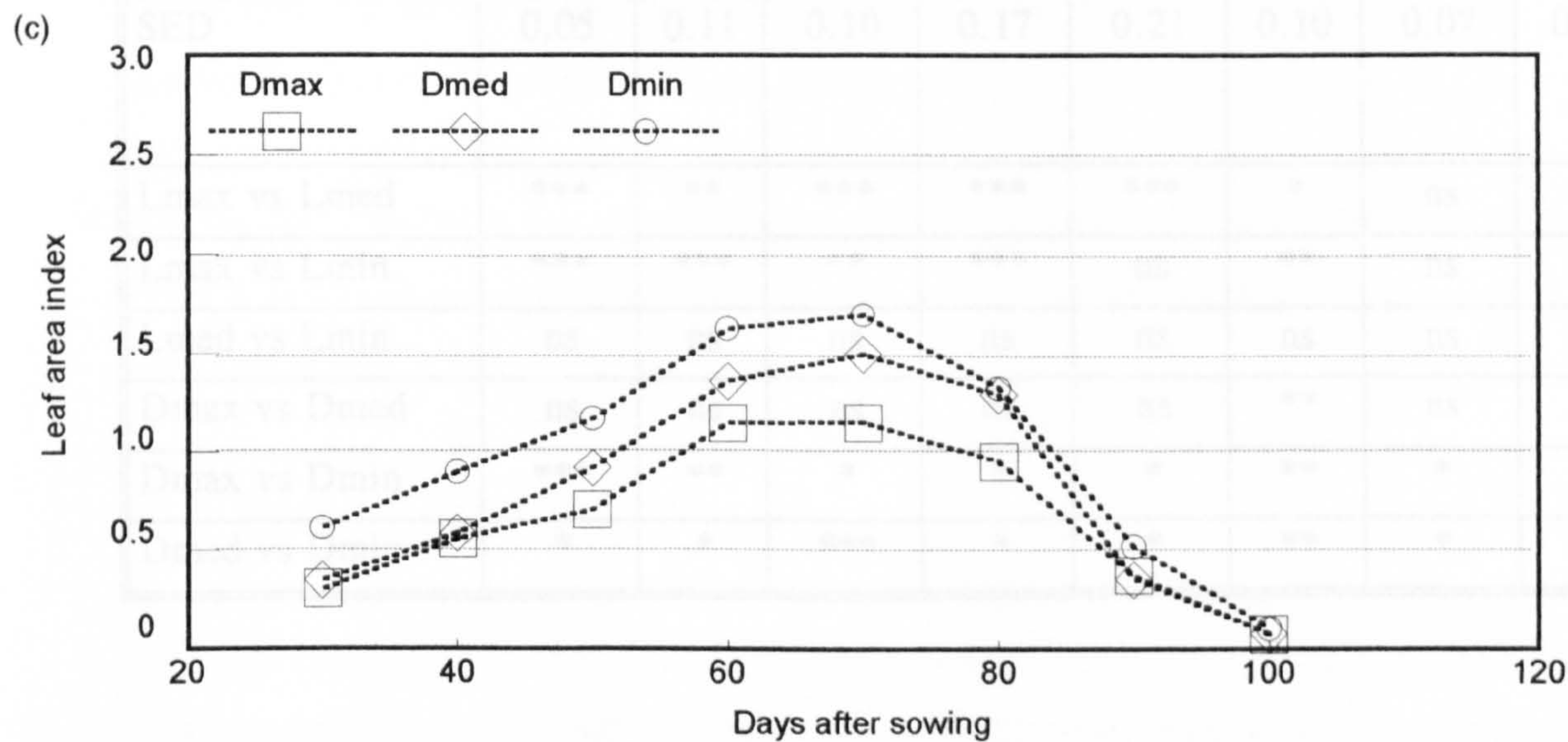
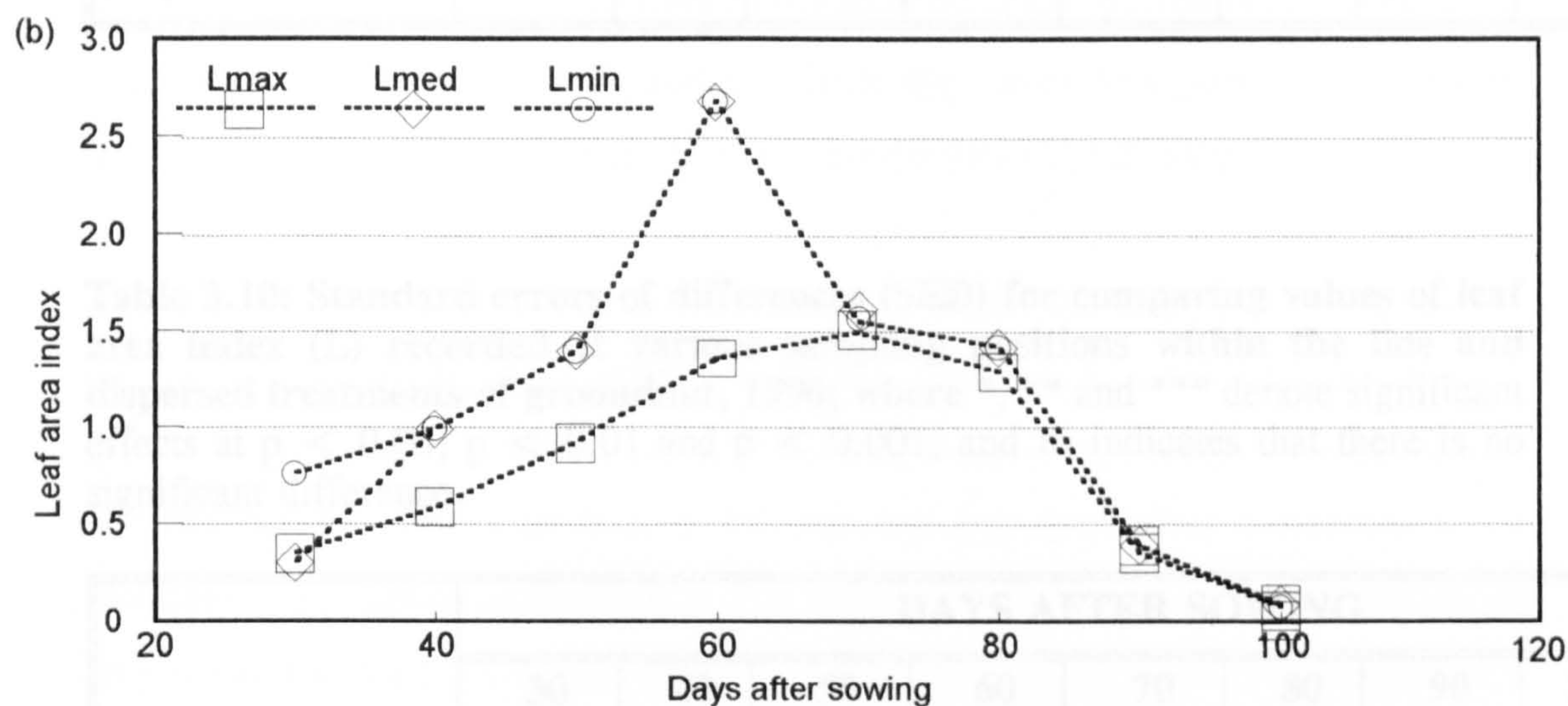
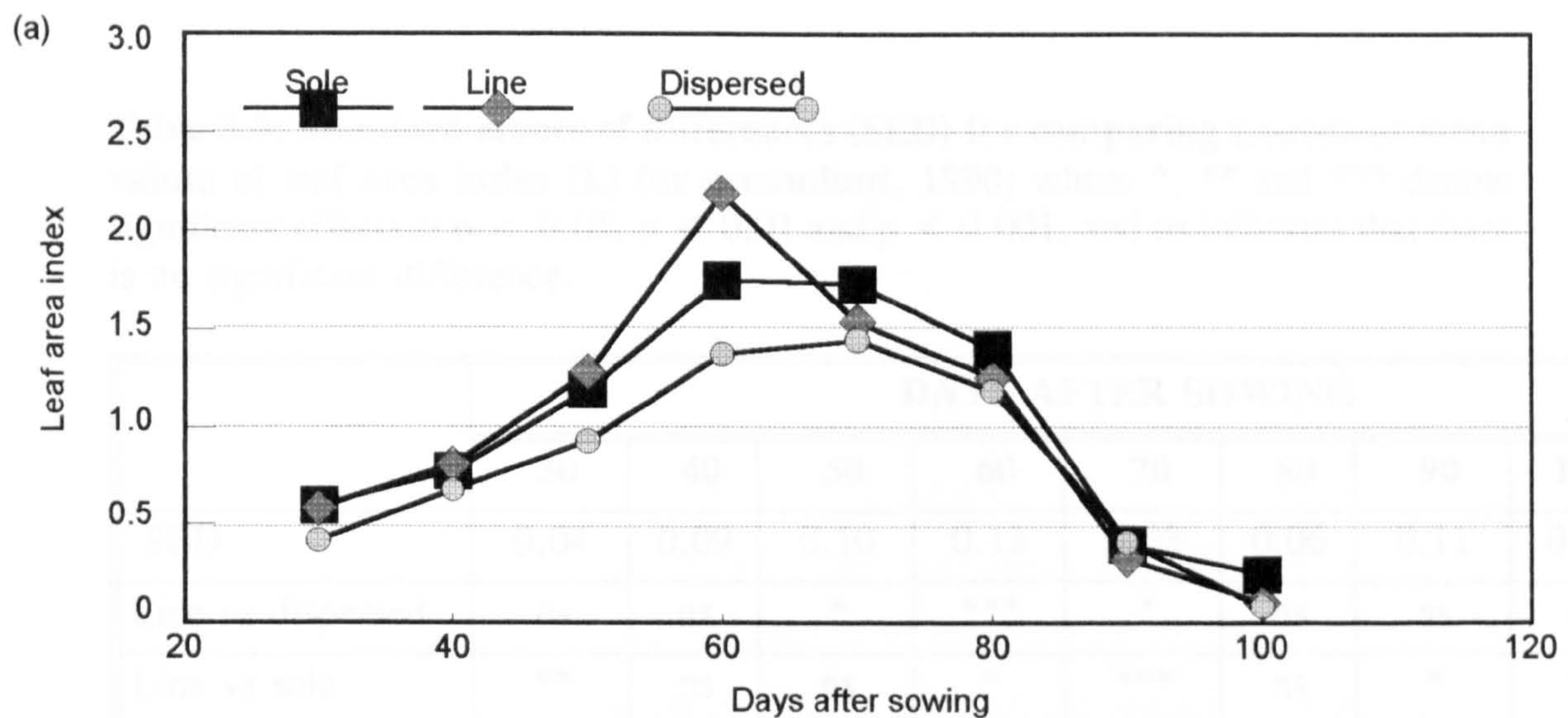


Figure 3.9: Leaf area index in groundnut, 1990: (a) treatment means, (b) sampling positions within the the line treatment and (c) sampling positions within the dispersed treatment.

Table 3.9: Standard errors of differences (SED) for comparing treatment mean values of leaf area index (L) for groundnut, 1990; where *, ** and * denote significant effects at $p < 0.05$, $p < 0.01$ and $p < 0.001$, and ns indicates that there is no significant difference.**

	DAYS AFTER SOWING							
	30	40	50	60	70	80	90	100
SED	0.04	0.09	0.10	0.13	0.03	0.06	0.11	0.03
Line vs dispersed	ns	ns	*	***	*	ns	ns	ns
Line vs sole	**	ns	ns	*	***	ns	*	**
Dispersed vs sole	ns	ns	*	*	***	*	*	**

Table 3.10: Standard errors of differences (SED) for comparing values of leaf area index (L) recorded at various sampling positions within the line and dispersed treatments of groundnut, 1990; where *, ** and * denote significant effects at $p < 0.05$, $p < 0.01$ and $p < 0.001$, and ns indicates that there is no significant difference.**

	DAYS AFTER SOWING							
	30	40	50	60	70	80	90	100
SED	0.05	0.11	0.10	0.17	0.21	0.10	0.07	0.04
Lmax vs Lmed	***	**	***	***	***	*	ns	ns
Lmax vs Lmin	***	***	**	***	ns	**	ns	ns
Lmed vs Lmin	ns	ns	ns	ns	ns	ns	ns	ns
Dmax vs Dmed	ns	ns	ns	ns	ns	**	ns	ns
Dmax vs Dmin	***	**	*	*	*	**	*	ns
Dmed vs Dmin	*	*	***	*	*	**	*	ns

treatment. L reached a maximum at 60 DAS in all treatments, and this was followed by a steady decline until final harvest. Maximum values of 2.7, 2.5 and 1.4 were recorded for Lmin, Lmed and Lmax respectively. As Table 3.10 shows, there was no significant difference between Lmed and Lmin, which both exhibited a rapid increase in L between 30 and 60 DAS to values considerably higher than in the sole groundnut; this was followed by a rapid decline to 100 DAS. Although Lmax reached a maximum at 70 DAS, the peak was less pronounced than at the other two locations. The values for Lmin and Lmed were significantly greater than those for Lmax throughout the measurement period. At 30 DAS the value for Lmin was 0.8, or 130% greater than at Lmax. After the peak at 60 DAS, the positional differences progressively decreased until 90 and 100 DAS there were no significant differences between locations; by 100 DAS, L was approximately 0.1 at all positions.

Figure 3.9c shows the positional variation in L within the dispersed treatment. At all sampling locations, there was a gradual increase in L to maximum values at 70 DAS of 1.2, 1.5 and 1.7 for Dmax, Dmed and Dmin respectively. This maximum was reached ten days later than in the line and sole groundnut treatments at all locations. The initial increase in L was delayed in Dmed and Dmax relative to Dmin, causing significant differences to be apparent by 30 DAS. L increased at a similar rate at positions Dmin and Dmed to a maximum at 70 DAS. The difference between the values for positions Dmax, Dmed and Dmin increased between 40 - 80 DAS and decreased thereafter. L was consistently greater at Dmed than at Dmax between 30 - 90 DAS, but this difference was significant only at 80 DAS ($p < 0.05$). L at Dmed was significantly lower than at Dmin at all sampling dates except 100 DAS (Table 3.10).

3.3.2 Total dry matter (TDM)

Total dry matter production (TDM) in groundnut followed the typical sigmoidal growth pattern described by Ketring *et al.* (1982). The treatment means and corresponding analysis of variance (ANOVA) are shown in Figure 3.10a and Table 3.11. In all treatments, growth followed an exponential pattern from the first

measurement at 30 DAS to reach a maximum TDM at 80 DAS of 290 g m⁻² in the line planting and sole groundnut and 246 g m⁻² in the dispersed arrangement. The mean growth rate over this period was 3 g m⁻² d⁻¹ for the dispersed treatment and 5 g m⁻² d⁻¹ for the line and sole groundnut treatments. After 80 DAS there was a sharp decline in TDM in all treatments which coincided with leaf senescence and led to reductions of 30, 37 and 24 % in the values for the line, dispersed and sole groundnut treatments by the final growth analysis at 100 DAS. TDM was consistently lower in the dispersed treatment than in the line and sole treatments of groundnut, significantly at all sampling dates except 60 and 90 DAS. TDM was 16.2 g m⁻² greater in the sole groundnut than in the dispersed treatment at 30 DAS, 44.6 g m⁻² greater at 80 DAS and 68.4 g m⁻² greater at 100 DAS, corresponding to differences of approximately 40, 20 and 40 % respectively. Over most of the measurement period, there was no significant difference between the line planted and sole groundnut treatments, although TDM was significantly greater in the former treatment at 50 ($p < 0.01$) and 60 DAS ($p < 0.05$), but significantly lower at 100 DAS ($p < 0.05$).

Figure 3.10b shows the positional variation in TDM within the line planting. Lmax produced significantly less dry matter, reaching a maximum of only 201 g m⁻² at 80 DAS, as compared with 340 g m⁻² at Lmin on the same date. The mean growth rates between 30 and 80 DAS were 3.5, 5.4 and 5.5 g m⁻² d⁻¹ for Lmax, Lmed and Lmin, respectively. The difference in TDM between Lmax and Lmed and Lmin increased to a maximum at 80 DAS, before declining slightly because of the more rapid decrease in the latter two treatments. There was no significant difference between Lmed and Lmin at any of the harvest dates, although it is interesting to note that Lmin reached its maximum TDM at 70 DAS, ten days earlier than Lmed or Lmax. Lmed and Lmin both produced more TDM than the sole treatment, but the substantial reduction in growth at position Lmax was sufficient to preclude any significant difference in the overall mean values for the line and sole treatments.

In the dispersed treatment, TDM reached a maximum at 80 DAS at all sampling positions (Fig. 3.10c), with values of 192, 248 and 299 g m⁻² being attained at

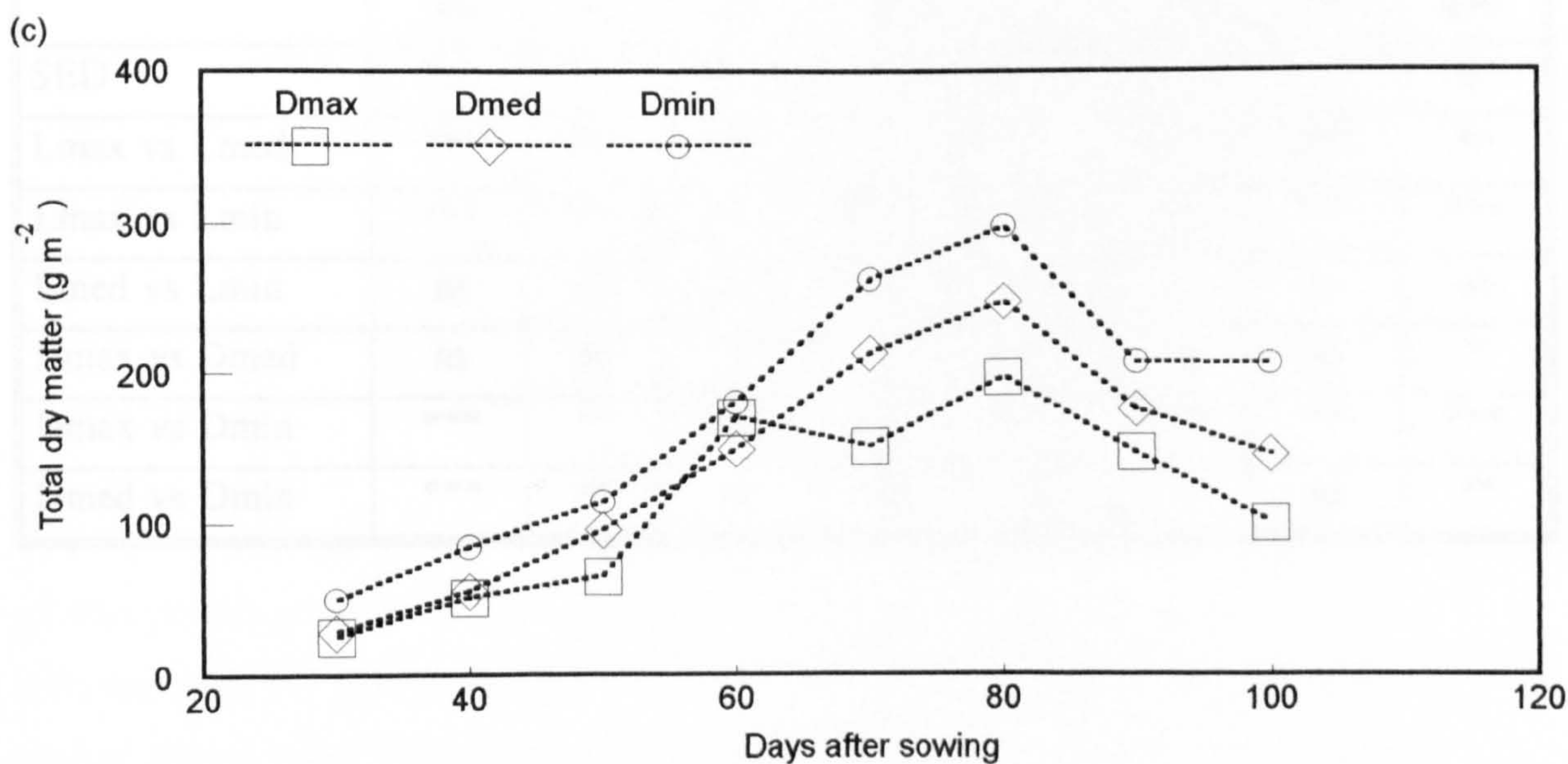
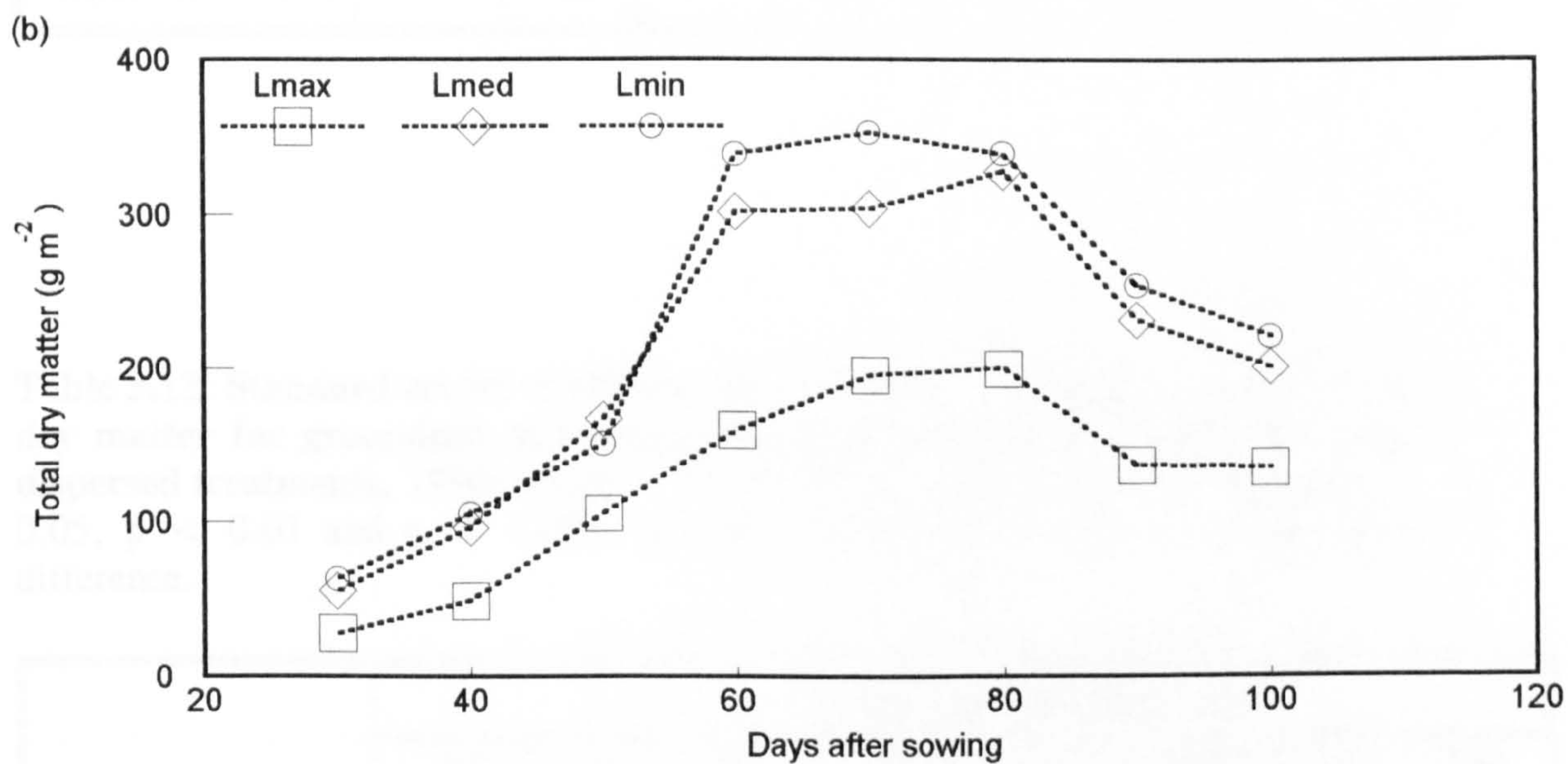
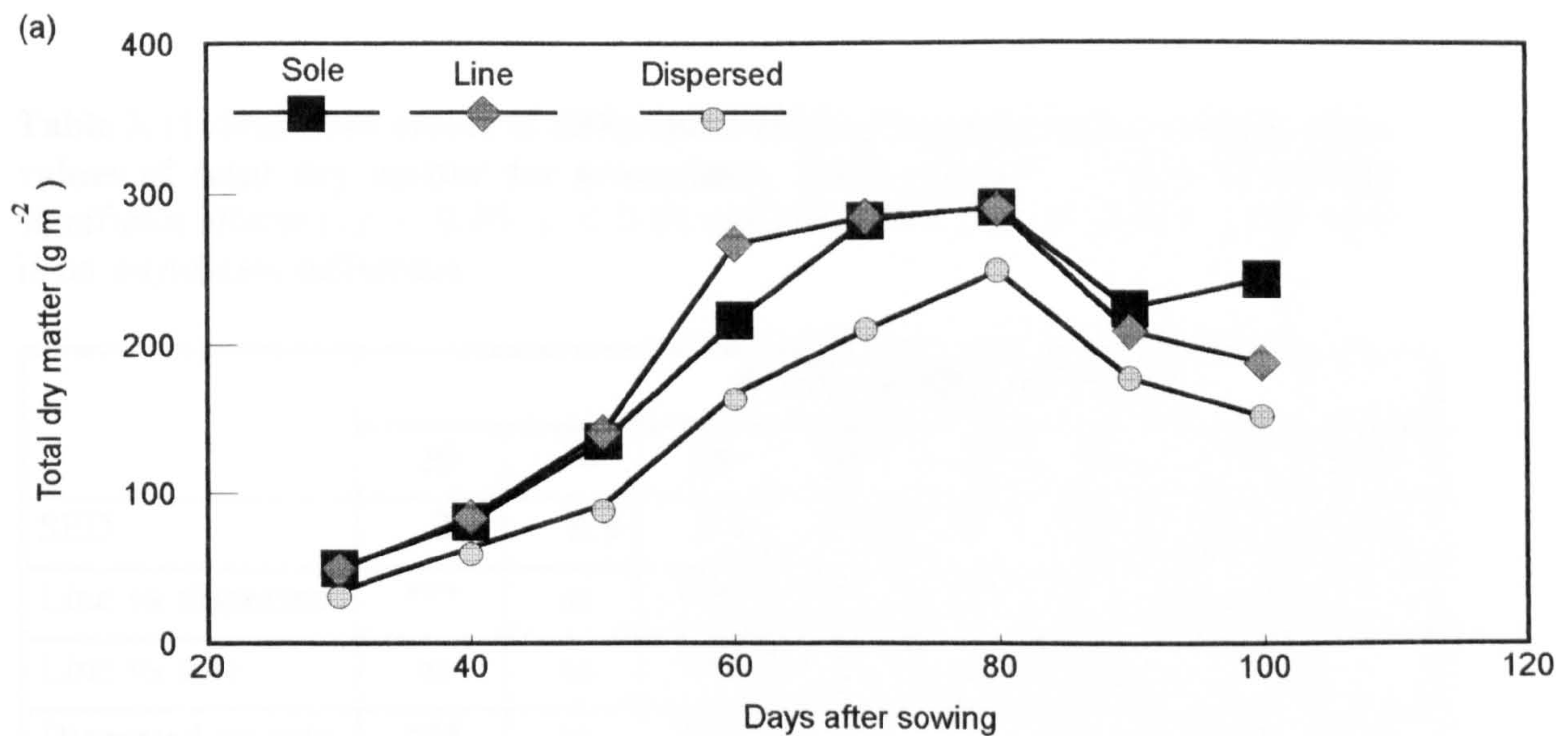


Figure 3.10: Total dry matter in groundnut, 1990: (a) treatment means, (b) sampling positions within the line planting and (c) sampling positions within the dispersed planting.

Table 3.11: Standard errors of differences (SED) for comparing treatment mean values of total dry matter for groundnut, 1990; where *, ** and *** denote significant effects at $p < 0.05$, $p < 0.01$ and $p < 0.001$, and ns indicates that there is no significant difference.

	DAYS AFTER SOWING							
	30	40	50	60	70	80	90	100
SED	2.5	8.9	3.4	19.8	16.2	10.4	17.1	11.2
Line vs dispersed	***	ns	***	**	**	**	ns	*
Line vs sole	ns	ns	***	*	ns	ns	ns	*
Dispersed vs sole.	***	ns	***	ns	**	**	ns	***

Table 3.12: Standard errors of differences (SED) for comparing values of total dry matter for groundnut at various sampling positions within the line and dispersed treatments, 1990; where *, ** and *** denote significant effects at $p < 0.05$, $p < 0.01$ and $p < 0.001$, and ns indicates that there is no significant difference.

	DAYS AFTER SOWING							
	30	40	50	60	70	80	90	100
SED	3.6	8.4	11.0	34.0	24.0	18.5	18.3	16.1
Lmax vs Lmed	***	***	***	**	***	***	***	**
Lmax vs Lmin	***	***	**	***	***	***	***	***
Lmed vs Lmin	ns	ns	ns	ns	ns	ns	ns	ns
Dmax vs Dmed	ns	ns	*	ns	*	*	ns	*
Dmax vs Dmin	***	**	***	ns	***	***	**	***
Dmed vs Dmin	***	**	ns	ns	ns	*	ns	**

positions Dmax, Dmed and Dmin respectively. The corresponding mean growth rates between 30 - 80 DAS were 3.3, 4.4 and 5.0 g m⁻² d⁻¹. Dmin produced significantly more dry matter than Dmax at all sampling dates except 60 DAS. As in the line planted treatment, the difference in TDM between Dmin and Dmax was greatest between 70-80 DAS. TDM production at Dmed was intermediate between Dmin and Dmax at all dates except 60 DAS (Fig. 3.10c); the values for TDM at Dmed were significantly lower than at Dmin at 30, 40, 80 and 100 DAS (Table 3.12). The values for Dmed were consistently higher than at Dmax (significantly, $p < 0.05$ at 50, 70, 80 and 100 DAS).

Dry matter production was lower at the Dmax and Dmin sampling positions than in the sole groundnut, indicating that competition was sufficient to reduce TDM relative to the control, TDM production at Dmax and Dmed was also significantly lower than at positions Lmed and Lmin in the line planting. However, the TDM values for the sites of greatest expected competition in each treatment, namely Lmax and Dmax, were similar throughout the season.

3.3.3 Pod dry weight

Pods were first observed at 60 DAS in all treatments, indicating that pod development began between 51 and 60 DAS. This was followed by an almost linear increase in pod dry weight between 60 and 80 DAS (Fig. 3.11a), during which the mean growth rates were 3.2, 3.6 and 3.1 g m⁻² d⁻¹ for the sole, line and dispersed treatments respectively. There was little further change in the values for the line planted and dispersed treatments between 80-100 DAS, whereas pod dry weight increased by 20 % in the sole groundnut.

Pod dry weight was consistently lower in the dispersed treatment than in the line planted or sole groundnut (Fig. 3.11a). Pod initiation was also apparently delayed, with the result that pod dry weight remained lower than the other treatments despite similar growth rates. The values for sole groundnut were significantly greater than

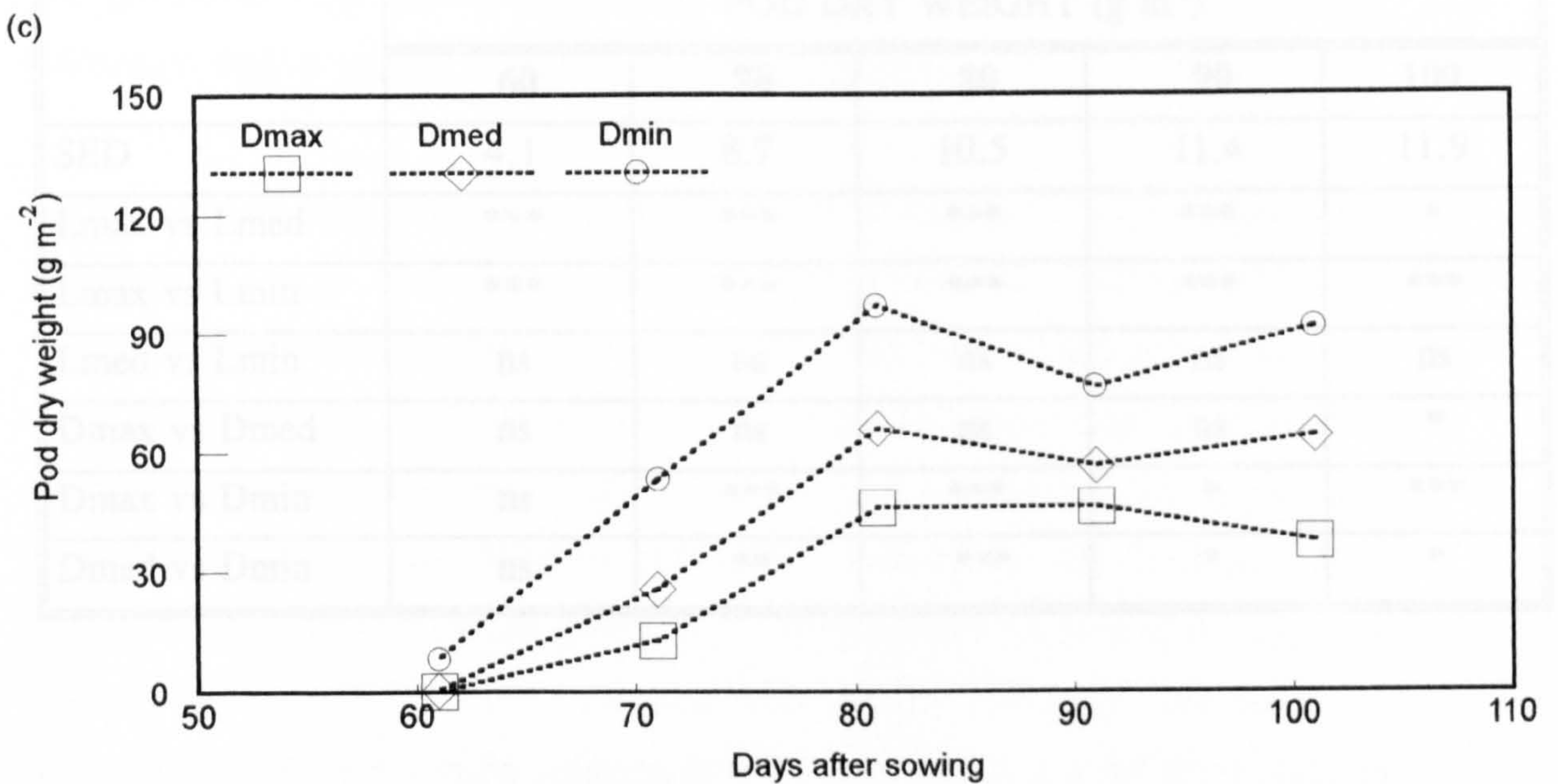
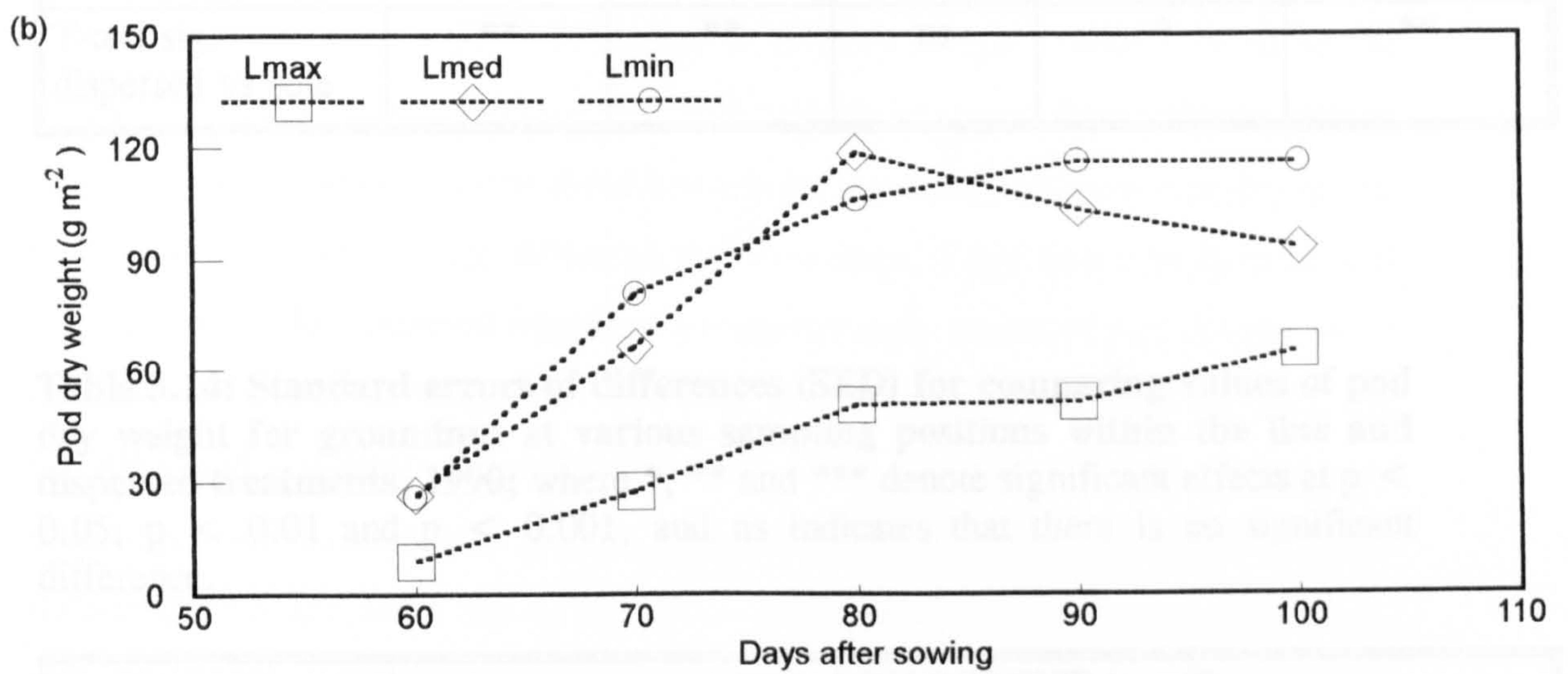
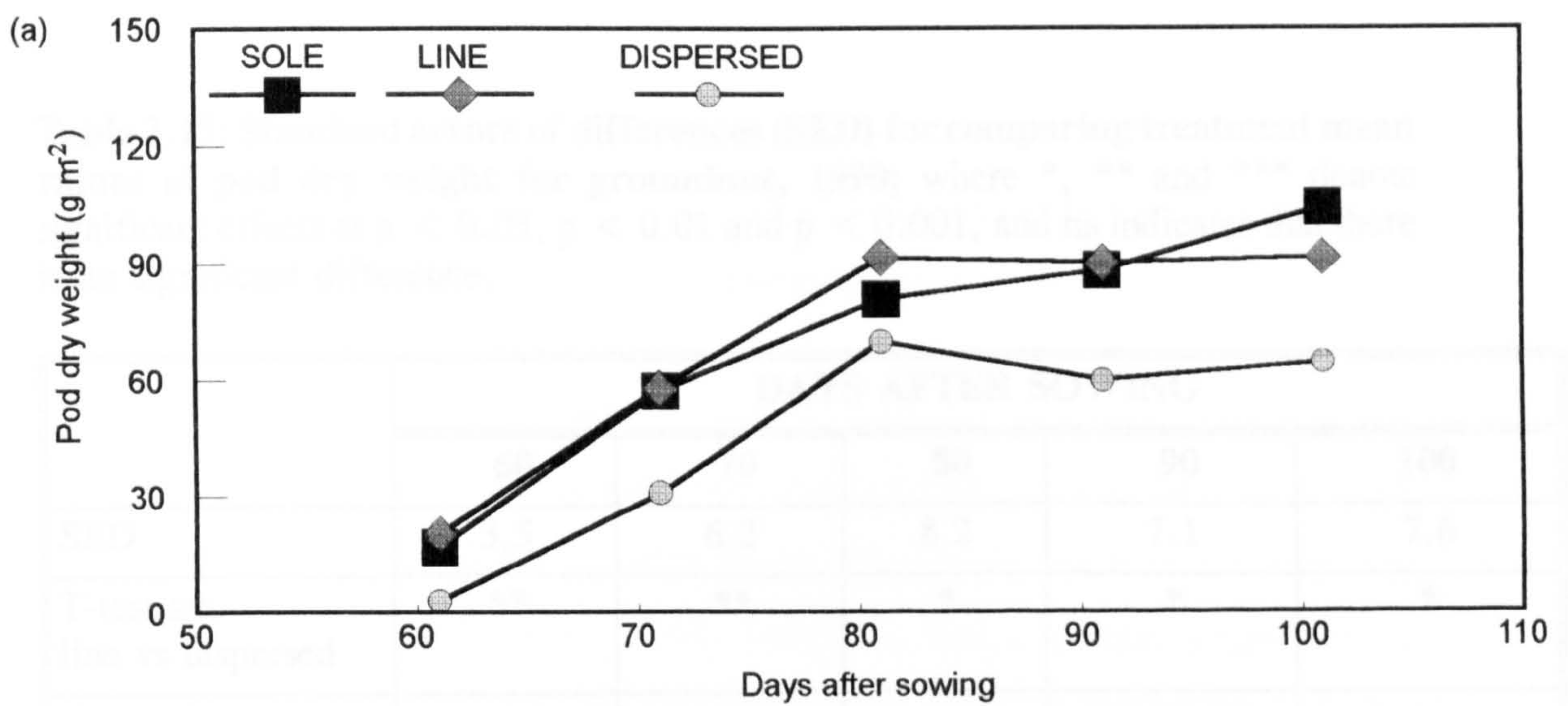


Figure 3.11: Pod dry weight in groundnut, 1990: (a) treatment means, (b) sampling positions in the line treatment and (c) sampling positions in the dispersed treatment.

Table 3.13: Standard errors of differences (SED) for comparing treatment mean values of pod dry weight for groundnut, 1990; where *, ** and * denote significant effects at $p < 0.05$, $p < 0.01$ and $p < 0.001$, and ns indicates that there is no significant difference.**

	DAYS AFTER SOWING				
	60	70	80	90	100
SED	3.5	6.2	8.2	7.1	7.6
T-test sig. line vs dispersed	**	**	*	*	*
T-test sig. line vs sole	ns	ns	ns	ns	ns
T-test sig. dispersed vs sole	**	**	ns	*	**

Table 3.14: Standard errors of differences (SED) for comparing values of pod dry weight for groundnut at various sampling positions within the line and dispersed treatments, 1990; where *, ** and * denote significant effects at $p < 0.05$, $p < 0.01$ and $p < 0.001$, and ns indicates that there is no significant difference.**

	POD DRY WEIGHT (g m ⁻²)				
	60	70	80	90	100
SED	4.1	8.7	10.5	11.4	11.9
Lmax vs Lmed	***	***	***	***	*
Lmax vs Lmin	***	***	***	***	***
Lmed vs Lmin	ns	ns	ns	ns	ns
Dmax vs Dmed	ns	ns	ns	ns	*
Dmax vs Dmin	ns	***	***	*	***
Dmed vs Dmin	ns	**	***	*	*

in the dispersed treatment at all sampling dates except 80 DAS (Table 3.13). The slightly reduced difference in pod weight at 80 DAS is consistent with the concurrent increase in TDM in the dispersed as compared to the sole treatment (Fig. 3.10a).

The difference in pod dry weight between the sole and dispersed treatments was considerably greater at 60 and 70 DAS than that in TDM; for example, by 70 DAS the sole groundnut had produced 84% more pod dry weight than the dispersed groundnut, but only 30% more TDM, indicating that a greater proportion of assimilates had been used for pod development in the sole groundnut over this period. However, by 80 DAS there was only an 18 % difference in TDM between the two treatments and a 22 % difference in pod dry weight. Table 3.15 shows the percentage of dry matter present in the pods in each treatment during the pod filling phase and demonstrates a clear trend towards an increasing allocation of dry matter to the pods in all treatments. Although the percentage of dry matter in the pods was much lower in the dispersed treatment during the early stages of pod development, the pods accounted for 46.6, 49.7 and 47.1 % of plant dry weight in the sole, line and dispersed treatments respectively by 100 DAS. The values for the line planted treatment were significantly greater than those for the dispersed treatment at all sampling dates, but there was no significant difference between the line planted and sole groundnut. The partitioning of dry matter to the pods in the line planting followed a similar pattern to that in the sole groundnut.

Figure 3.11b shows accumulated pod dry weight at each sampling location in the line planting, while Table 3.14 shows the standard error of difference (SED) for comparing means for each date. Pod weights for Lmax were significantly lower than those for Lmed and Lmin at all sampling dates, but there was no significant difference between Lmed and Lmin at any stage of the season. The differences between Lmin and Lmax remained relatively constant from 60 DAS until final harvest, whereas those between Lmed and Lmax narrowed because of the apparent loss of pod weight in the former treatment between 80 - 100 DAS. The mean rate of increase in pod dry weight between 60 - 80 DAS was $4.0 \text{ g m}^{-2} \text{ d}^{-1}$ at position Lmin, as compared to $2.1 \text{ g m}^{-2} \text{ d}^{-1}$ at Lmax.

The values for Lmax were consistently lower than those for the sole groundnut. However, since there was no difference between mean pod dry weights for the line planted and sole groundnut treatments, it is clear that the lower pod weights at Lmax relative to the sole groundnut were offset by increased productivity at positions Lmed and Lmin, where pod dry weights were significantly greater than in the sole stand. Pod dry weight at position Lmed increased to a maximum at 80 DAS, before declining to 93 g m² at 100 DAS. Pod dry weight increased by 9 % at position Lmin between 80-100 DAS but, although values were consistently greater than at Lmax, the differences were not significant. Pod dry weights recorded at Lmed and Lmin did not alter significantly between 60 - 80 DAS.

The pods comprised a higher proportion of TDM at position Lmin than at Lmax (Table 3.15); at 70 DAS they contributed 23 % of the TDM at position Lmin, as compared to 14 % at Lmax. However, these differences in partitioning between treatments decreased with time; by 90 DAS the pods constituted 46 % of TDM at position Lmin and 37 % at Lmax and by 100 DAS the corresponding values were 52 % and 48 %. Contributory reasons for these changes include the possibility that there may have been fewer pods available to fill at position Lmax (as discussed in Section 3.3.4), or simply that development was slower at this location as a result of the greater competition with pigeonpea.

Figure 3.11c shows the timecourses for pod dry weights at each sampling location in the dispersed treatment. Maximum pod dry weight was reached at 80 DAS at all sampling locations, and the mean growth rates up to this time were 4.4, 3.3 and 2.3 g m² d⁻¹ for positions Dmax, Dmed and Dmin respectively. The rate for Dmin was 40 % greater than that for the sole groundnut over the same period. A consistently higher proportion of total dry matter was partitioned to the pods at position Dmin than at positions Dmed or Dmax (Table 3.15). The most likely explanation is that fewer pods were initiated at Dmax, as is discussed further in Section 3.3.4.

Pod dry weights at position Dmin were significantly greater than those at Dmax for all sampling dates (Table 3.14). By 60 DAS, Dmin had produced a pod dry weight

Table 3.15: Pod dry weight in groundnut expressed as a percentage of TDM, 1990. Overall treatment means and mean values for specific sampling positions within treatments are shown.

DAS	60	70	80	90	100
sole	7.8	20.2	27.8	30.2	46.6
line	7.6	20.4	31.7	38.6	49.7
dispersed	1.7	14.8	26.8	29.0	47.1
Lmin	7.7	22.9	31.2	45.5	52.3
Lmed	8.8	21.8	36.1	44.5	46.0
Lmax	5.4	14.0	25.1	37.4	47.8
Dmin	4.6	20.5	32.5	37.1	44.6
Dmed	0.3	12.1	26.7	32.3	44.1
Dmax	0.2	8.6	24.2	31.6	37.6

of 8.4 g m⁻², whilst the corresponding value for Dmax was only 0.3 g m⁻², again suggesting that the initiation of pod filling was delayed at the site of greatest competition with the pigeonpea. This difference in pod weight between Dmin and Dmax continued to increase until 80 DAS and then remained almost constant until final harvest; the slight decrease in the difference between these two positions at 90 DAS resulted from the decreased pod dry weight recorded for Dmin on this date. The values for Dmax were consistently smaller than those for Dmin and Dmed, although the difference between Dmax and Dmed was not significant at 60, 70 and 90 DAS. The values for Dmed were invariably intermediate between Dmin and Dmax, and were significantly smaller than at Dmin, except at 90 DAS.

3.3.4 Pod number

Figure 3.12 shows the timecourses for pod number between 50 and 100 DAS. 'Large' pods were classified as those greater than 1 cm in length, and 'small' pods as anything less than this. There were consistently many fewer small pods than large pods in all treatments (Table 3.16). The line planted groundnut possessed significantly more large and fewer small pods than the sole treatment at all sampling dates except 100 DAS, possibly because of the earlier pod fill and maturation in the former. The dispersed groundnut had considerably fewer pods in both categories than either the sole or line treatments throughout the measurement period. Regression analysis of pod dry weight against pod number for the period between 50 and 100 DAS (Fig. 3.13) shows a strong correlation between these two variables in all treatments, indicating that the relatively low total pod dry weight in the dispersed treatment was the result of fewer pods being set, rather than smaller pods being produced. At 90 and 100 DAS this relationship broke down for the dispersed and line planted treatments as there was an apparent decrease in pod number (Fig. 3.12), although pod dry weight was maintained (Fig. 3.11a).

The number of large pods in the sole and line planted treatments followed a similar increasing trend until 80 DAS, after which the numbers continued to increase in the former but decreased in the latter (Table 3.16). Small pod numbers were consistently

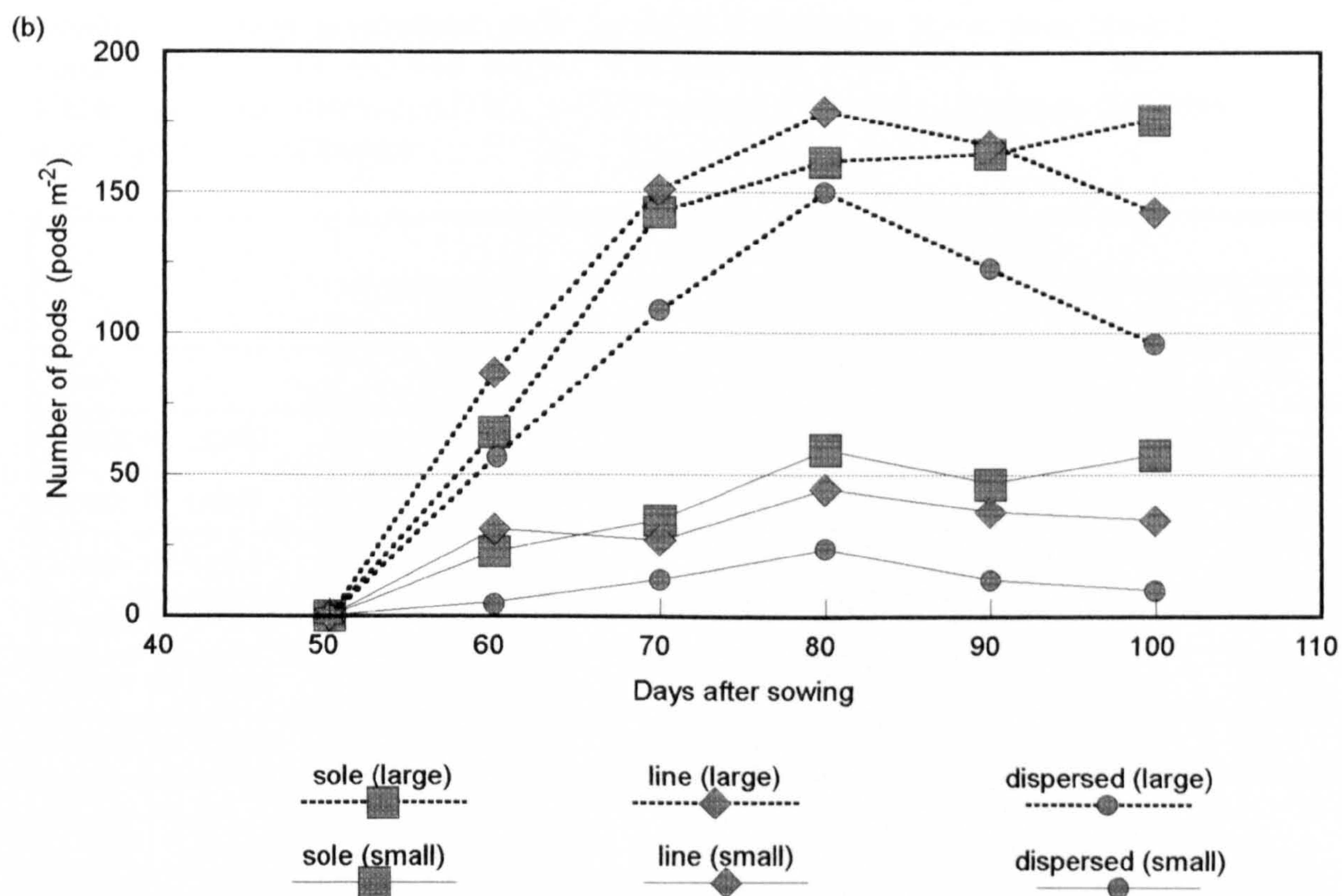
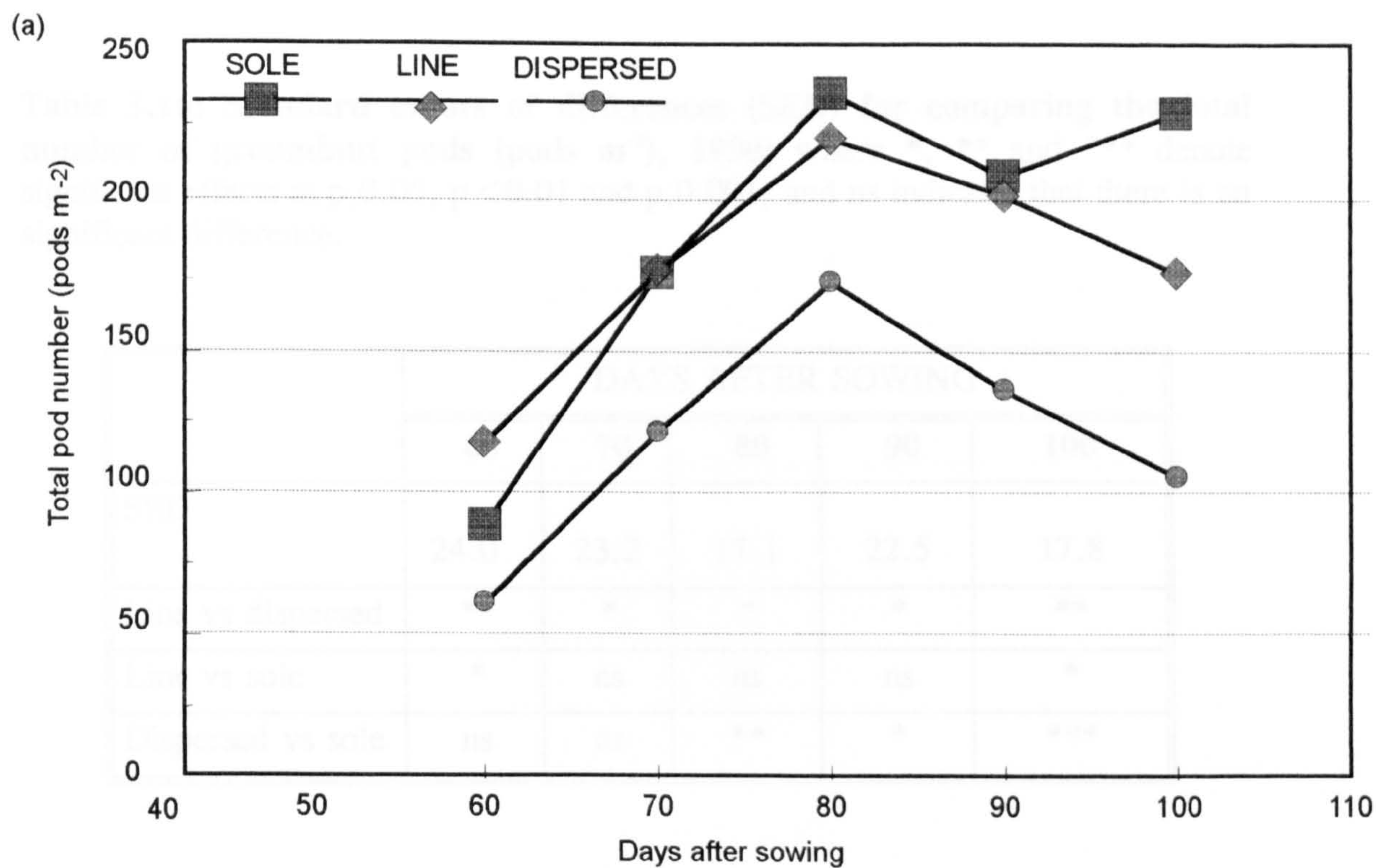


Figure 3.12: Number of groundnut pods, 1990: (a) treatment mean total pod numbers and (b) treatment mean large pods (>1 cm length) and small pods (<1 cm length).

Table 3.16: Standard errors of differences (SED) for comparing the total number of groundnut pods (pods m⁻²), 1990; where *, ** and * denote significant effects at p,0.05, p<0.01 and p,0.001, and ns indicates that there is no significant difference.**

	DAYS AFTER SOWING				
	60	70	80	90	100
SED	24.0	23.2	17.1	22.5	17.8
Line vs dispersed	**	*	*	*	**
Line vs sole	*	ns	ns	ns	*
Dispersed vs sole	ns	ns	**	*	***

Table 3.17: Ratio of large to small pods in groundnut, 1990

DAS	60	70	80	90	100
Sole	2.8	4.2	2.7	3.5	3.1
Line	2.7	5.6	4.0	4.5	4.2
Dispersed	11	8.3	6.3	9.5	10.3

Table 3.18: Standard errors of differences (SED) for comparing the mean numbers of large groundnut pods (pods m⁻²) recorded at various sampling positions within the line and dispersed treatments, 1990; where *, ** and * denote significant effects at p,0.05, p<0.01 and p,0.001, and ns indicates that there is no significant difference.**

	DAYS AFTER SOWING				
	60	70	80	90	100
SED	14.2	23.2	17.1	22.5	17.8
Lmax vs Lmed	***	*	***	**	**
Lmax vs Lmin	***	***	**	***	***
Lmed vs Lmin	ns	ns	**	ns	ns
Dmax vs Dmed	ns	**	*	ns	ns
Dmax vs Dmin	**	ns	***	ns	ns
Dmed vs Dmin	**	ns	***	ns	ns

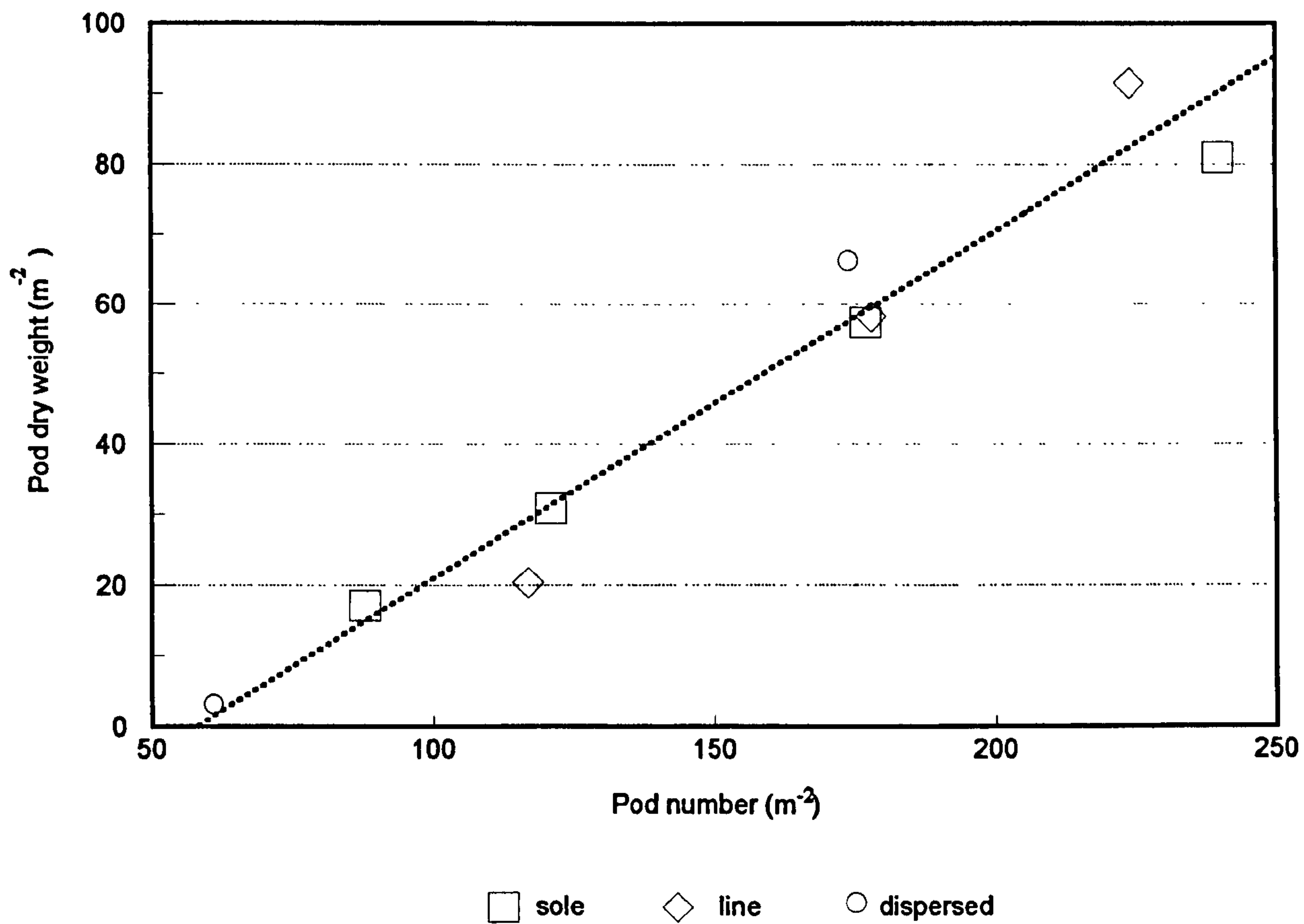


Figure 3.13: Relation between total pod dry weight and pod number in groundnut, 1990; treatment mean values, 60-80 DAS. ($y = 0.5 x - 29$; $r^2 = 0.96$)

greatest in the sole treatment and lowest in the dispersed planting between 70 - 100 DAS. Table 3.17 shows the ratio of large to small pods in each treatment. There was a consistently higher proportion of large pods in the dispersed treatment, providing additional evidence for the argument that the lower total pod dry weight probably resulted from a shorter duration of pod set, and that a higher proportion of the pods set were filled.

Figure 3.14 shows total pod number at each sampling location within the line planting (Fig. 3.14a) and also the numbers of large and small pods at each location (Fig. 3.14b) between 50 and 100 DAS. As indicated by the previous results for pod dry weight and the linear relationship between pod weight and number, significantly fewer pods were produced at position Lmax than at Lmed and Lmin. A marked difference in the number of large pods, and hence in total pod number, was already apparent between Lmax and the other two positions by 60 DAS (Fig. 3.14). This difference was maintained at all sampling dates, although there was an apparent decrease in pod number between 80 and 100 DAS at positions Lmed and Lmax and between 90 and 100 DAS at Lmin. Lmax reached a maximum of 121 large pods m⁻² at 80 DAS, as compared to a maximum of 207 large pods m⁻² at 90 DAS for Lmin. There was little difference between Lmed and Lmin and, although the latter had significantly more large pods at 70 DAS and significantly fewer at 80 DAS, and reached a maximum at 90 DAS, ten days after Lmed.

There was no significant difference between the number of small pods at each sampling position at most sampling dates, the only exceptions being that Lmax possessed significantly fewer small pods than Lmed and Lmin at 60 DAS and significantly fewer than Lmed at 90 DAS.

Figure 3.15 shows that total pod number was consistently greatest at position Dmin and least at position Dmax in the dispersed planting. As with the line planting, there were no significant differences between the various sampling positions in the number of small pods present at most sampling dates (Fig. 3.15b), although there were significantly more small pods at position Dmin at 70 DAS (22 pods m⁻²) than at positions Dmed or Dmax (9 and 7 pods m⁻² respectively). Significantly fewer large

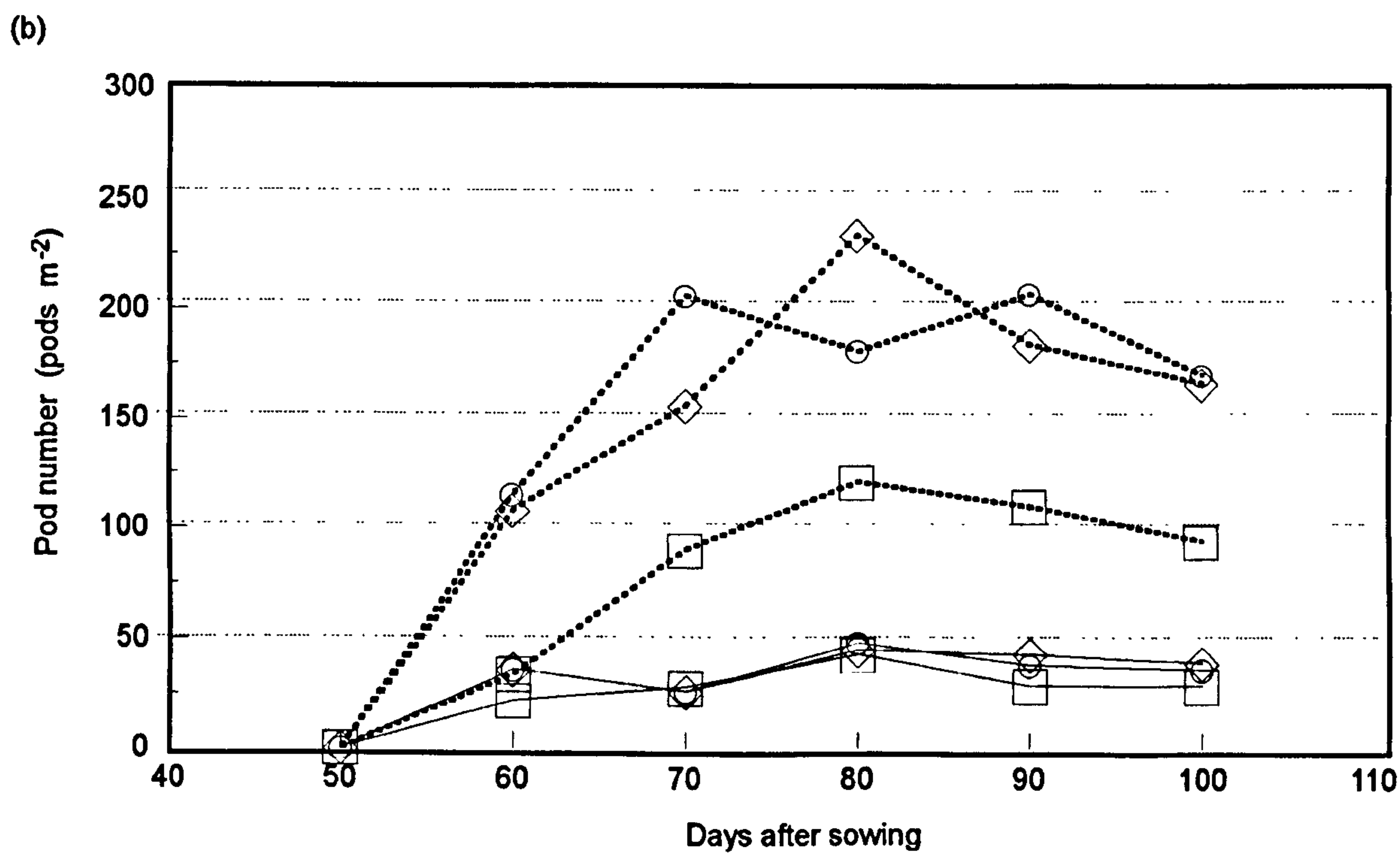
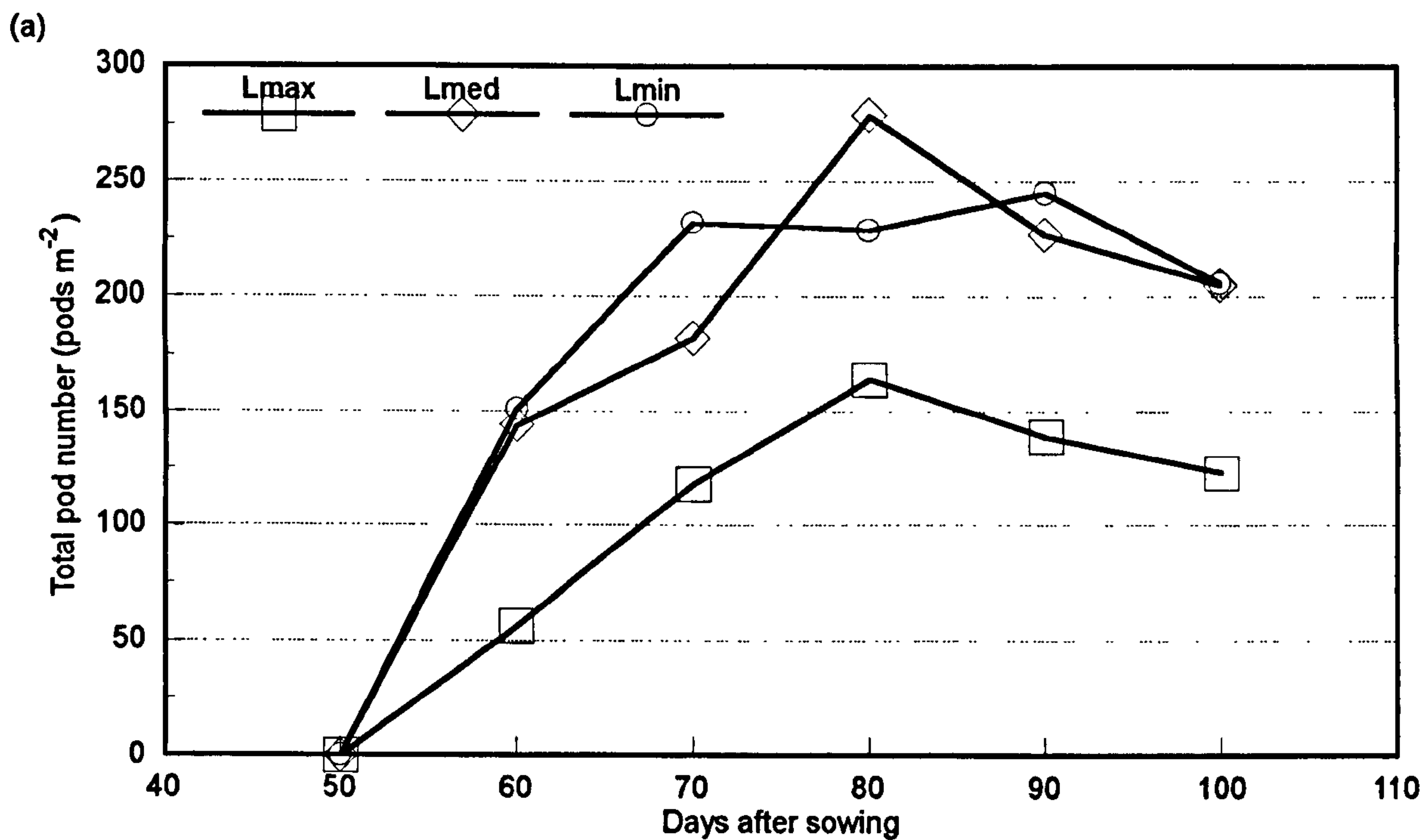


Figure 3.14: Number of groundnut pods, 1990: (a) various sampling positions within the line planting and (b) large and small pods at each sampling position.

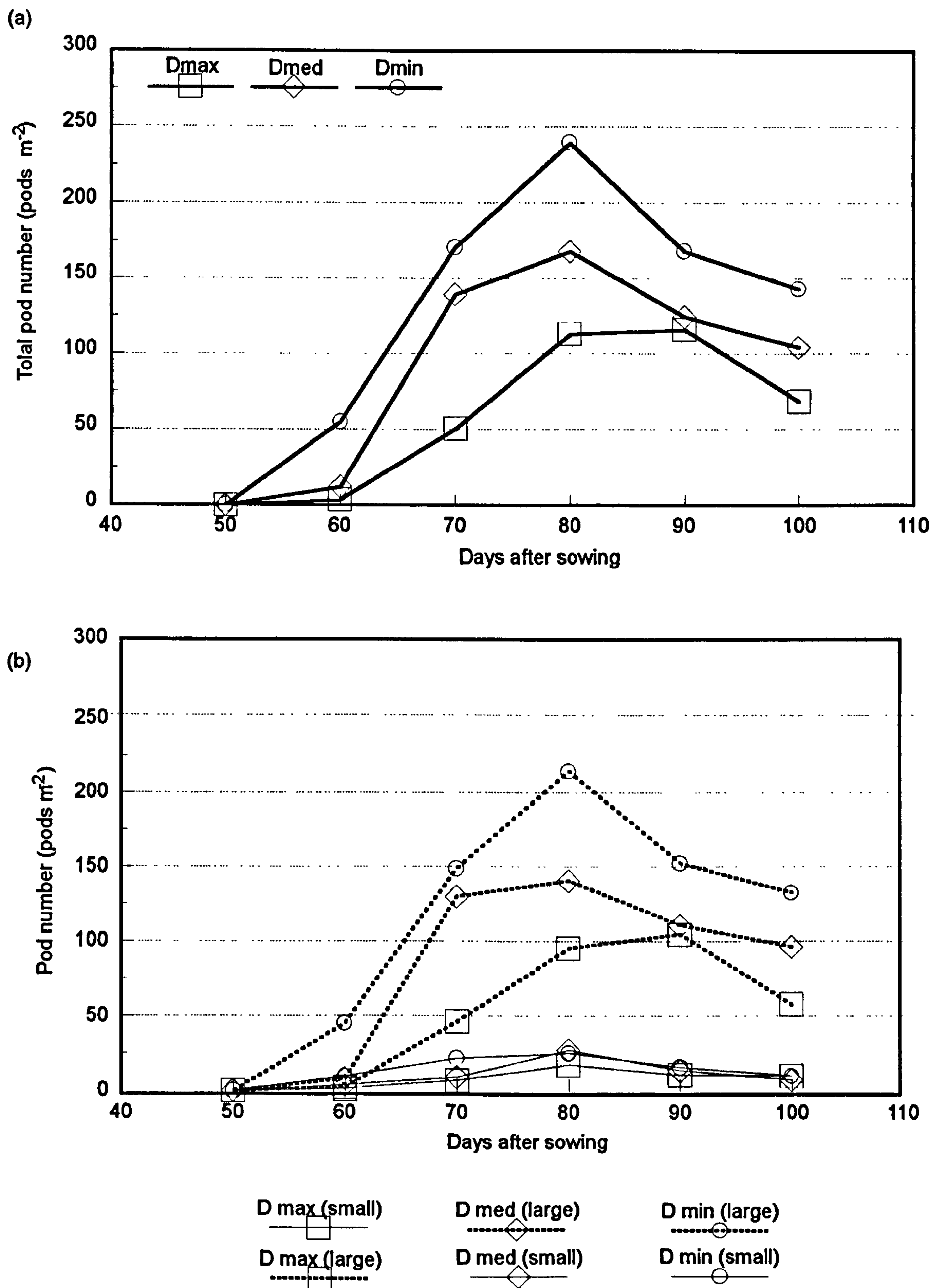


Figure 3.15: Number of groundnut pods, 1990: (a) various sampling positions within the dispersed planting and (b) large and small pods at each sampling position.

Pods were recorded at position Dmax than at Dmin throughout the sampling period (Table 3.18). Although Dmed produced fewer large pods than Dmin at all sampling dates, this difference was not significant at 70 and 90 DAS. Pod development was initially slower at position Dmed than at Dmin, but there was no significant difference between Dmax and Dmed at 60 DAS, when mean values of 2.4, 8.3, and 45.2 pods m² were recorded for positions Dmax, Dmed and Dmin respectively. Pod number increased more rapidly between 60 and 70 DAS at Dmed than at the other two locations, so that by 70 DAS Dmed had 2.8 times more pods than Dmax and was not significantly different from Dmin. Dmin and Dmed attained their maximum numbers of large pods at 80 DAS (214 and 141 pods m²) as compared to a maximum of 105 large pods m² at Dmax at 90 DAS. At this time, there was no significant difference between the three locations, although they were still ranked in the order Dmin > Dmed > Dmax. The loss of a substantial number of large pods was surprising and there is no obvious explanation other than the possibility of rodent damage or sampling error.

3.4 PIGEONPEA GROWTH AND DEVELOPMENT - 1989

Table 3.19 shows the dates of the grain and fodder harvests and major developmental stages for perennial pigeonpea throughout the experimental period. Although there were no differences between treatments in the timing of major developmental phases, differences in leaf area index, mainstem height, stem diameter and the number of primary branches were observed; these are discussed below.

3.4.1 Total dry matter

Table 3.20 shows dry matter production for pigeonpea at the first harvest on 31 January 1990. The values exclude roots, dry matter below the 50 cm cutting height and the leaf litter. The sole pigeonpea produced significantly more fodder and pod dry weight ($p < 0.01$) than either the line or dispersed treatments. The fodder dry weight in the sole pigeonpea (7.0 t ha⁻¹) was more than five times greater than in the line and dispersed treatments (1.2 and 1.3 t ha⁻¹ respectively). Pod dry weight in the

Table 3.19: Pigeonpea 1989-1990. Dates of grain and fodder harvests

	DATE	JULIAN DAY	DAYS AFTER SOWING PIGEONPEA.
Planting	July 3 1989	184	
Growth analysis	October 30 1989	303	113
Grain and fodder harvest	January 31 1990	31	206
Fodder cut	April 16 1990	106	281
Fodder cut	May 22 1990	142	317
Population in sole crop reduced to 0.5 plants m ² .	June 1 1990	152	327
Fodder cut	August 8 1990	220	395
Grain and fodder harvest	January 25 1991	25	565

Table 3.20: Treatment mean dry matter production in pigeonpea, 1989. SED represents the standard error of difference for comparing treatment means

Dry matter (t ha ⁻¹)	Sole	Line	Dispersed	SED
pod	1.16	0.27	0.26	0.06
fuel and fodder	7.00	1.20	1.30	0.48
total	8.16	1.47	1.56	

sole crop (1.16 t ha⁻¹) exceeded the corresponding values for the line and dispersed treatments by approximately four-fold. Thus, the mean harvest index (ratio of pod to total dry weight above 50 cm) was lower in the sole crop (0.17) than in the line (0.23) or dispersed treatments (0.20). The values for sole pigeonpea are similar to those obtained by Odongo *et al.* (1995) who reported that stem and fodder production was 5.6 t ha⁻¹ and grain production was 0.97 t ha⁻¹ in the first year after planting perennial pigeonpea (cultivar ICP 8094) at a density of 8.3 plants m⁻² in 1988 at ICRISAT Center.

In both cases some loss of grain was caused by pod borer (*Helicoverpa armigera*), even though the crop was sprayed twice with Endosulphan during pod maturation. A sub-sample of five plants taken from each of the twelve final yield samples was used to assess pod borer damage and determine actual grain weight as a proportion of total pod dry weight (Table 3.21). The percentage of damaged pods in the sole crop (30 %) was significantly greater ($p < 0.5$) than in the line treatment, but the number of pods per unit land area was approximately six fold greater than in the other treatments. As there was only an approximately four-fold difference in pod dry weight, this suggests that the pods were smaller in the sole crop. The grain accounted for approximately 60 % of total pod dry weight in all treatments.

3.4.2 Mainstem height

Figure 3.18 shows treatment means for mainstem height between 79 DAS and first harvest at 212 DAS. The majority of stem growth occurred between 79 and 157 DAS in all treatments, before the period of pod development and maturation. The period of most rapid main stem extension appeared to precede flowering (115 DAS).

The mean rates of growth between 79 and 157 DAS were 1.1 and 0.9 cm d⁻¹ in the line and dispersed treatments respectively, although there were no significant differences between these treatments at any time (Table 3.22). The final values at 205 DAS were 190 and 183 cm in the line and dispersed treatments. The sole pigeonpea exhibited a similar pattern of increasing mainstem height but was

significantly taller than in the other treatments (Fig. 3.18). The greater plant population in the sole stand may have resulted in intense shading of the lower branches, causing etiolation of the main stem. The final height at 205 DAS was 231 cm. Odongo *et al.* (1995) also reported that plant height was greater in sole pigeonpea (cultivar ICP 8094) planted at 8.3 plants m² than in the intercropped pigeonpea, although the differences were again not significant.

3.4.3 Stem diameter

Figure 3.17 shows mean values for main stem diameter 10 cm above ground level for all treatments between 79 and 212 DAS. Mean stem diameter in the sole pigeonpea was similar to that in the dispersed and line treatments on the first two measurement dates (79 and 101 DAS) but thereafter increased at a much lower rate of 0.03 mm d⁻¹. These results suggest that growth in this treatment was limited from 101 DAS onwards by intraspecific competition for resources.

Stem diameter increased much more rapidly between 79 and 157 DAS in the line and dispersed treatments, at mean rates of 0.10 and 0.14 mm d⁻¹ respectively. However, during the period of pod development and maturation between 157 and 212 DAS, the increase in stem diameter was much smaller. The pigeonpea in the dispersed treatment, which was expected to suffer little or no interspecific competition in the first year of growth, had a larger stem diameter than the line-planted trees, presumably because the latter were affected by within-row competition. Stem diameter was significantly greater in the dispersed treatment than in either the line or sole treatments between 130 and 157 DAS (Table 3.23); and the mean diameters at 157 DAS were 20.1, 17.1 and 14.6 mm for the dispersed, line and sole stands.

3.4.4. Number of primary branches

Figure 3.18 shows the mean number of primary branches recorded between 79 DAS and the first grain harvest at 212 DAS. Branch number increased rapidly prior to

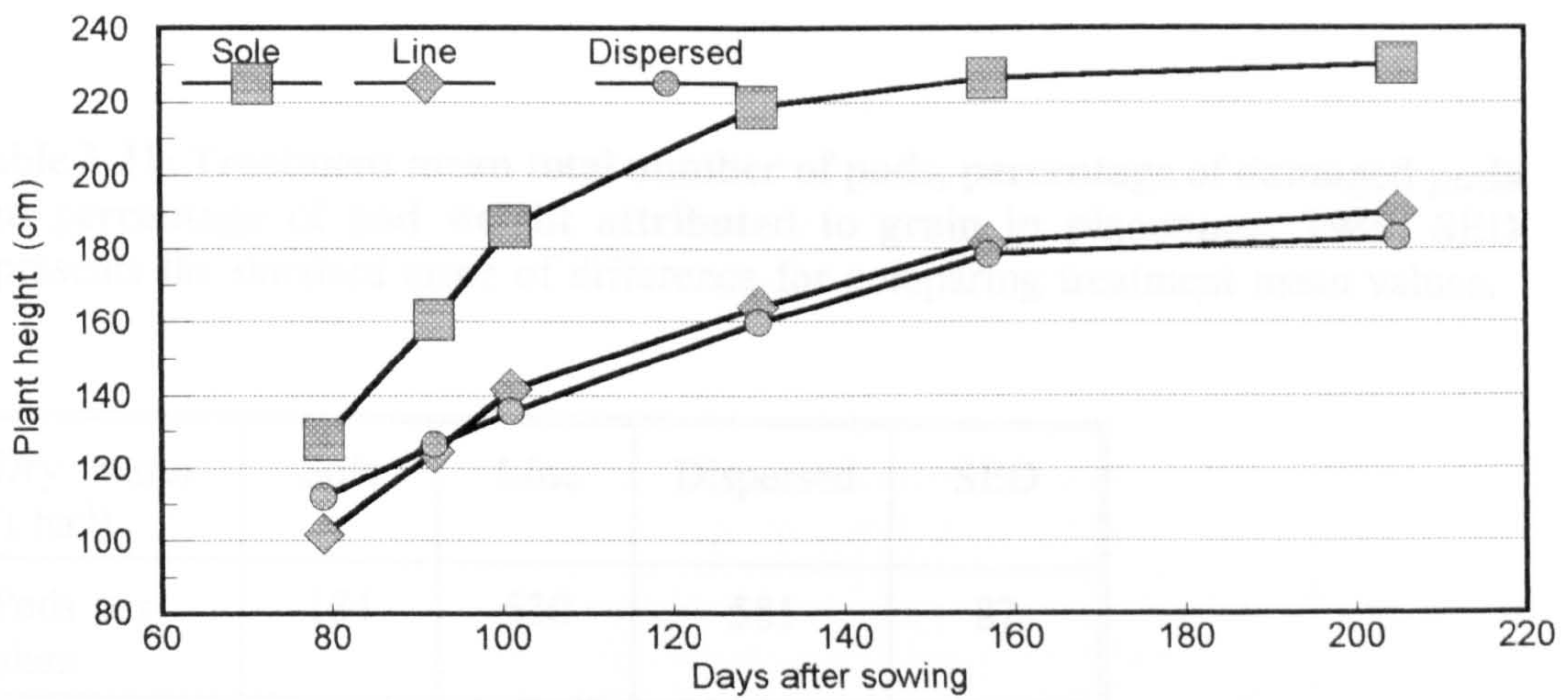


Figure 3.16: Treatment mean values for plant height in pigeonpea ,1989 (n=4).

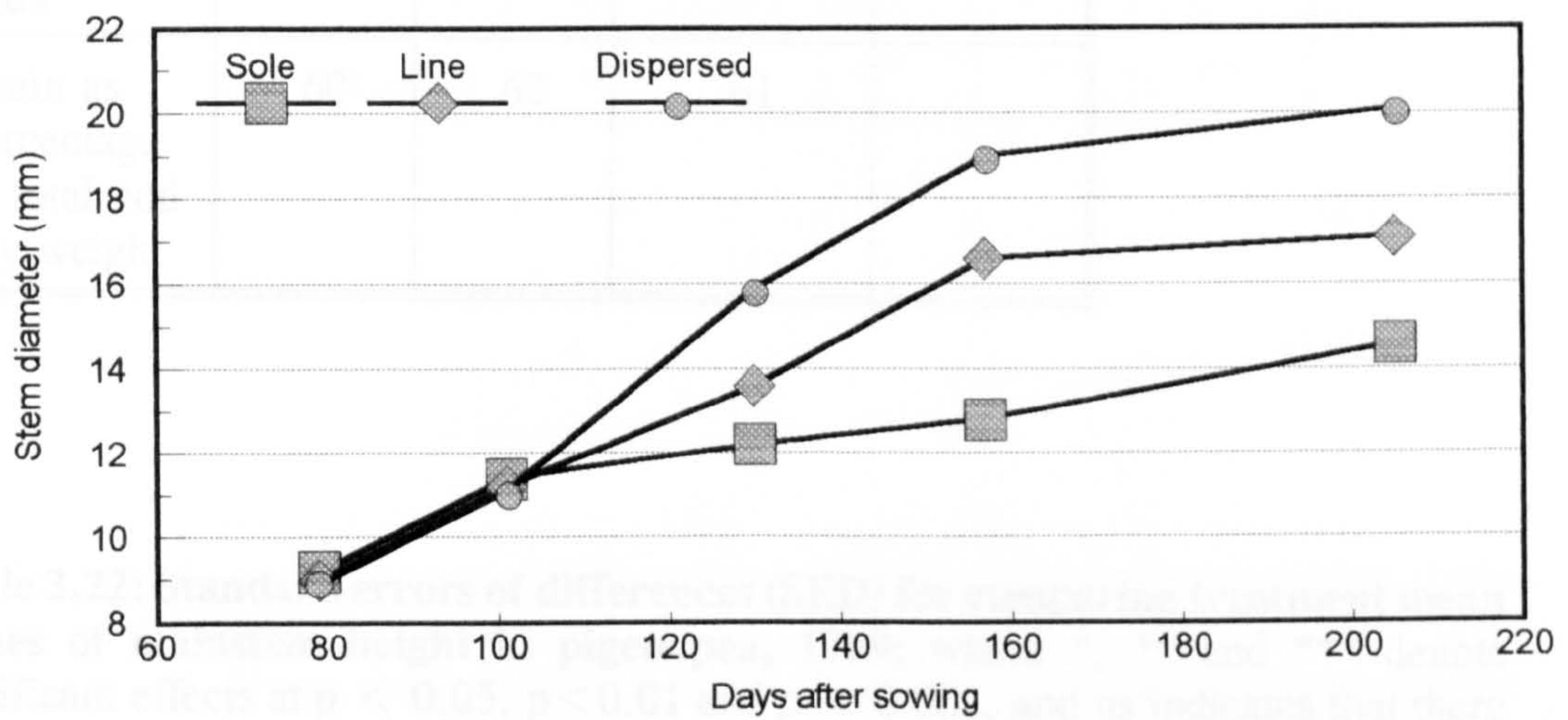


Figure 3.17: Treatment mean values for stem diameter in pigeonpea, 1989 (n=4).

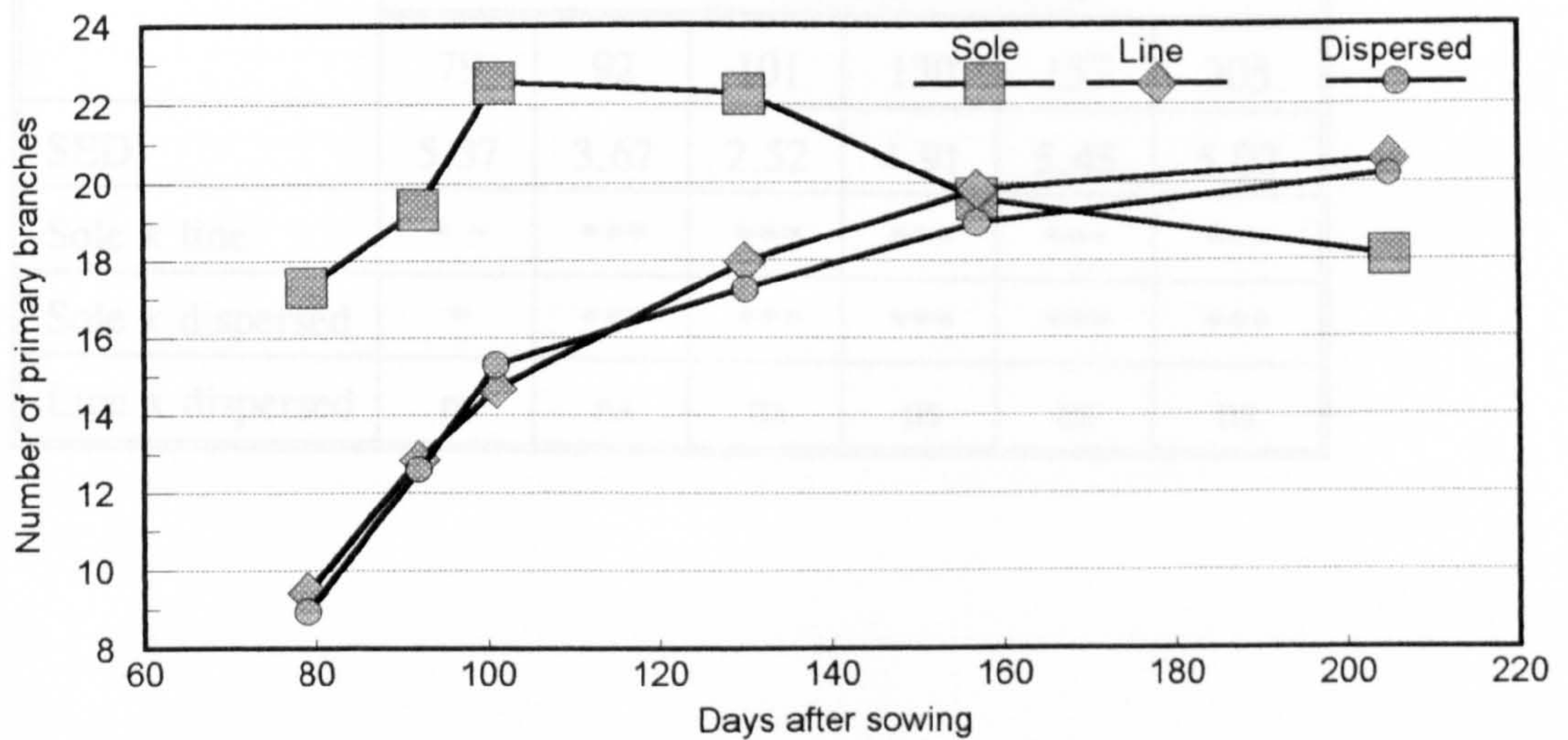


Figure 3.18: Treatment mean values for the number of primary branches per plant in pigeonpea, 1989 (n=4).

Table 3.21: Treatment mean total number of pods, percentage of damaged pods and percentage of pod weight attributed to grain in pigeonpea, 1989. SED represents the standard error of difference for comparing treatment mean values.

Dry matter (t ha ⁻¹)	Sole	Line	Dispersed	SED
Pods per plant	184	530	581	87
Pods m ⁻²	1656	265	291	
% damaged pods	30	25	29	4.2
Grain as percentage of total pod dry weight	60	62	61	

Table 3.22: Standard errors of differences (SED) for comparing treatment mean values of mainstem height in pigeonpea, 1989; where *, ** and *** denote significant effects at p < 0.05, p < 0.01 and p < 0.001, and ns indicates that there is no significant difference

	DAYS AFTER SOWING					
	79	92	101	130	157	205
SED	5.37	3.67	2.52	4.91	5.45	5.02
Sole x line	* *	***	***	***	***	***
Sole x dispersed	*	***	***	***	***	***
Line x dispersed	ns	ns	ns	ns	ns	ns

Table 3.23: Standard errors of differences (SED) for comparing treatment mean values of stem diameter in pigeonpea, 1989; where *, ** and *** denote significant effects at $p < 0.05$, $p < 0.01$ and $p < 0.001$, and ns indicates that there is no significant difference

	DAYS AFTER SOWING				
	79	101	130	157	205
SED	0.90	0.54	0.92	0.63	0.80
Sole x line	ns	ns	ns	***	*
Sole x dispersed	ns	ns	**	***	***
Line x dispersed	ns	ns	*	**	**

Table 3.24: Standard errors of differences (SED) for comparing treatment mean values of the number of primary branches in pigeonpea, 1989; where *, ** and *** denote significant effects at $p < 0.05$, $p < 0.01$ and $p < 0.001$, and ns indicates that there is no significant difference

	DAYS AFTER SOWING					
	79	92	101	130	157	205
SED	0.78	1.16	1.26	1.10	1.27	1.01
Sole x line	***	**	***	**	ns	ns
Sole x dispersed	***	**	**	**	ns	ns
Line x dispersed	ns	ns	ns	ns	ns	ns

flowering at 115 DAS in all treatments, at mean rates between 79 and 101 DAS of 0.24 branches plant⁻¹ in the dispersed and line treatments and 0.29 branches plant⁻¹ in the sole stand. Branch number was initially much greater in the sole pigeonpea, reaching a maximum of 22.6 branches plant⁻¹ at 101 DAS, as compared to 14.7 and 15.3 branches plant⁻¹ in the line and dispersed treatments respectively. Branch number continued to increase in the line and dispersed treatments at mean rates of 0.06 and 0.05 branches d⁻¹ between 101 and 205 DAS. The maximum number of branches recorded at 205 DAS was 20.6 and 20.2 branches plant⁻¹ for the line and dispersed treatments respectively.

Although differences between the line and dispersed treatments were never significant (Table 3.24), branch number in the sole treatment was significantly higher than in the other treatments until 130 DAS. There was an apparent decrease in the number of primary branches in the sole pigeonpea between 120 and 205 DAS, presumably because the intense competition between plants resulted in the senescence and death of some of the lower branches. At 205 DAS there were 18.3 primary branches plant⁻¹ in the sole pigeonpea which was lower, although not significantly so, than in the line and dispersed treatments.

3.4.5 Stem density

Because the woody portion of pigeonpea stems is often harvested for firewood, the density of the dry wood produced is of interest since high density wood is likely to have a higher heat value and burn for longer. The density of stem samples taken between 50 and 60 cm above the soil surface was determined as described in Section 2.3 to quantify any treatment effects. The results obtained (Table 3.25) indicate that the density of wood from the dispersed planting was significantly greater than that from the line ($p < 0.05$) and sole treatments ($p < 0.001$).

At each pigeonpea harvest, the percentage water content of the wood was determined (Section 2.2); the results obtained indicate that there was no significant difference between treatments. Thus, the woody material from the dispersed planting contained

Table 3.25: Density of pigeonpea stem sections taken between 50 and 60 cm from the soil surface on January 31 1990; where SED represents the standard error of differences for comparing treatment means; *, ** and * denote significant effects at p,0.05, p<0.01 and p,0.001, and ns indicates that there is no significant difference.**

	Density (g cm ⁻³)
Sole	0.67
Line	0.73
Dispersed	0.83
SED	0.04
Line x dispersed	*
Line x sole	ns
Dispersed x sole	***

the greatest quantity of biomass per unit volume, although biomass production per unit land area was considerably less than in the sole treatment.

3.4.6. Plant mortality

By the time of grain harvest, the mean mortality across all treatments was 15 %, with the lowest mortality being observed in the dispersed planting (9 %) (data not presented), although the treatment differences were not significant. Mortality was again assessed at the start of the 1990 rainy season and any dead trees were replaced; care was taken to ensure that the transplanted trees were not used for subsequent biological or physiological measurements.

3.5 PIGEONPEA GROWTH AND DEVELOPMENT - 1990

3.5.1. Leaf area index (L)

Table 3.26 shows values of L for pigeonpea calculated from the destructive samples taken in 1990. At first harvest on April 16, L was significantly higher in sole pigeonpea (1.10; $p < 0.005$) than in the dispersed (0.12) or line treatments (0.11). This effect was largely attributable to the much greater population of 8.9 plants m^{-2} in the sole treatment at this time, as compared with 0.5 plants m^{-2} in the other two treatments. The sole population was reduced to 0.44 plants m^{-2} on June 1 1990, prior to the next destructive sample, for the reasons described in Section 2.1.5. The L values for all treatments were lower than those recorded at the other destructive harvests, because sampling occurred during the dry season, when pigeonpea growth was restricted by the limited availability of soil moisture.

The second destructive sample taken on August 8 1990, during the rainy season, showed a marked increase in L in all treatments. There was little difference in L between the sole (1.61) and dispersed treatments (1.58), suggesting that the remaining plants in the sole crop had rapidly compensated for those that had been

removed. L was lower in the line-planted pigeonpea (1.15) than the other treatments, although not significantly so.

The final destructive estimate of L was obtained on December 12 1990. Unfortunately, because this was a very demanding time in terms of field operations, no simultaneous estimate was made for the sole pigeonpea. The L value for dispersed pigeonpea (1.16) was almost double that for the line-planted pigeonpea (0.62; $p < 0.005$).

3.5.2. Total dry matter (TDM)

The pigeonpea was cut twice for fodder at a height of 50 cm above ground level during the dry season of 1990 (April 17 and May 22). This was followed by a third fodder cut on August 8 1990 to reduce competition with the groundnut, which had been planted three weeks earlier, and grain and fodder were again harvested on January 25 1991. Dry matter production was recorded on each occasion. The pigeonpea plants were cut down to ground level at the end of the experiment on April 3 1991 to establish the quantity of dry matter accumulated in the stem below the 50 cm cutting level imposed in previous harvests.

Table 3.27 shows dry matter production at each harvest during the 1990-1991 growing season. At the first dry season cut on April 17 1990, there was no significant difference between the sole and dispersed pigeonpea (0.20 and 0.25 t ha⁻¹ respectively), even though the sole planting still had a population of 8.9 plants m⁻² as compared to 0.5 plants m⁻² in the other treatments. This demonstrates the high level of plasticity in the relationship between plant population and biomass production in pigeonpea. The yield for the line planting was significantly lower ($p < 0.05$), at only 0.06 t ha⁻¹. The higher productivity of the dispersed and sole pigeonpea may reflect their ability to extract water from the much larger soil volume available to individual plants in these planting arrangements (cf. Section 3.5.5). The close intra-row spacing in the line planting may have been an additional limiting factor for root development, as compared to the dispersed treatment.

Table 3.26: Leaf area index values for pigeonpea, 1990; (a) estimates of L obtained from destructive samples and (b) significant differences between values; *, ** and * denote significant differences at $p < 0.05$, $p < 0.01$ and $P < 0.001$ respectively**

(a)

	Sole	Line	Dispersed	
Date	L	L	L	SED
16/4/90	1.10	0.11	0.12	0.06
8/8/90	1.61	1.15	1.58	0.23
21/12/90		0.62	1.16	0.05

(b)

Sample date	Sole vs dispersed	Line vs dispersed	Line vs sole
16/4/90	***	ns	***
8/8/90	ns	ns	ns
21/12/90	N/A	***	N/A

Between April 17 1990 and the second fodder cut on May 22, the dispersed crop produced 0.23 t ha⁻¹ of biomass, significantly greater ($p < 0.01$) than in the line planting (0.03 t ha⁻¹) and also greater, although not significantly, than in the sole stand (0.12 t ha⁻¹). Although dry matter production by the dispersed pigeonpea was similar to that during the preceding sampling interval, production in the line and sole treatments was approximately half that recorded on April 17. During this period the quantity of available soil moisture would have reached its minimum for the year. Trees in the dispersed planting did not experience the intense intra-row competition of the line planted arrangement and, unlike the sole crop, were established at a lower population of 0.5 plants m⁻². Consequently, the dispersed trees probably produced the most extensive root system (Section 3.5.5), and would therefore have been able to extract greater quantities of stored soil moisture, thereby supporting the greater biomass production.

The dispersed pigeonpea produced significantly more dry matter (1.32 t ha⁻¹) than the sole pigeonpea (0.72 t ha⁻¹) between May 22 and the rainy season fodder cut on August 8 1990 ($p < 0.01$). Since the sole crop was reduced to a population of 0.44 plants m⁻² on June 1, the remaining plants had little time to compensate for those that had been removed. The line-planted pigeonpea also produced less dry matter (1.0 t ha⁻¹) than the dispersed pigeonpea, although not significantly so.

At the second harvest for grain and fodder on January 25 1991, there were no significant treatment differences in pod dry weight (0.74, 0.69 and 0.38 t ha⁻¹ for the sole, dispersed and line treatments). The values were all relatively low due to a severe infestation of *Helicoverpa armigera*. The dispersed planting produced 3.82 t ha⁻¹ of fodder, significantly more ($p < 0.01$) than the line planting (1.71 t ha⁻¹), but not significantly greater than the sole crop (3.06 t ha⁻¹). By this stage, the remaining sole pigeonpea plants had probably adapted to the reduction in intraspecific competition resulting from the reduced population density, by substantially increasing their individual resource use and productivity. The estimated harvest indices (calculated using biomass values above 50 cm height, cf. Table 3.27) for the sole and line crops were very similar (0.22 and 0.24 respectively), but the

Table 3.27: Dry matter production in pigeonpea between grain and fodder harvest on January 31 1990 and termination of the trial on April 3 1991. *, ** and * denote significant differences between treatment means at the $p < 0.05$, $p < 0.01$ and $P < 0.001$ and ns indicates that there is no significant difference between treatments**

Treatment	Dry matter production (t ha ⁻¹)						
	17/4/90	22/5/90	8/8/90	25/1/91	25/1/91	3/4/91	TOTAL
	Fodder cut at 50 cm	Fodder cut at 50 cm	Fodder cut at 50 cm	Fodder cut at 50 cm	Pod	Stem cut at ground level	
Sole	0.20	0.12	0.72	3.06	0.74	0.63	5.58
Line	0.06	0.03	1.00	1.71	0.38	0.60	3.78
Dispersed	0.25	0.23	1.32	3.82	0.69	1.14	7.34
SED	0.05	0.05	0.12	0.36	0.17		
sole x line	*	ns	ns	**	ns	ns	
sole x dispersed	ns	**	**	ns	ns	*	
line x dispersed	*	ns	ns	**	ns	*	

Table 3.28: Standard errors of differences (SED) for comparing treatment mean mainstem height in pigeonpea, 1990; where *, ** and * denote significant differences between treatment means at the $p < 0.05$, $p < 0.01$ and $P < 0.001$ and ns indicates that there is no significant difference between treatments**

	DAYS AFTER SOWING			
	394	448	499	570
SED	1.97	1.66	5.40	4.71
Sole vs line	ns	**	ns	*
Sole vs dispersed	ns	***	ns	ns
Line vs dispersed	**	ns	ns	ns

dispersed planting had a lower value of 0.18. Quantitative measurements of pod borer infestation were not made but, since the problem did not appear to be any greater in the dispersed planting, it seems unlikely that this was responsible for reducing harvest index relative to other treatments.

There was little additional fodder production between the grain harvest on January 25 and termination of the experiment on April 3 1991, when the biomass values consisted mainly of the cumulative dry matter production in the stem below the 50 cm cutting height. The dispersed planting produced 1.14 t ha⁻¹ of stem biomass during this period, significantly more ($p < 0.05$) than the line and sole pigeonpea (0.60 and 0.63 t ha⁻¹ respectively).

The dispersed planting exhibited the greatest productivity at each harvest, resulting in the highest overall productivity between April 1990 and April 1991 of 7.43 t ha⁻¹. The line planting produced 5.47 t ha⁻¹ and the sole crop 3.72 t ha⁻¹, approximately half of the value for the dispersed treatment.

3.5.3 Mainstem height

Figure 3.19 shows mean mainstem heights for pigeonpea at four measurement dates between 394 DAS (August 1 1990, just prior to the rainy season fodder cut) and 570 DAS (January 22 1991, just prior to the second grain harvest). All treatments exhibited similar timecourses for plant height, which increased almost linearly until 499 DAS at mean rates of 0.57, 0.64 and 0.61 cm d⁻¹ for the sole, line and dispersed treatments respectively. The rate of increase in mainstem height subsequently declined during pod development.

At 394 DAS there was no significant difference in height between the line and sole treatments (98.5 and 102.4 cm respectively; Table 3.28), but the line-planted pigeonpea was significantly shorter ($p < 0.01$) than in the dispersed treatment. By 448 DAS the height of the sole pigeonpea (133.8 cm) was significantly less than in the line ($p < 0.01$) and dispersed ($p < 0.001$) treatments (142.0 and 145.1 cm

respectively). There was no significant difference in treatment means at 499 DAS. The final values at 570 DAS were 171.6, 183.3 and 180.2 cm for the sole, line and dispersed treatments respectively.

3.5.4 Mainstem diameter

Figure 3.20 shows the mean values for mainstem diameter at a height of 10 cm above ground level. Stem diameter increased more rapidly in all treatments between 448 and 499 DAS than between 499 and 636 DAS; there was little change between the latter two dates, which coincided with the period of pod development and maturation.

Although the values for the line-planted treatment were consistently higher than in the sole treatment, no significant difference in stem diameter was detected (Table 3.29). Stem diameter in the dispersed treatment was significantly greater than in the sole stand on all three measurement dates ($p < 0.01$ at 448 and 499 DAS, and $p < 0.05$ at 636 DAS), and was significantly greater than in the line treatment at 448 and 499 DAS ($p < 0.05$). By the final measurement date, the dispersed trees had a mean stem diameter of 35.1 mm as compared to 30.4 and 31.5 mm for the sole and line treatments.

3.5.5 Root distribution

Characteristics of the soil profiles examined

The eight soil profiles in which root distribution was recorded in the line and dispersed treatments are shown in Figures 3.21 and 3.22 respectively. The soils in field RP15 are atypical Patancheru series Alfisols due to their exceptionally deep B horizon (Section 2.1.1). The various layers of the B horizon are not well defined because they have been mixed by deep ploughing operations in previous years, making it difficult to distinguish between them. Despite the lack of clear boundaries between the B horizons, there was a gradual progression from the very sandy loam

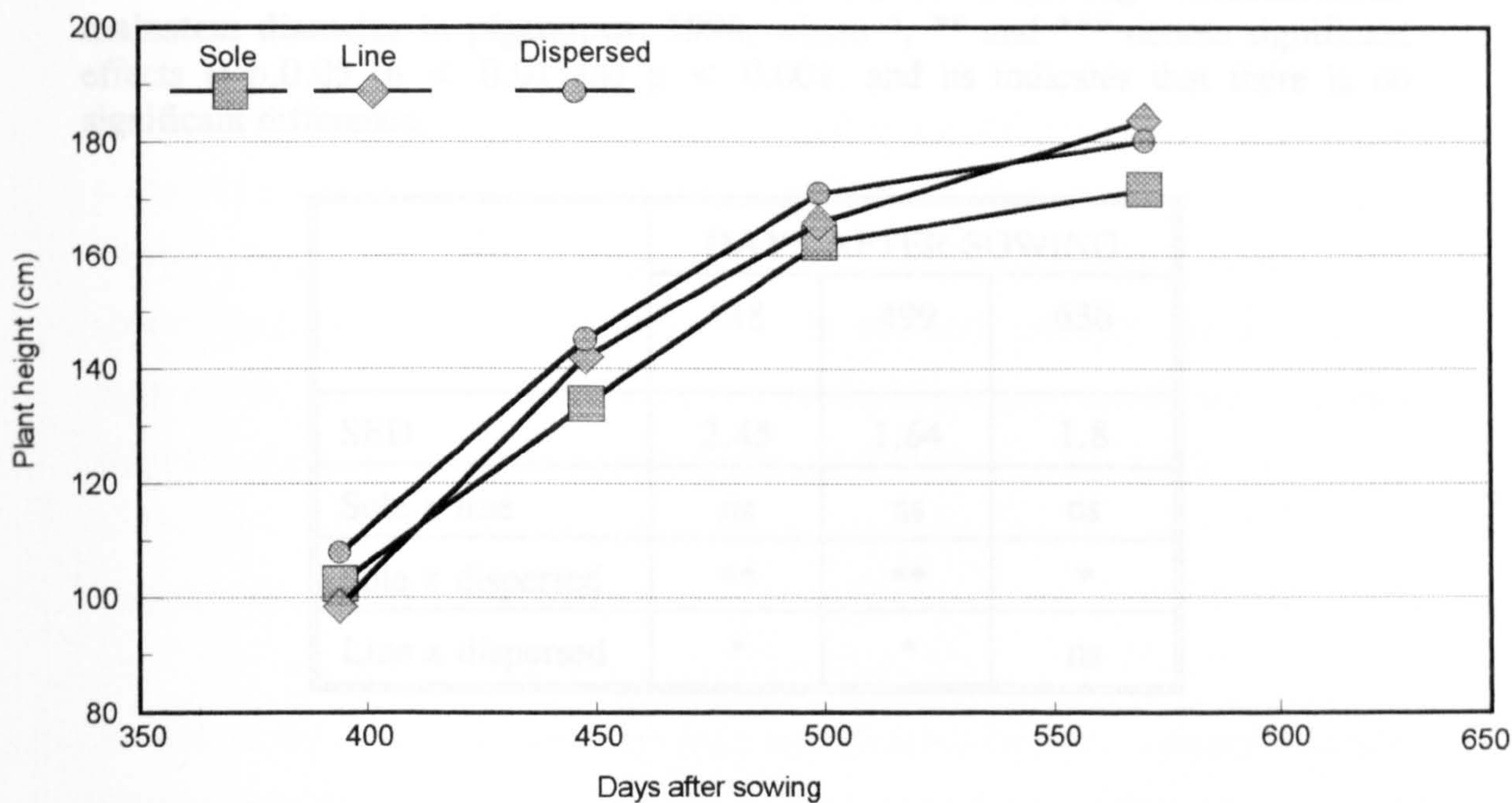


Figure 3.19: Treatment mean values for plant height in pigeonpea, 1990 (n=4).

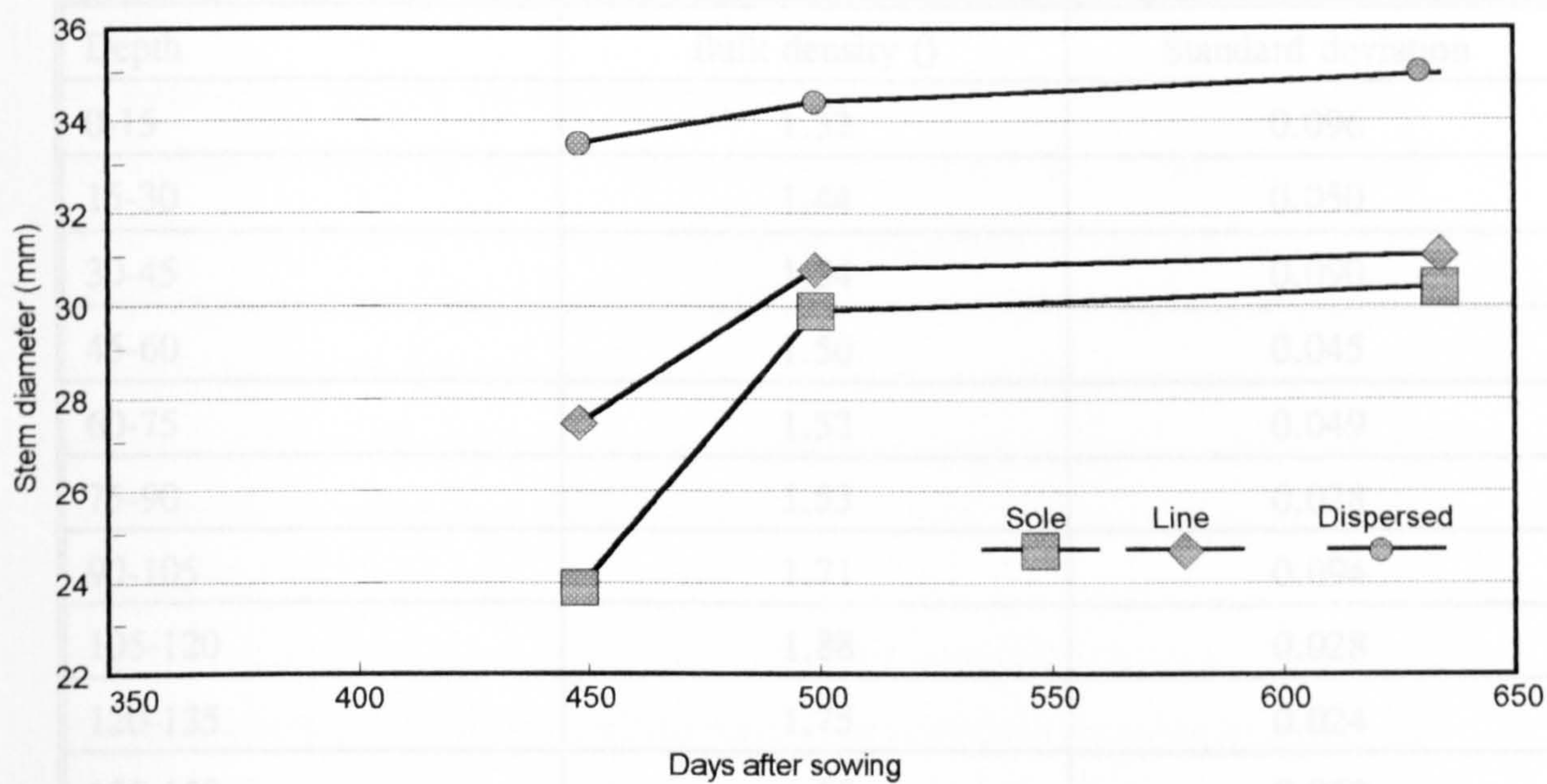


Figure 3.20: Treatment mean values for stem diameter in pigeonpea, 1990 (n=4).

Table 3.29: Standard errors of differences (SED) for comparing treatment mean mainstem diameter in pigeonpea, 1990; where *, ** and * denote significant effects at p,0.05, $p < 0.01$ and $p < 0.001$, and ns indicates that there is no significant difference.**

	DAYS AFTER SOWING		
	448	499	636
SED	2.45	1.64	1.8
Sole x line	ns	ns	ns
Sole x dispersed	**	**	*
Line x dispersed	*	*	ns

Table 3.30: Soil bulk density recorded in the line planting in field RP15 (n=6).

Depth	Bulk density ()	Standard deviation
0-15	1.32	0.096
15-30	1.44	0.050
30-45	1.54	0.090
45-60	1.50	0.045
60-75	1.52	0.049
75-90	1.53	0.028
90-105	1.71	0.094
105-120	1.88	0.028
120-135	1.75	0.024
135-150	1.68	0.050

Soil profile exploitation by pigeonpea roots

Figures 3.21 and 3.22 show the root maps prepared from the counts of the number of exposed roots in each of the eight soil profiles. Treatment mean root distributions were not calculated because of the extensive variability between individual profiles. This variation resulted partly from the fact that the position of the trees relative to the counting grid varied slightly between profiles.

In the line-planting arrangement, pigeonpea roots were present to the full 200 cm sampling depth up to 100 cm from the pigeonpea row, whilst lateral root extension across the full grid width occurred only in the top 50 cm of the profile. However, in the dispersed planting, roots were distributed throughout the profile to the full sampling depth and also across the entire area between adjacent trees, although there were grid areas in which no roots appeared. The mean percentage of grid sectors within which pigeonpea roots were present was 75 % in the dispersed planting (95 % confidence interval ± 10 %) and 41 % in the line planting (95 % confidence interval ± 7 %). Although the number of roots present clearly decreased with increasing depth in both treatments, some roots were present in the murram layer and there was no obvious reduction in root number with increasing bulk density (Table 3.30).

The mean total numbers of root ends present were 1055 root ends m^{-2} (95% confidence interval ± 128) in the dispersed planting and 365 root ends m^{-2} (95% confidence interval of ± 123) in the line-planting. The extremely large confidence interval in the line planting reflects the fact that the root density of profile 2 was unusually high. If Profile 2 is omitted and the calculation repeated, the mean becomes 315 root ends m^{-2} , and the 95% confidence interval is reduced to ± 50 despite the lower number of degrees of freedom. Thus, the higher productivity of the dispersed pigeonpea was clearly correlated with a more extensive root system which was able to exploit a greater proportion of the soil profile to a depth of at least 2 m.

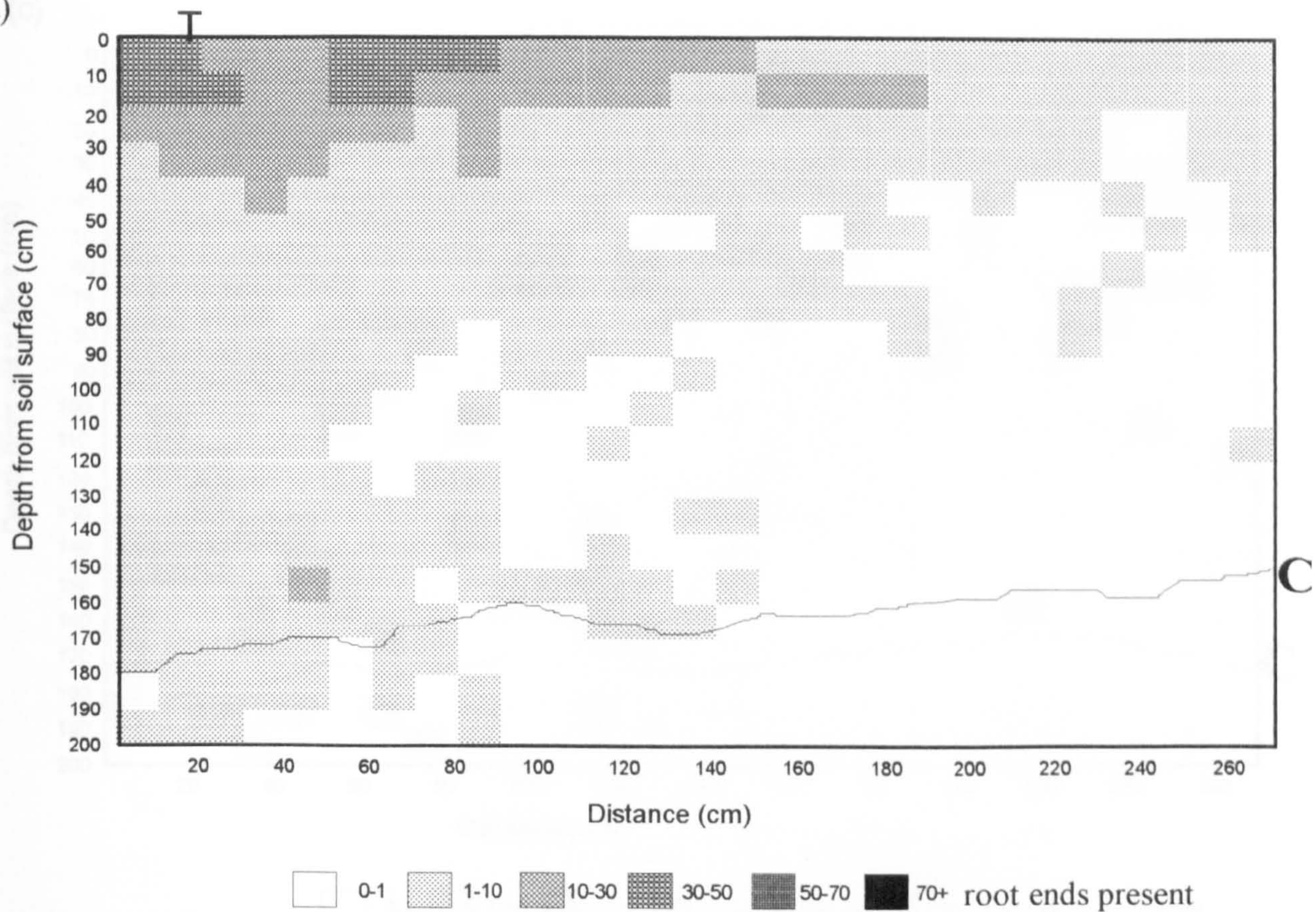
of the upper B horizon to the gravelly sandy clay loam of the lower B horizons. The boundary of soil horizon C was obvious and is marked in Figures 3.21 and 3.22; this boundary coincided with a marked change in soil texture. The C horizon was composed mainly of gravel and weathered fragments of granite often referred to as murrum. In the line planting, an area of sandy clay loam with a higher gravel content than the adjacent soil layers, but with less rock material than the murrum layer below, was visible. Bulk density for the various layers was determined using soil cores taken at 15 cm depth increments, as described in Section 2.3.3.

Quantitative analysis of measurements

In order to determine whether there were significant differences between treatment means for the line and dispersed plantings, it would have been necessary to separate variation attributable to treatment effects from that due to environmental and other factors. To achieve this, it would have been necessary to examine soil profiles from both treatments in each replicate or, alternatively, a number of profiles for each treatment randomly selected from the four replicate blocks. These approaches were not possible because the number and position of trenches for root distribution studies were constrained by the need to minimise damage to the rest of the experimental area. Because of these restrictions, statistical comparison of the treatment means would not have been valid, and so individual treatment means and confidence intervals around them were calculated from the four profiles for each treatment examined. The confidence intervals quoted for a given parameter are valid only for the replicate in which the measurements were made, as opposed to the entire experimental site.

Another potential error in assessing the number of pigeonpea roots resulted from the presence of weed roots. Although the soil surface was apparently clear of weeds, there were some roots in the upper horizons of a distinctly darker colour, which were assumed to be weeds (or groundnut roots that had not yet decomposed); these were excluded from the count. It is possible that there were a number of additional weed roots that could not be distinguished from the pigeonpea.

(a)



(b)

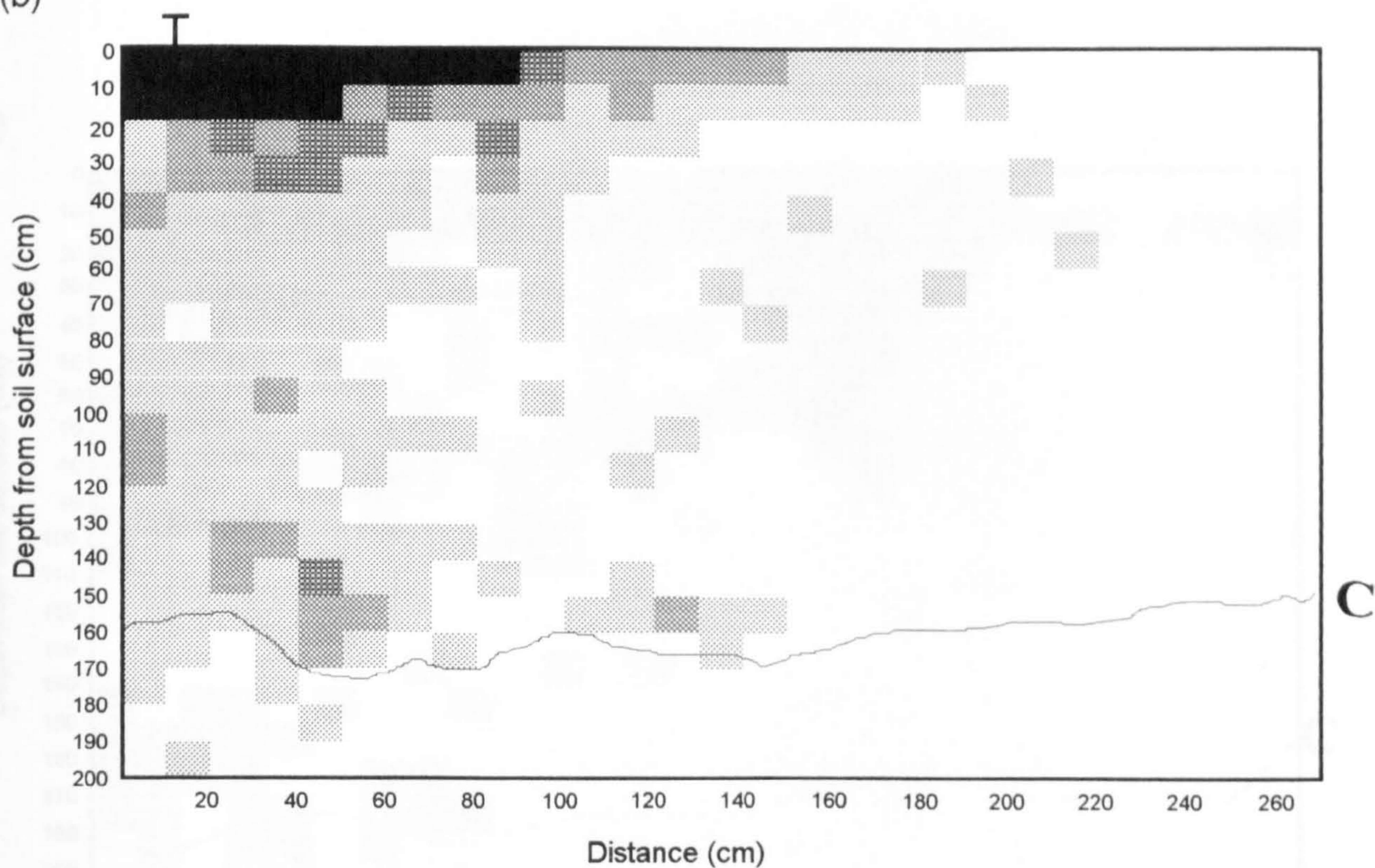
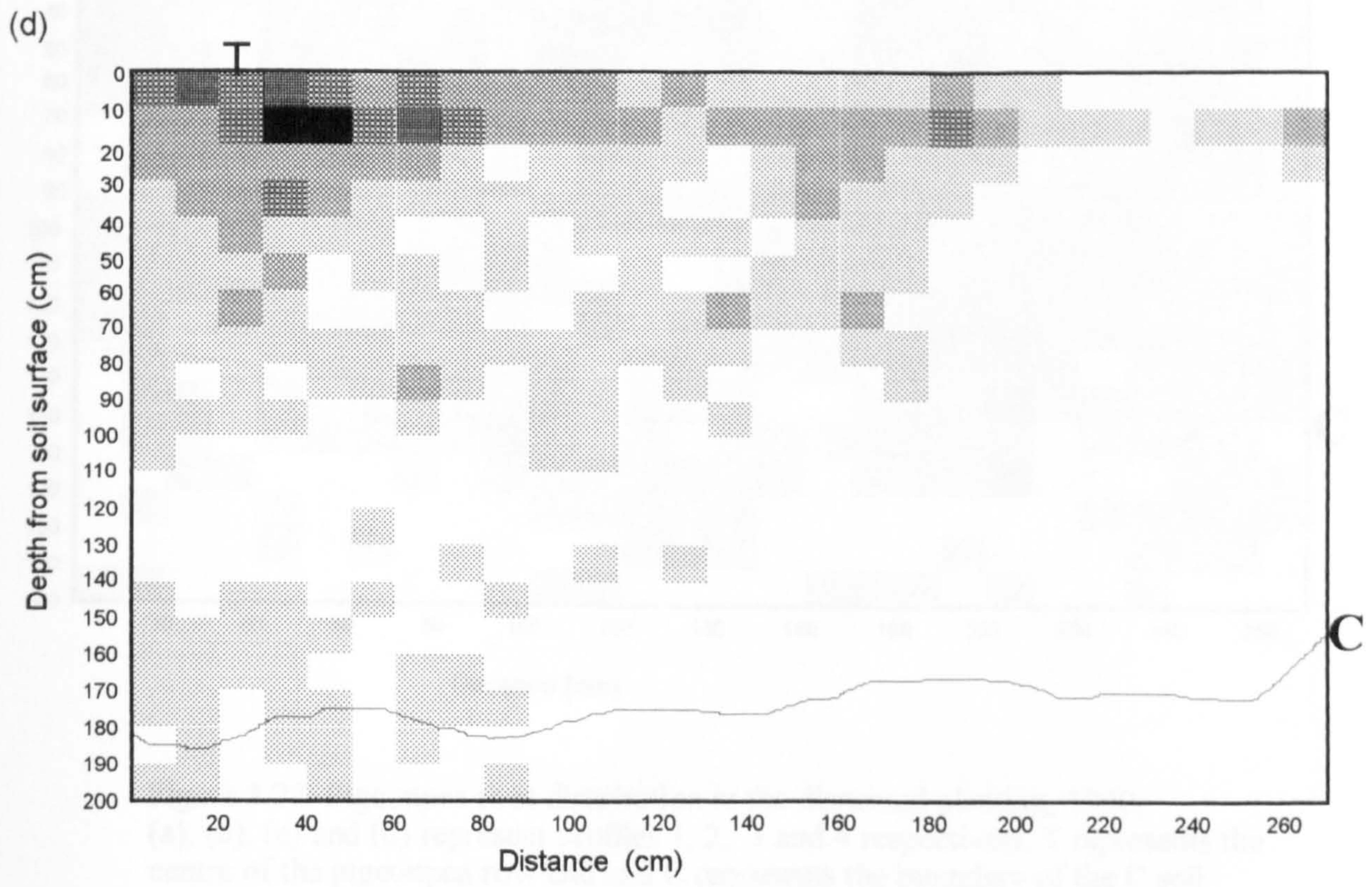
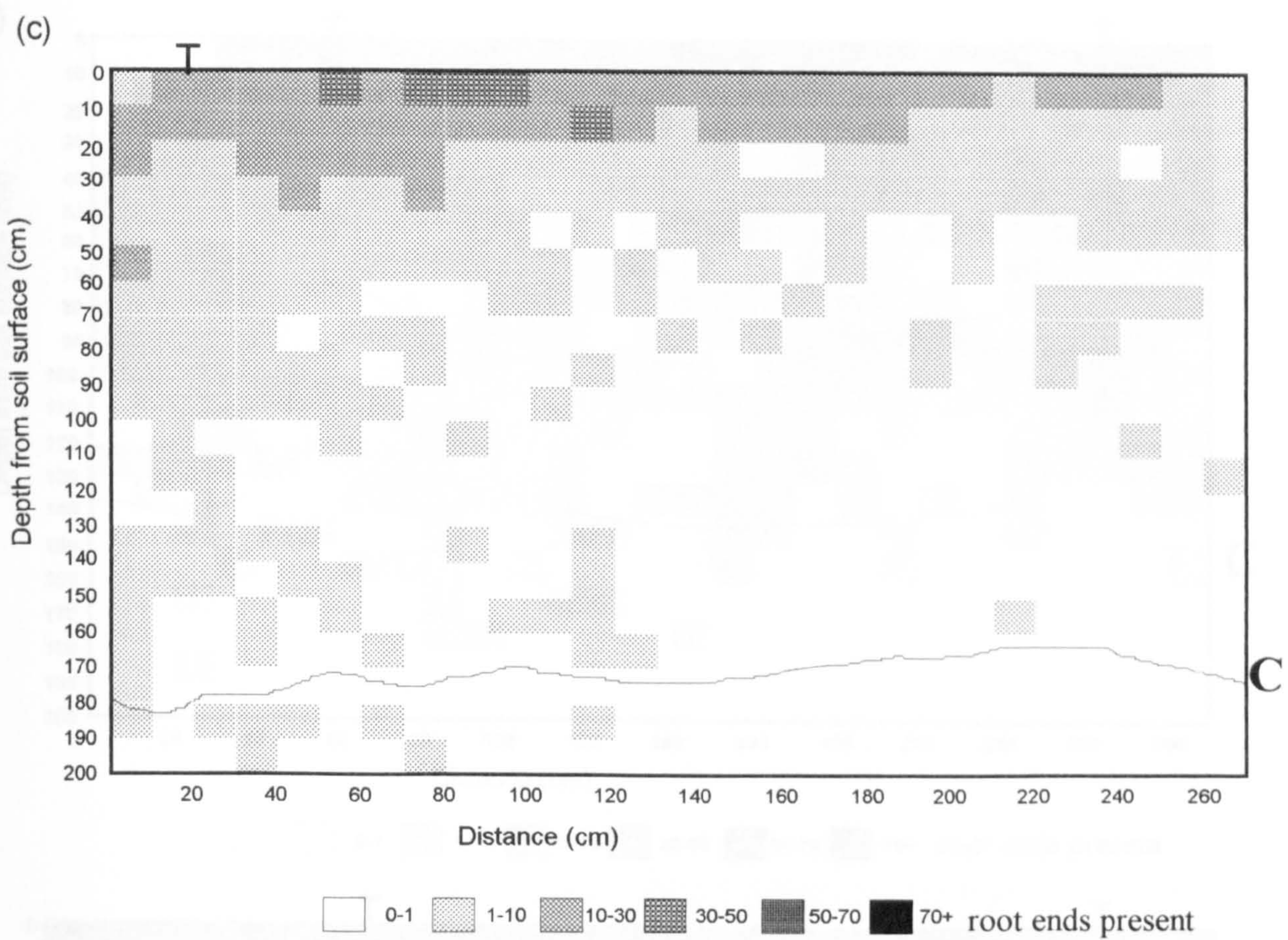


Figure 3.21: Pigeonpea root distribution in the line planting, 1990; (a), (b), (c) and (d) represent profiles 1, 2, 3 and 4 respectively, T represents the the centre of the pigeonpea row end and C denotes the boundary of the C soil horizon.



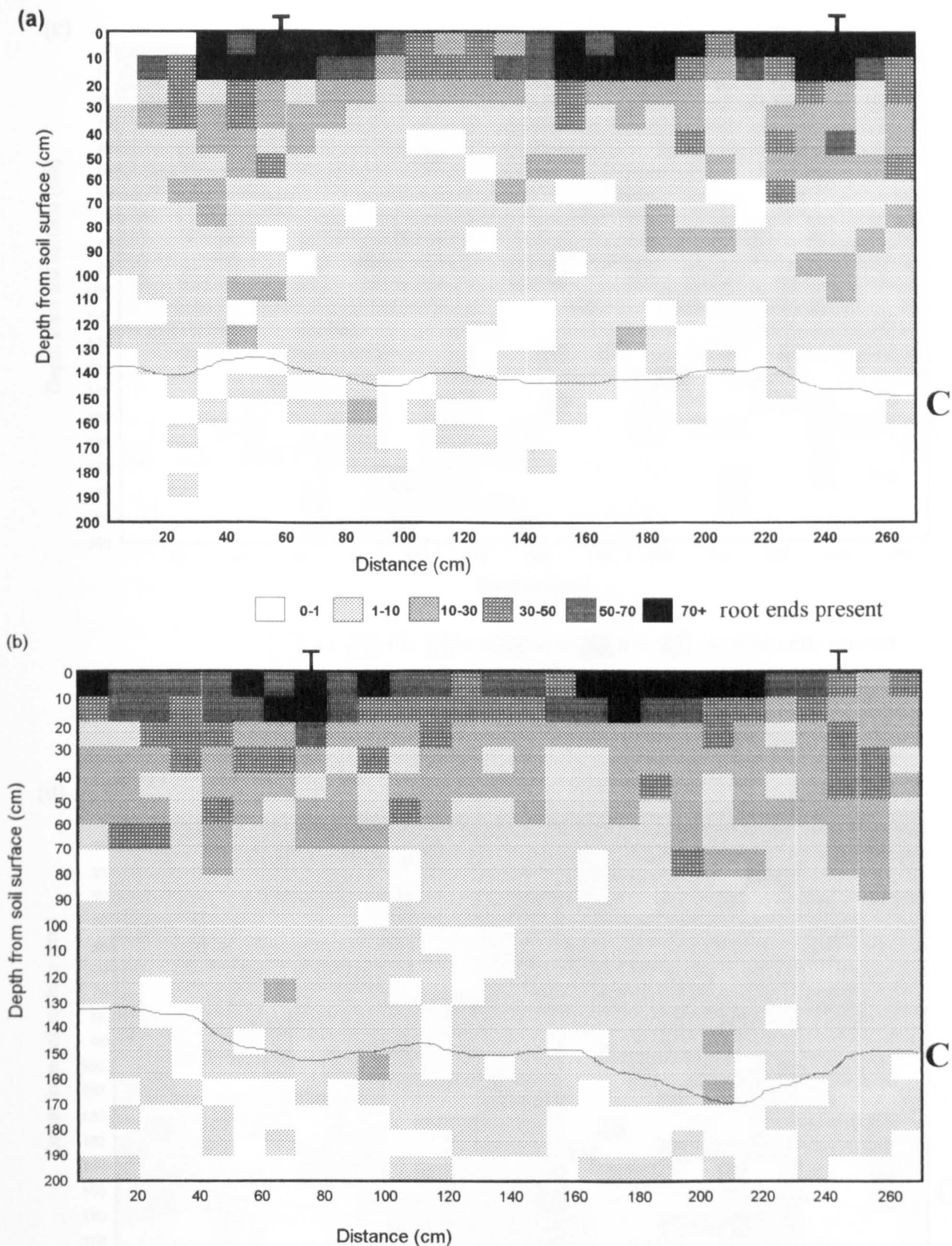
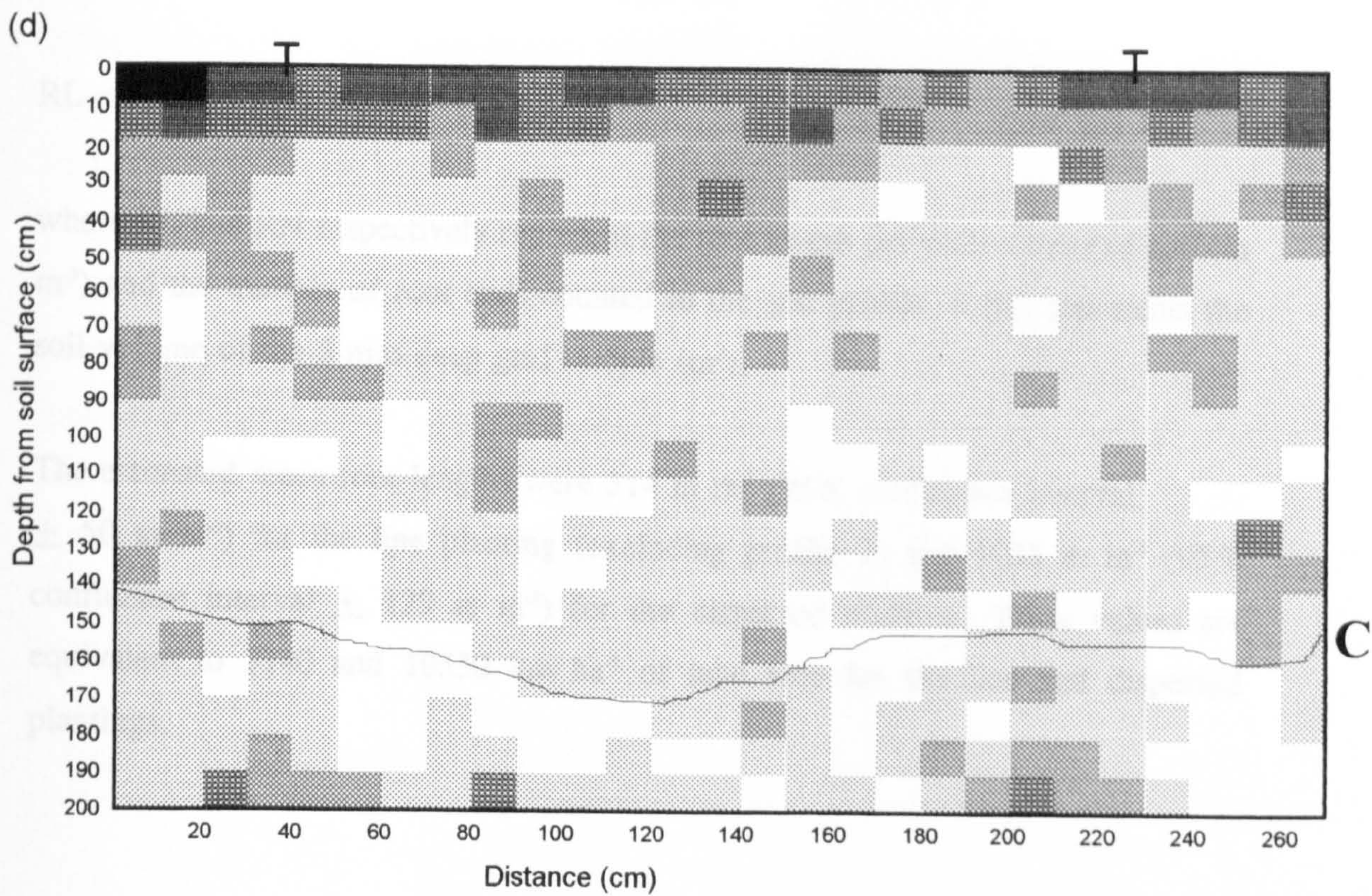
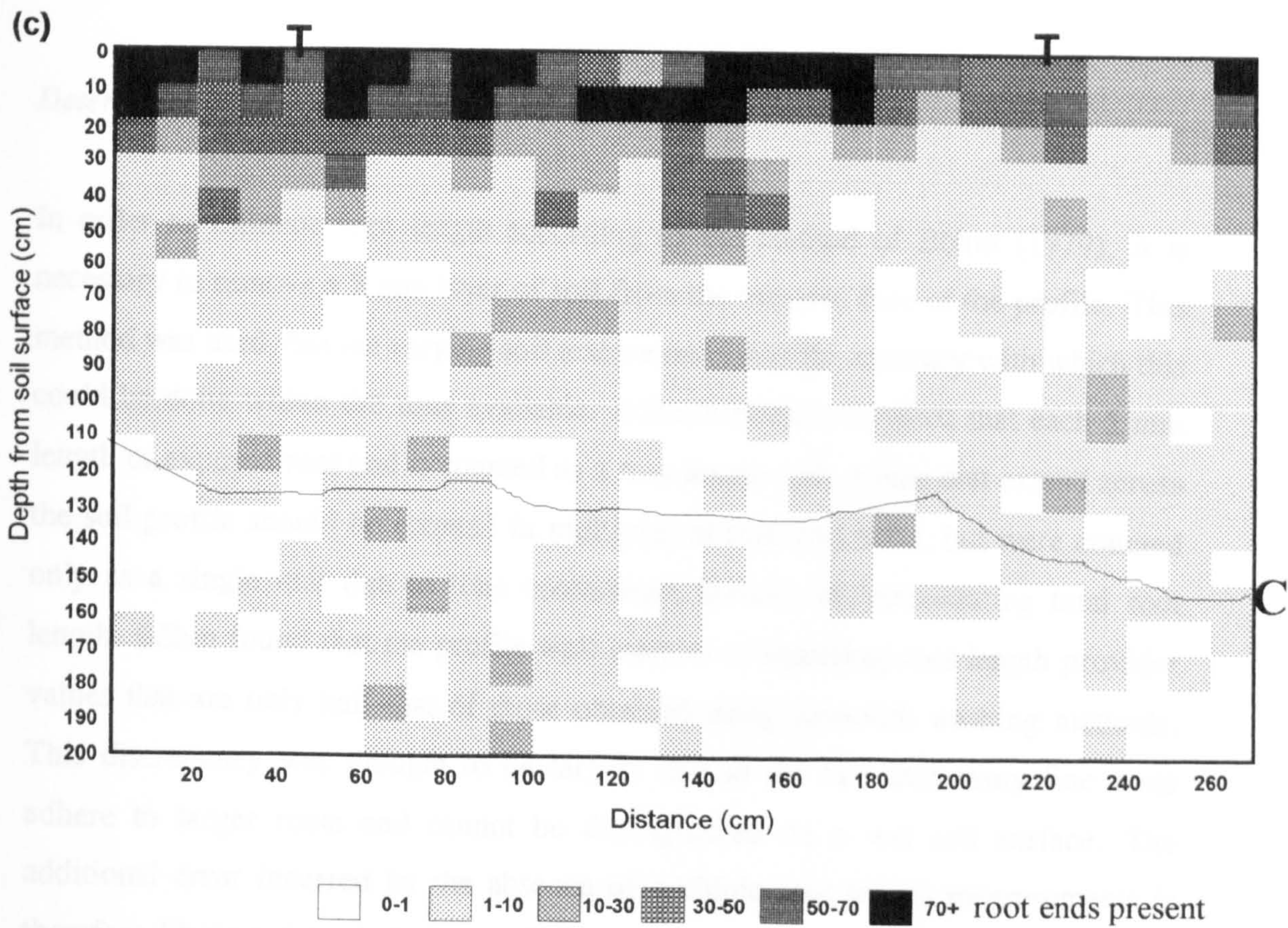


Figure 3.22: Pigeonpea root distribution in the dispersed planting, 1990; (a), (b), (c) and (d) represent profiles 1, 2, 3 and 4 respectively, T represents the centre of the pigeonpea row end and C represents the boundary of the C soil horizon.



Determination of root length

In order to estimate root length according to the method of Böhm (1979), it is necessary to remove a 5 mm layer of soil from the exposed face of the profile. This method was used, but the varying soil texture restricted the accuracy with which this could be done within the time available. Böhm's method requires that each 5 mm length of exposed root end is counted as a root length unit. Roots that extend across the soil profile should be counted in multiples of root end units, but were counted only as a single unit due to time constraints, thereby underestimating total root length. Böhm found that the profile wall method of assessing root length provides values that are only half that of those obtained using monolith washing methods. This discrepancy was thought to be largely due to the fact that many fine roots adhere to larger roots and cannot be distinguished on a wet soil surface. The additional error incurred by the absence of multiple root length measurements is therefore likely to be relatively small.

Root length for each profile was calculated as:

$$RL = (0.005 RN) 1/0.027 \quad \text{equation 3.1}$$

where RL and RN respectively represent the root length per unit volume of soil (m m^{-3}) and the number of root ends counted in the soil profile. 0.027 represents the soil volume of the 5 mm deep grid sample (m^3).

The estimated mean root lengths were 314 m m^{-3} (95% confidence interval $\pm 50 \text{ m m}^{-3}$) for the line planting (excluding profile 2) and 1055 m m^{-3} (95% confidence interval $\pm 129 \text{ m m}^{-3}$) for the dispersed planting. These values are equivalent to 3140 and 10550 km ha^{-1} of land area for the line and dispersed plantings.

Root diameter

The exposed root endings were placed in three categories according to their diameter, large (> 1 cm), medium (0.5-1.0 cm) and small (< 0.5 cm). The large and medium roots were confined to the top 30 cm of the profile in both treatments. In the horizontal plane, the large roots were all located within 50 cm of the pigeonpea stem in the line-planting but extended across the entire grid in the dispersed planting. The mean numbers of large roots present in the 5.4 m² grid area were 14 (standard deviation 4.2) and 5 (standard deviation 2.0) for the dispersed and line plantings. There were larger numbers of medium roots; 64 (standard deviation 21) for the dispersed planting and 21 (standard deviation 8) for the line planting. Small roots were distributed throughout the profile.

Vertical root distribution

Although there was extensive variation in the actual number of root ends present both within and between treatments, their vertical distribution was similar. The proportion of the total roots present within 10 cm depth increments is shown in Figure 3.23, and the 95 % confidence intervals are given in Table 3.31. Previous studies during the first year of pigeonpea growth have shown that approximately 70 % of the root biomass and 50 % of root length are located in the top 30 cm of the profile (Lawn and Troedson, 1990). The results presented here indicate that a similar situation applies during the second year of growth. Thus, 66 % (95 % confidence interval ± 11 %) of the total roots counted were present in the top 30 cm of the soil profile in the line planting and 62 % (95 % confidence interval ± 13 %) in the dispersed planting.

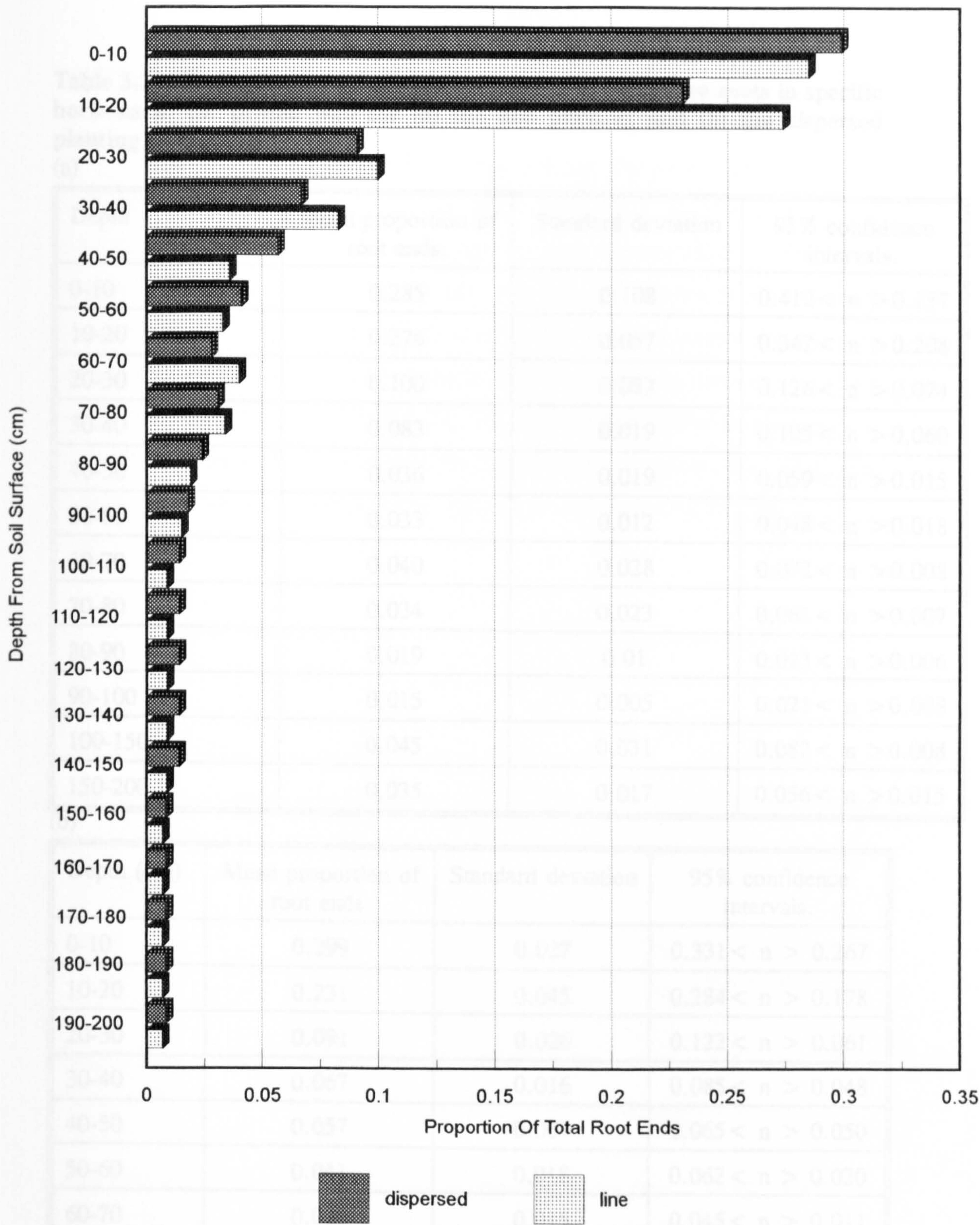


Figure 3.23: Vertical distribution of pigeonpea roots expressed in terms of the proportion of total root ends present in each 10 cm depth increment (treatment mean values, n=4).

Table 3.31: Treatment means for the proportion of pigeonpea roots in specific horizons in the profile wall for (a) the line planting and (b) the dispersed planting (n=4).

(a)

Depth	Mean proportion of root ends.	Standard deviation	95% confidence intervals.
0-10	0.285	0.108	0.412 < n > 0.157
10-20	0.274	0.057	0.342 < n > 0.208
20-30	0.100	0.022	0.126 < n > 0.074
30-40	0.083	0.019	0.105 < n > 0.060
40-50	0.036	0.019	0.059 < n > 0.015
50-60	0.033	0.012	0.048 < n > 0.018
60-70	0.040	0.028	0.072 < n > 0.008
70-80	0.034	0.023	0.061 < n > 0.007
80-90	0.019	0.01	0.013 < n > 0.006
90-100	0.015	0.005	0.021 < n > 0.008
100-150	0.045	0.031	0.082 < n > 0.008
150-200	0.035	0.017	0.056 < n > 0.015

(b)

Depth (cm)	Mean proportion of root ends	Standard deviation	95% confidence intervals.
0-10	0.299	0.027	0.331 < n > 0.267
10-20	0.231	0.045	0.284 < n > 0.178
20-30	0.091	0.026	0.122 < n > 0.061
30-40	0.067	0.016	0.085 < n > 0.048
40-50	0.057	0.007	0.065 < n > 0.050
50-60	0.041	0.018	0.062 < n > 0.020
60-70	0.028	0.015	0.045 < n > 0.011
70-80	0.031	0.008	0.040 < n > 0.022
80-90	0.024	0.010	0.035 < n > 0.012
90-100	0.018	0.007	0.026 < n > 0.010
100-15	0.070	0.022	0.096 < n > 0.043
150-200	0.043	0.045	0.096 < n >

Lateral root distribution

Several studies on Alfisols have indicated that, although the roots of pigeonpea may reach depths of 1.0 - 1.2 m (e.g. Gregory and Reddy, 1982), most roots are located in the top 30 cm of the profile, as is the case for most legumes (Squire, 1990). The relationship between pigeonpea root density and distance from the trees was closely examined for the top 30 cm of the soil profile. The sample variance for the mean number of roots present at specific distances from the pigeonpea was extremely high in both treatments examined (Table 3.32). On the basis that similar trends may have existed despite the differences in absolute values between profiles, the relationship between root number and distance from the tree was examined for each profile (Fig. 3.24).

For the line-planted pigeonpea, the number of root ends was plotted against distance from the tree over the range 0 - 250 cm, which spanned almost the entire distance to the mid-point between trees. Logarithmic, linear and exponential regression curves were fitted to the values for each profile. In all cases, an exponential decay curve fitted the values most closely (r^2 values of 0.65, 0.92, 0.76 and 0.77 for profiles 1 to 4 respectively). The basic equation to describe these exponential curves is as follows:

$$y = y_0 e^{-Qd} \quad \text{equation 3.2}$$

where Q is a constant, y the number of root ends in the top 30 cm of the profile at a distance d from the tree and y_0 the number of roots ends adjacent to the tree.

Table 3.33 shows the equations for the exponential decay curves fitted. Due to the difference in the absolute values of root number between profiles, the values for y_0 show considerable variability. The value of Q is an indicator of the rate of decrease in root number with increasing distance from the tree, confirming that profile 2 > profile 1 > profile 3 > profile 4. The Q values for profiles 1 to 3 are similar, whilst that for profile 4 is considerably lower.

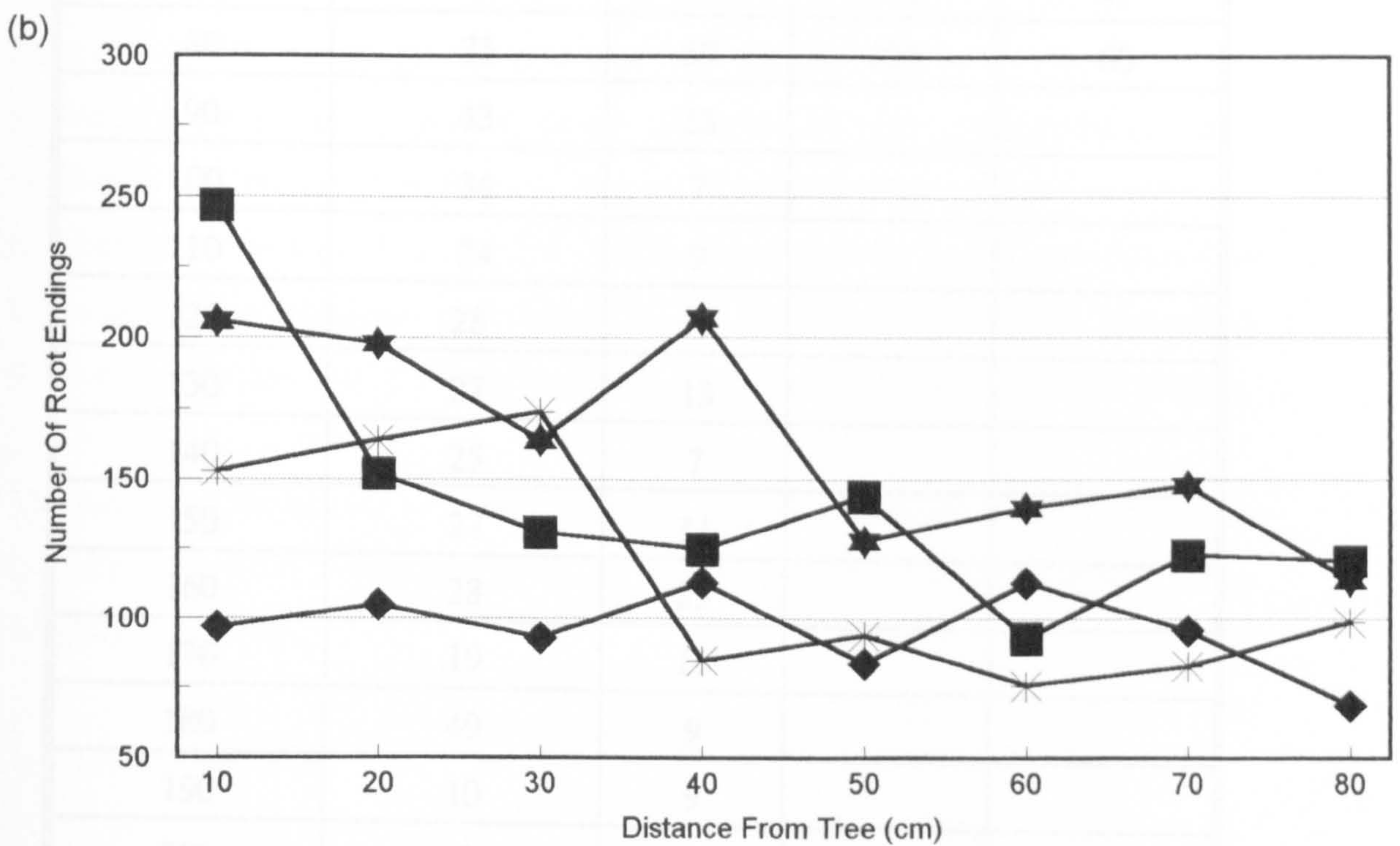
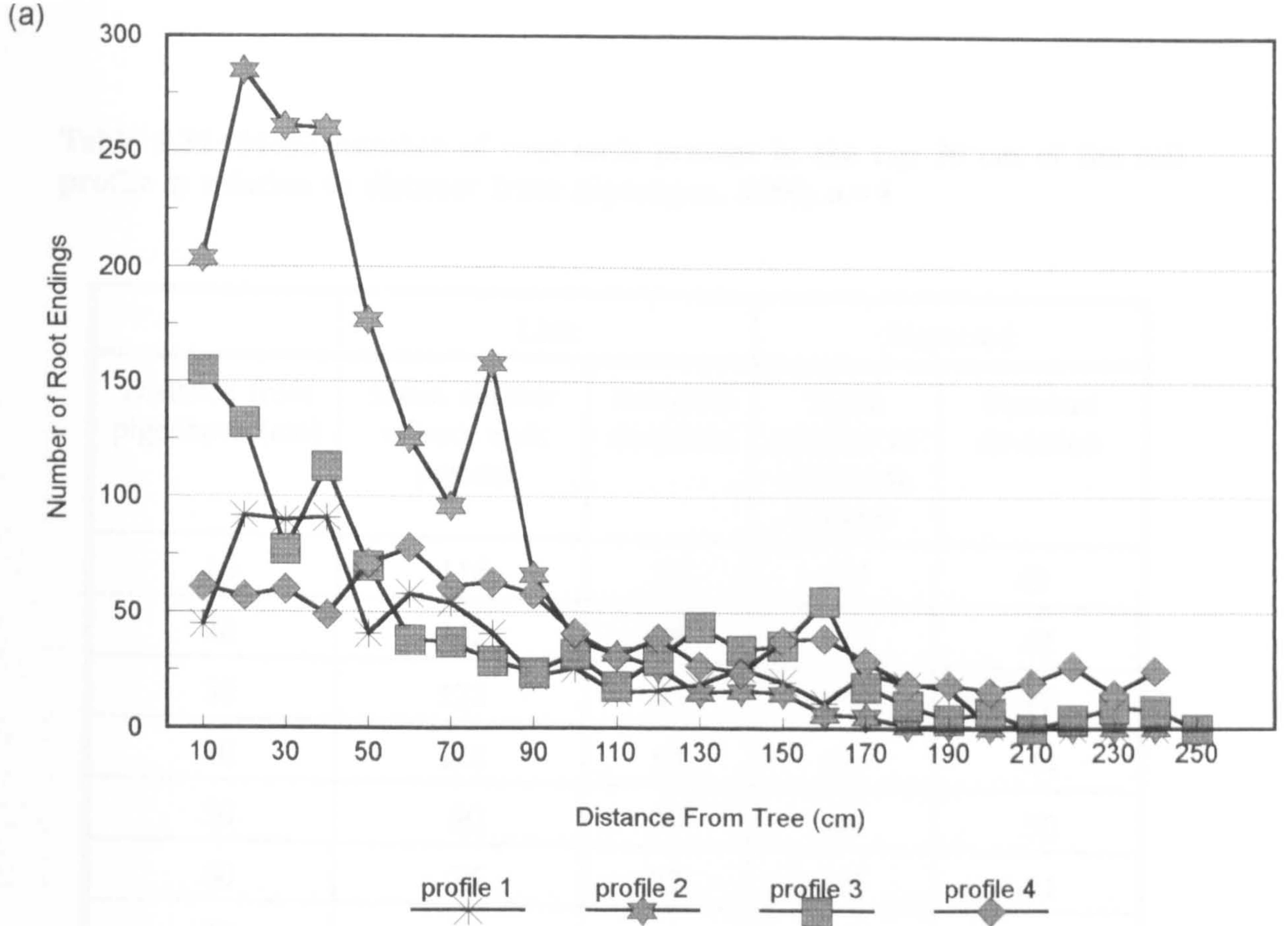


Figure 3.24: Relationship between the number of pigeonpea root endings in the top 30 cm of the soil profile and distance from the tree in (a) the line planting and (b) the dispersed planting (N.B. Note the very different distance scales on the x axis).

Table 3.32: Mean number of root ends present in the top 30 cm of the soil profile in relation to distance from pigeonpea, 1990; n=4

	Line		Dispersed	
Distance from pigeonpea (cm)	Mean number of root ends present	Standard deviation	Mean number of root ends present	Standard deviation
10	116	76	157	63
20	142	100	153	47
30	122	93	136	47
40	128	92	131	44
50	90	60	111	50
60	75	37	105	31
70	62	25	112	47
80	73	59	103	60
90	43	23		
100	34	7		
110	24	9		
120	28	10		
130	27	13		
140	25	7		
150	27	11		
160	28	23		
170	19	10		
180	49	9		
190	10	9		
200	6	7		
210	5	10		
220	8	13		
230	6	7		
240	8	12		

From these data, it seems reasonable to conclude that the relationship between root number in the top 30 cm of the soil profile and distance from pigeonpea trees in the line planting exhibited an exponential decay. However, it would be misleading to produce a general equation to describe the precise nature of this relationship due to the substantial variation between replicate profiles. The evidence suggests that the observed trend of decreasing groundnut productivity with increased proximity to pigeonpea was at least partly attributable to differences in below-ground competition.

Table 3.32 shows mean root numbers in relation to distance from the pigeonpea in the dispersed planting and the large standard deviations of the means. Due to the extensive variability between samples, the trends for each profile were examined individually, as in the line planting. Because of the closer spacing of rows within the dispersed planting, two pigeonpea trees were included in each profile, and measurements extended from 0 - 90 cm from each pigeonpea stem. Most roots were found within 0-10 cm of the tree in all samples, but the trend of decreasing root number with distance from the tree was less marked than in the line planting, probably because of the greater lateral extension of roots of individual trees, combined with the fact that the root systems of trees in adjacent rows would have overlapped in many parts of the soil profile. Thus, there is no clear evidence that below-ground competition contributed to the observed variation in groundnut productivity at distances greater than 10 cm from the tree in the dispersed planting.

The extensive lateral root extension observed in both treatments confirms the need for large plot sizes and border areas in agroforestry experiments, such as those adopted in this trial.

3.5.6 Plant mortality

Little mortality of pigeonpea was observed prior to the second grain harvest in January 1991, but substantial mortality had occurred in all treatments by the end of the experiment in April 1991 (Table 3.34). At the January 1991 harvest, all trees were left with a small number of green shoots but many produced little or no

Table 3.33: Equations describing the exponential decay curves of root end number in the top 30 cm of the soil profile in relation to distance from pigeonpea trees in the line planting; y represents the number of root ends and d distance from the tree

	Exponential equation	r ²
Profile 1	$y = 125 e^{-0.02 d}$	0.65
Profile 2	$y = 751 e^{-0.03 d}$	0.92
Profile 3	$y = 130 e^{-0.013 d}$	0.76
Profile 4	$y = 78 e^{-0.006 d}$	0.77

Table 3.34. Treatment mean values for plant mortality (%) in pigeonpea, March 29 1991. SED represents the standard error of difference for comparing treatment means and *, ** and * denote significant differences at p < 0.05, p < 0.01 and p < 0.001 respectively; ns indicates no significant difference between treatments**

Mortality (%)	Sole	67
	Line	47
	Dispersed	37
Treatment mean square		933.3
Residual mean square		72.9
SED		4.93
Line x dispersed		ns
Line x sole		**
Dispersed x sole		***

Table 3.35: Summary of the soil analysis carried out on samples taken on February 13 1991; means of two bulked soil samples. EC represents exchangeable cations.

Depth (cm)	pH	EC (mmhos cm ⁻¹)	P (ppm)	K (ppm)	Zn (ppm)	Fe (ppm)	Mn (ppm)
0-15	6.19	0.12	6.13	55	0.41	17.3	32.2
15-30	6.96	0.15	3.50	59	0.93	15.7	28.8

regrowth, and died shortly afterwards. Mortality was highest in the sole pigeonpea, in which 67 % of the plants present after thinning died. The 37 and 47 % mortality values for the dispersed and line plantings were significantly lower than in the sole treatment ($p < 0.05$ and 0.001 respectively). The greater mortality in the sole stand resulted from the death of some trees soon after the reduction in plant population on June 1 1990; there was no obvious explanation, although some damage may have occurred during the thinning process.

The generally high mortality observed in 1991 may have occurred because insufficient stored moisture remained available to sustain growth throughout the dry season of the second year. This possibility is considered further in the context of the overall water balance in Section 4.3.3. Pigeonpea is also susceptible to nematode attack, which can reduce plant vigour and cause death. The two major nematode pests associated with pigeonpea roots in Andhra Pradesh are *Heterodera cajani*, the cyst nematode, and *Meloidogyne incognita*, the root knot nematode (Reddy, Sharma and Nene, 1990). Pigeonpea roots were examined in the field by ICRISAT pathologists for evidence of nematode activity, but none was apparent.

Soil samples were also taken to investigate the possibility that nutrient disorders may have contributed to the high pigeonpea mortality, even though there were no visible symptoms of mineral deficiency on the remaining foliage. Six random soil samples were taken from replicates 1 and 2 of the sole pigeonpea plots at 0-15 cm and 15-30 cm depths. The samples were then bulked for each depth and analysed by the ICRISAT Soil Science Department. A summary of the results obtained is given in Table 3.35. constraints on time and resources prohibited examination of samples from greater depth or analysis of nitrogen content.

There have been relatively few investigations of mineral nutrition in pigeonpea, most of which have been confined to pot studies. Responses to both phosphate and potassium applications have been observed in Andhra Pradesh and, although there are few recorded effects of trace elements, field studies suggest that pigeonpea responds positively to zinc (Johansen, 1990). However, some reports suggest that

pigeonpea is generally less responsive to fertilisers than other comparable crops in the semi-arid tropics (Johansen, 1990).

Pigeonpea is known to tolerate a broad range of soil pH, with growth being reasonable within the pH range 5.0 - 8.5 (Edwards, 1981); the values for the present field site of 6.2 and 7.0 for the 0-15 and 15-30 cm depths fall well within this range. Similarly, an acceptable level of DTPA-extractable zinc for pigeonpea growth in the top 30 cm of soil is 0.5-0.7 ppm in the top 30 cm of the soil (Burford, pers. comm.). The values obtained for the 0-15 and 15-30 cm depths were 0.41 and 0.93 ppm, producing an acceptable mean value of 0.67 ppm. All other variables measured were within acceptable limits for successful pigeonpea growth. However, it is important to note that there are numerous potential interactions both between individual nutrients, and also between individual nutrients and other growth-limiting factors, which make meaningful comparisons difficult. For instance, the relatively dry soil conditions during the post rainy season period may have limited the availability of the nutrients present.

3.6 ANNUAL PRODUCTIVITY

Table 3.36 shows the treatment mean values for pod, fodder and total biomass production of groundnut at final harvest in 1989 (Table 3.36a) and 1990 (Table 3.36b). The pod yields for sole groundnut were similar in both years, but fodder production at final harvest was lower in 1990 due to foliar disease. At final harvest in 1990, the treatment mean values for pod dry weight were ranked in the order sole > line > dispersed planting, and the differences were highly significant ($p < 0.001$).

Biomass production for each of the treatments examined in 1989 and 1990 is shown in Tables 3.37 and 3.38. In 1989, the sole pigeonpea produced 8.16 t ha^{-1} , 1.4 fold the dry matter production of the sole groundnut, and approximately 82 % more than in the line and dispersed treatments. In 1990, total biomass production in the dispersed planting was double that in 1989 (9.13 t ha^{-1}) due to the rapid growth of the pigeonpea and was 63 % greater than the line treatment. The productivity of the

Table 3.36: Dry matter production by groundnut at final harvest in (a) 1989 and (b) 1990; *, ** and * denote significant effects at $p < 0.05$, $p < 0.01$ and $p < 0.001$; ns indicates no significant difference**

(a)1989

	Pod dry weight (t ha ⁻¹)	Fodder dry weight (t ha ⁻¹)	Total dry weight (t ha ⁻¹)
Sole	1.20	2.19	3.39
Line	1.05	1.85	2.90
Dispersed	1.12	1.91	3.03
Treatment mean square	0.02	0.08	0.27
Residual mean square	0.05	0.10	0.11
SED	0.05	0.10	0.19
Line vs dispersed	ns	*	ns
Line vs sole	*	*	*
Dispersed vs sole	*	ns	ns

(b)1990

	Pod dry weight (t ha ⁻¹)	Fodder dry weight (t ha ⁻¹)	Total dry weight (t ha ⁻¹)
Sole	1.18	1.34	2.52
Line	0.94	0.88	1.82
Dispersed	0.64	1.04	1.68
Treatment mean square	0.004	0.156	0.191
Residual mean square	0.003	0.023	0.014
SED	0.03	0.09	0.07
Line vs dispersed	***	ns	***
Line vs sole	***	*	***
Dispersed vs sole	***	**	***

Table 3.37: Treatment mean values for total system dry matter production between July 3 1989 and January 31 1990

Treatment	Pigeonpea dry matter at harvest (t ha ⁻¹)		Groundnut dry matter at final harvest (t ha ⁻¹)		Treatment total dry matter (t ha ⁻¹)
	Grain	Fuel and fodder	Pod	Fodder	
Sole pigeonpea	1.16	7.00			8.16
Sole groundnut			1.20	2.19	3.39
Line	0.27	1.20	1.05	1.85	4.37
Dispersed	0.26	1.30	1.12	1.91	4.59

Table 3.38: Treatment mean values for total system dry matter production between January 31 1990 and April 3 1991

Treatment	Pigeonpea dry matter at harvest (t ha ⁻¹)		Groundnut dry matter at final harvest (t ha ⁻¹)		Treatment total dry matter (t ha ⁻¹)
	Grain	Fuel and fodder	Pod	Fodder	
Sole pigeonpea	0.74	4.84			5.58
Sole groundnut			1.18	1.34	2.52
Line	0.38	3.40	0.94	0.88	5.60
Dispersed	0.69	6.76	0.64	1.04	9.13

sole pigeonpea, which was clearly now at a suboptimal population, was only 5.58 t ha⁻¹.

3.7 DISCUSSION

3.7.1 Sole crop growth and development

3.7.1.1 *Groundnut*

The sole crop pod yields (1.2 t ha⁻¹ in 1989 and 1990) are typical of the values obtained at ICRISAT Center during the rainy season, and are intermediate between the 2.9 t ha⁻¹ mean for the high input groundnut production systems adopted in the USA and the 0.8 t ha⁻¹ mean yield from rainfed systems in developing countries (Gibbons, 1986).

A comparison of growth and development in sole groundnut in 1989 and 1990 provides an indication of the extent to which seasonal variation in environmental conditions may have contributed to the overall differences in productivity in the line and dispersed treatments. Despite the similar sole crop pod yields, there were considerable differences in TDM between the two years from 40 DAS onwards. Maximum TDM was reached at 80 DAS in both years, but was 4.16 t ha⁻¹ in 1989 as compared to only 2.91 t ha⁻¹ in 1990. This difference may have been attributable to the development and maintenance of a more extensive canopy in 1989 when L was consistently greater, reaching a maximum of 2.69 at 70 DAS as compared to only 1.75 at 60 DAS in 1990. Fodder production at final harvest was 1.34 t ha⁻¹ in 1990, 39 % less than in 1989 (Table 3.36). The earlier decline in L in 1990 and the associated reduction in TDM were attributable to a severe attack of foliar disease. The rate of leaf expansion may be reduced during a mild drought (Squire, 1990), and this may have accounted for the lower L in 1990, prior to the onset of foliar disease (Fig. 3.9).

Because the lower TDM at final harvest in 1990 was entirely attributable to effects

on fodder production, the harvest index (HI, expressed as the weight of pods divided by the total above-ground biomass) was considerably higher than in 1989 (0.35 and 0.47 in 1989 and 1990 respectively).

Fewer pods were initiated in 1989 when rainfall was relatively high (838 mm between groundnut sowing and harvest). The possibility that mild water stress limited vegetative growth in 1990, reducing mainstem height relative to 1989 and enabling more pegs to reach the soil, cannot be discounted, but unfortunately the measurements needed to verify this hypothesis were not made. Stirling (1988) has shown that early season soil water deficits decrease mainstem height in groundnut and it is possible that a similar effect occurred in 1990, when rainfall was lower, allowing more pegs to reach the soil and produce pods. Very little rainfall was received during the early vegetative phase in 1990 (47 mm from 7-20 DAS), but this was followed by a period of substantial rainfall up to 50 % flowering (198 mm from 21-36 DAS). In 1989 a similar amount of rainfall was received during the 15 days preceding 50 % flowering (186 mm from 20-35 DAS), but total rainfall during the vegetative phase was considerably higher (386 mm from 7-35 DAS).

Pod development is dependent on current rather than stored assimilates (Stirling, 1988). Rainfall, incident radiation and temperature during the pod filling period were similar in both years (Figs. 3.1-3.4), indicating that the major limitation on pod filling in 1990 was probably canopy size and duration. Thus, if foliar disease had not considerably reduced leaf area during the pod filling period in 1990, pod yield might have exceeded that in 1989.

3.7.1.2 *Sole pigeonpea*

Phenology

In 1989, 50 % flowering occurred in pigeonpea at 115 days and maturity at 212

days in all treatments (Table 3.19). The timing of these phenological stages was very similar to those reported by Odongo *et al.*, (unpublished), who observed flowering at 129 DAS and maturity at 194 DAS, when ICP-8094 was planted at ICRISAT in July 1988. However, in another study at ICRISAT, Daniel and Ong (1990) concluded that ICP 8094 is a typical long duration pigeonpea, flowering after about 195 days and reaching maturity at about 250 days. As pigeonpea is a quantitatively short day species, a delay in planting tends to decrease the time to flowering (Odongo *et al.*, 1995). The earlier flowering and maturity observed in the current study are likely to have been at least partly due to the later planting date (July 3, as opposed to June 10 in the study of Daniel and Ong). There are also likely to have been other contributory factors. For example, pigeonpea phenology is responsive to both temperature and day length (Saxena and Sharma, 1990) and a marked annual variation in time to flowering can be induced by differences in temperature. Other factors such as waterlogging can also have a major influence on phenology (Odongo *et al.*, 1995).

Productivity

The potential annual productivity of perennial pigeonpea at ICRISAT Center is in excess of 15 t ha⁻¹ when water is not limiting, comprising approximately 2 t of grain, 3 t of leaf litter, 9 t of stem and 1 t of crop residue (Daniel and Ong, 1990). In the present study, the dry matter production of sole pigeonpea in January 1990 (8.2 t ha⁻¹ TDM and 1.2 t ha⁻¹ grain yield) compared favourably with other rain fed experiments using ICP 8094 at ICRISAT. Ranganathan (1993) reported TDM production values at the first grain harvest of 6.6 and 6.8 t ha⁻¹ for populations of 12 and 6 plants m⁻² respectively, and a grain yield of 0.9 t ha⁻¹ in both cases. Daniel (1989) obtained grain yields of 2 t ha⁻¹ at first harvest when ICP 8094 was grown at a population of 10 plants m⁻² on a vertisol. However, grain yields from traditional pigeonpea cropping systems are relatively low. For example, in a study involving six villages in Andhra Pradesh, Ryan *et al.* (1984) found that 66 % of households grew pigeonpea, mainly as an intercrop, and produced an average grain yield of about 130 kg ha⁻¹.

Dry matter production for the harvests taken during the dry season in April and May 1990 was low (0.32 t ha^{-1}), probably because of severe intraspecific competition in the sole pigeonpea plots. In contrast, Daniel (1990) obtained 5.8 t ha^{-1} from dry season cuts in 1989, when ICP 8094 was grown at a population of 10 plants m^{-2} on a vertisol at ICRISAT Center. The higher available water holding capacity of vertisols (150-250 mm) as compared with alfisols (60-100 mm) may be the major reason for the relatively high dry season productivity in Daniel's study.

The reduction of the sole pigeonpea population to $0.44 \text{ plants m}^{-2}$ at the beginning of the rainy season in 1990 was followed by a marked increase in the growth rate of individual trees. Thus, the fodder cut on August 8 1990 (0.72 t ha^{-1} of dry matter) was followed by continued rapid growth to produce a total TDM yield at the final grain harvest of 2.1 t ha^{-1} . Grain yield was 36 % lower in 1991 than in 1990 (0.72 vs. 1.16 t ha^{-1}), resulting in a harvest index (grain yield expressed as a percentage of dry matter above 50 cm height at the January harvest) of 14 % in 1990 and 24 % in 1991. As there is little variation in grain number per pod or in the individual grain weight, grain yield per plant is largely determined by the numbers of branches per plant and pods per branch (Daniel, 1989), both of which are reduced at high populations (Lawn *et al.*, 1990). It is well established that pigeonpea pods are borne mainly on branches exposed to direct sunlight (Daniel, 1989), with the result that fewer pods are produced at high populations where there is extensive mutual shading between plants. This phenomenon may well have contributed to the lower harvest index recorded at the January 1990 harvest.

In the first year, the sole crop yield was comparable with other studies using ICP 8094 at ICRISAT Center (Daniel and Ong, 1990), but biomass production was disappointing in the second year. Previous studies (Daniel *et al.*, 1991; Odongo *et al.*, 1995) have shown that the growth of perennial pigeonpea during the first year is slower than annual crops, but that during the rainy season of the second year growth is more vigorous than that of annual crops. Rao and Willey (1983) observed a consistent increase in stem yield (from approximately 4 to 7 t ha^{-1}) when sole

pigeonpea (ICP-1) was grown as an annual at populations between 1.5 and 13 plants m², although there was no apparent increase in seed yield above 4 plants m². This observation provided the rationale for assuming that the optimum population for TDM production by sole pigeonpea during its first year of growth is relatively high. The population was reduced in June 1990 because preliminary observations on perennial pigeonpea indicated that the optimum population for the second year was considerably lower (Ong, pers. comm.), and that maintaining high populations would result in extensive mortality. However, Odongo *et al.* (1995) maintained a sole pigeonpea population of ICP 8094 at a density of 8 plants m² over a two year period between June 1988 and May 1990 at ICRISAT. Total dry matter production up to June 1989 was approximately 7 t ha⁻¹ and increased to 18 t ha⁻¹ in the second year. Ranganathan (1993) subsequently showed that there were no consistent differences in TDM production, in either the first or second year after sowing, when ICP-8094 was sown in sole stands at densities ranging between 1.5 and 12 plants m². This evidence suggests that in the present study TDM production by the sole crop after thinning was lower than might have been expected if a similar population had been established initially in 1989. The ability of the sole crop to capture and utilise resources was reduced after thinning until the remaining trees were able compensate for those that had been removed. Thus, a period of several months was required before the trees adjusted to the reduced intraspecific competition, thereby reducing total dry matter accumulation during the 1990 rainy season. The lower productivity of the sole pigeonpea in 1990-91 has important consequences when assessing the yield advantages of the line and dispersed systems.

3.7.2 Tree-crop interactions

3.7.2.1 *Line planting*

Groundnut

Like medium duration genotypes, perennial pigeonpea develops slowly in the first year of growth and is often less competitive than the annual crop component of

intercropping systems (Daniel and Ong, 1990). For this reason, there was little reduction in groundnut yield in the line planting as compared to the sole crop in 1989. Previous studies have found that there is no loss of groundnut yield at higher pigeonpea populations; for example, Willey *et al.* (1986), working with medium duration pigeonpea, found that overall biomass was increased when pigeonpea was grown at higher populations than the traditional 8-20 rows of groundnut for each row of pigeonpea, although groundnut yield decreased at high pigeonpea populations. Odongo *et al.* (1995) also reported that groundnut yields were 62-68 % of the sole crop in the first year in a 1:4 perennial pigeonpea:groundnut planting arrangement, but were only 10-12 % of the sole crop in the second year. In many traditional systems, major reductions in groundnut yield are unacceptable. One objective of the present study was to establish a line planted treatment based on traditional systems, that provided fodder during the dry season, but required minimal changes in crop husbandry. If a higher pigeonpea population had been established in the current study in 1989, frequent pruning of the pigeonpea would probably have been required in 1990 to maintain an acceptable groundnut yield.

There is a possibility that competition from the groundnut may have reduced biomass production by pigeonpea in the line planting in 1989, as reported by Odongo *et al.* (1995). However, because the sole pigeonpea crop was not established at the same population, there was no comparable sole stand with which to compare productivity.

In 1990, there was a 20 % reduction in treatment mean pod yield for groundnut as compared with the sole crop; this was entirely due to lower productivity at location Lmax. The rate of leaf area development was lower at Lmax than at positions Lmed, Lmin or in the sole crop, although there was no difference in canopy duration. This contrasts with the findings of Stirling *et al.* (1990) who shaded groundnut during reproductive development and found that canopy duration was reduced relative to the unshaded control, but that there was no change in the rate of canopy development. Surprisingly, there was no significant difference in specific leaf area (SLA) between sampling positions in the line planting, or between any of these and the sole crop in the present study, since Stirling (1990) found that the leaves were significantly

thinner when groundnut was shaded throughout reproductive growth, than in the unshaded control.

Although there were similar numbers of small pods at all three sampling locations within the line planting, greater numbers of large pods were produced at positions Lmed and Lmin. This may have occurred because fewer pegs were produced at Lmax, rather than because pod initiation was delayed or stopped, as previous studies have shown that shading reduces flower and peg production (Farnham *et al.*, 1986). However, Stirling *et al.* (1990) found that stem height was significantly increased in shaded groundnut plants, which may have reduced the number of pegs able to reach the soil and hence the number of pods initiated. In addition, the possibility that similar numbers of pods were initiated at Lmax but that a smaller proportion were filled cannot be discounted because numerous pods appeared and developed into the large size category over consecutive 10 day harvest intervals. Not only was the total number of pods greater at Lmed and Lmin, but the rate of increase in the ratio of large:small pods between 50 and 80 DAS was higher than at Lmax (Fig. 3.14), indicating that a slower rate of pod fill also contributed to the lower final pod dry weight at Lmax. At 80 DAS, a smaller proportion of TDM was attributable to the pods (Table 3.15) at position Lmax and mean pod weight was lower (0.3 g pod^{-1}) than at positions Lmed and Lmin (0.5 g pod^{-1}). However, although the mean rate of pod growth was slower, the duration of pod fill was prolonged at Lmax. Consequently, the final partitioning of dry matter to pods was unaffected by proximity to the pigeonpea, and by 100 DAS the mean weight per pod was similar at all locations (0.5 g pod^{-1} at Lmax and Lmed and 0.6 g pod^{-1} at Lmin). As final dry matter partitioning was unaffected, it is likely that the lower pod yield resulted largely from a reduction in net assimilation at Lmax. By initiating fewer pods, the plants at Lmax were able to produce full size, reproductively viable pods at harvest despite their relatively limited supply of assimilate. The proportion of mature pods at the various sampling positions was not recorded at final harvest. However, although the proportion of large pods at Lmax was considerably lower up to 80 DAS, the continued increase in pod biomass at Lmax resulted in similar fractions of large pods at positions Lmax, Lmed, Lmin and in the sole crop at 100 DAS (81,

83, 76 and 76 % respectively). If the plants at Lmax had continued to partition biomass to the pods beyond 100 DAS, a higher proportion of mature pods might have been recorded for this sampling position. Stirling *et al.* (1990) reported that a significantly higher proportion of pods reached maturity in shaded groundnut plants.

Stirling *et al.* (1990) also found that fewer pods were initiated when a groundnut crop was shaded during reproductive development but, in contrast to the current study, this was due to a shorter duration of the period of rapid pod development since the rate of pod initiation was not reduced. Stirling's work was conducted using bamboo screens that intercepted 46 % of the incident radiation between 40 DAS and final harvest, whereas in the current experiment the groundnut was shaded by the pigeonpea canopy throughout the growing season. The implications of the degree and duration of shading on groundnut growth and development are discussed in Section 4.4.1. The presence of the pigeonpea canopy may also have modified the microclimate experienced by the groundnut and/or available soil moisture, thereby complicating the effects of shading by pigeonpea on groundnut growth and development. The combined effects of microclimatic modification and competition for light and water on growth and development in groundnut have previously been examined in intercropping systems. For example, Mathews *et al.* (1991), working with a sorghum/groundnut intercrop grown during the post-rainy season with infrequent irrigation, found that, although biomass accumulation was lowest in groundnut rows closest to the sorghum, leaf and pod numbers and harvest index were significantly higher in the most shaded row. In this case, water rather than light was the determining resource. This study concluded that the biomass of groundnut was reduced by aggressive competition from the sorghum for water, but that shading of the groundnut influenced developmental processes and biomass partitioning beneficially by reducing soil and tissue temperatures and maintaining more favourable plant water relations. However, Ong *et al.* (1991c) concluded that differences in soil and leaf temperature between sole and intercropped groundnut are likely to have a negligible influence on groundnut development or dry matter partitioning during the rainy season at Hyderabad, while Stirling (1988), working in the post-rainy season, found that the timing of rainfall and the availability of

water had a much greater influence on dry matter partitioning in groundnut than microclimatic modifications in intercropping systems. These findings are considered further in relation to resource partitioning and microclimatic conditions in Section 4.4.

Between 30-80 DAS, the rate of increase in TDM was significantly higher at Lmed and Lmin than in the sole crop, suggesting that microclimatic modifications resulting from the presence of pigeonpea increased net assimilation at these locations. Between 60-80 DAS, the total number of pods initiated and pod dry weights were significantly higher at positions Lmed and Lmin than in the sole crop, as were the rates of increase in the ratios of large to small pods, indicating that the rates of pod initiation and pod fill were greater than in the sole crop. The mean pod weights at 80 DAS were 0.3, 0.4 and 0.5 g pod⁻¹ for the sole crop, Lmed and Lmin respectively. However, the duration of pod fill was apparently longer in the sole crop, with the result that by 100 DAS there was no significant difference in total pod dry weight, dry matter partitioning or mean pod weight (0.4, 0.5 and 0.6 g pod⁻¹ in the sole crop, Lmed and Lmin respectively).

Pigeonpea

It is surprising that, although there were no significant differences in either stem diameter at 5 cm or plant height, biomass production in the line planting was approximately half that of the sole crop between August 8 and January 25 1991. The close intra-row spacing in the line planting probably resulted in a high degree of mutual shading, thereby reducing the quantity of intercepted radiation relative to the sole stand and hence the growth rate. The root profile studies (Fig. 3.21-3.22) indicated that the ability to capture below-ground resources was also reduced in the line-planted arrangement, in which roots were found in approximately half of the soil profile examined. Although there were no comparable measurements for the sole crop, it is probable that individual trees were able to exploit the profile more fully in 1990, in a similar manner to the dispersed planting. These restrictions to resource capture in the line planted treatment would have tended to limit leaf canopy

development, thereby decreasing the growth rate further relative to the sole crop.

3.7.2.2 *Dispersed planting*

Groundnut

In contrast to the line planting, groundnut productivity in the dispersed treatment was greatly reduced in 1990. Groundnut at sampling positions Dmax and Dmed was affected, with an inverse relationship between proximity to pigeonpea and the extent of the suppression of growth. The treatment mean pod yield for groundnut at final harvest was only 54% of that in the sole crop. This yield difference reflected the reduced rate of biomass accumulation throughout the season, as was also apparent from the timecourses of L and TDM accumulation (Figs. 3.9 and 3.10). As in the line planting, there were no differences in leaf area duration or specific leaf area between sampling positions or treatments. Similarly, although fewer pods were initiated in the dispersed planting, there was no significant difference in mean weight per pod at 100 DAS. The treatment mean rates of pod initiation were similar in the line and dispersed planting, but the actual number of pods was consistently lower in the dispersed planting. Although pods were first recorded at 60 DAS in all treatments, the onset of pod development may have been delayed in the dispersed planting since the 10 day growth analysis sampling interval permitted a difference in pod initiation of up to 9 days to remain undetected. At final harvest, there was little difference in biomass partitioning between treatments. However, although the increase in pod biomass ceased at 80 DAS in the dispersed planting, it continued in the sole crop until at least 100 DAS. If the duration of pod fill had not been longer in the sole crop, the harvest index of groundnut in the dispersed treatment would have been significantly higher.

Pigeonpea

TDM production by the dispersed pigeonpea between February 1990 and the end of the experiment in March 1991 (7.04 t ha⁻¹) was significantly greater than in the other

treatments ($p < 0.01$), representing a yield advantage of 26 and 46 % over the sole and line crops. As discussed earlier, considerably higher yields have been reported for perennial pigeonpea during the second year of growth when grown at higher populations in other studies at ICRISAT, suggesting that, although pigeonpea is able to produce a similar biomass over a wide range of population densities, the population of 0.5 plants m^{-2} was below this optimum range.

The plants in the dispersed planting had an advantage over the sole crop because they were established at a lower initial population of 0.5 plants m^{-2} , with the result that individual trees were larger at the onset of the 1990 rainy season, thereby enabling them to develop an extensive canopy and root system rapidly and to take full advantage of the available resources. This hypothesis is supported by the soil profile studies which confirmed that roots had occupied the entire soil profile to a depth of 2 m in the dispersed planting by December 1990. The relationships between light and water capture and conversion to TDM are examined further in Chapter 4.

3.7.3 Overall productivity

The most widely adopted method for assessing possible intercrop advantages is the land equivalent ratio (LER) (Willey, 1985), which provides an index of the relative amount of land area under sole crops required to produce the same yield as an intercrop composed of the same species. The LER for the line and dispersed treatments was calculated as:

$$LER = \frac{Y_{PPI}}{Y_{PPS}} + \frac{Y_{GNI}}{Y_{GNS}} \quad \text{equation 3.3}$$

where Y_{PPI} and Y_{PPS} represent the yield ($t\ ha^{-1}$) of the pigeonpea in the intercrop and sole treatments respectively over a given time period and Y_{GNI} and Y_{GNS} are the corresponding values for groundnut. Values for LER were calculated for pod/grain yield and TDM (Table 3.39).

The LER values for 1989-90 indicate that there was a slight intercrop advantage

during the first year of growth, because an almost full yield of groundnut was supplemented by the additional yield obtained from the pigeonpea from the same land area. The partial LER values for both components of the intercrop were lower when calculated in terms of total productivity as opposed to pod/grain yield, due to the slightly lower harvest index of the sole crops. The LER values were much higher for the period between January 31 1990 and January 25 1991 (3.39b) and because pigeonpea productivity was extremely low during the dry season (January 31 1990 - May 22 1990; Table 3.27), there was little difference in LER when this period is excluded.

In order for calculations of LER to provide a valid assessment of intercrop advantages, the sole crops of both components must be planted at their optimum population. Because the sole pigeonpea was below its optimum in 1990, the LER values overestimate the true advantage of the agroforestry system. When the LER values for 1990 were recalculated on the basis of the productivity of the sole pigeonpea in 1989 to give a more realistic idea of the advantage of the agroforestry system, they were reduced by approximately 18-30 %. Calculated on this basis, The LER for the line planting (1.17) was similar to the 1989 value. The substantial increase in pigeonpea productivity, was offset by the concurrent decrease in groundnut yield. However, the LER for TDM in the dispersed planting increased from 1.08 in 1989 to 1.98 (Table 3.39b) in 1990, even though the reduction in groundnut TDM (34 %) was greater than in the line treatment (28 %) because the greater productivity of the pigeonpea (Table 3.38) was more than sufficient to compensate for this. The true LER values may have been even lower because the expected productivity of the sole pigeonpea at its optimum population would have been greater than in 1989, in the absence of limitations imposed by water or nutrient availability.

LER values may overestimate the intercrop advantage because the land that is left unused after harvesting the shorter duration sole crop is not taken into account in the calculation. Hiebsch and McCollum (1987) introduced an area x time equivalency

Table 3.39: Land Equivalent Ratios (LER) for (a) groundnut pod and pigeonpea grain yields and (b) total dry matter production; Gnut and PPea represent the partial LER values for the groundnut and pigeonpea components.

(a)

	Line treatment			Dispersed treatment		
	Gnut	PPea	Total	Gnut	PPea	Total
2/7/89 - 31/1/90	0.88	0.23	1.11	0.93	0.22	1.15
31/1/90 - 25/1/91	0.80	0.51	1.31	0.54	0.93	1.47
31/1/90 - 25/1/91 based on 1989 sole pigeonpea production	0.80	0.32	1.13	0.54	0.59	1.13

(b)

	Line treatment			Dispersed treatment		
	Gnut	PPea	Total	Gnut	PPea	Total
2/7/89 - 31/1/90	0.86	0.18	1.04	0.89	0.19	1.08
22/5/90 - 25/1/91	0.72	0.68	1.40	0.67	1.32	1.98
31/1/90 - 25/1/91	0.72	0.67	1.39	0.67	1.33	1.98
22/5/90 - 25/1/91 based on 1989 sole pigeonpea production	0.72	0.45	1.17	0.67	0.85	1.52

Table 3.40: Area Time Equivalency Ratios (ATER) for total dry matter production.

	Line treatment	Dispersed treatment
2/7/89 - 30/1/90	0.72	0.69
22/5/90 - 25/1/91	1.00	1.30
22/5/90 - 25/1/91 based in 1989 sole pigeonpea production	0.77	1.10

ratio (ATER) to avoid this problem. ATER values were calculated for the line and dispersed plantings as:

$$ATER = \frac{\left(\frac{Y_{GNI}}{Y_{GNS}}\right)(T_{GN}) + \left(\frac{Y_{PPI}}{Y_{PPS}}\right)}{T_{PP}} \quad \text{equation 3.6.2}$$

where T_{GN} and T_{PP} denote the crop durations (d) of the groundnut and pigeonpea. In 1989, the productivity of both the line and dispersed treatments expressed in terms of area and time was less than if the pigeonpea and groundnut had been grown separately (Table 3.40). Any change in the LER of the longer duration component, i.e. the pigeonpea, will affect the ATER value to a greater extent than a similar change in the partial LER of the shorter duration component i.e. groundnut. However, although the partial LER values for pigeonpea in 1990-91 were much higher than in 1989-90, when calculations were based on sole pigeonpea productivity in 1989, the ATER value obtained (1.1) suggests that the intercrop advantage was small. Following a study of data from many intercropping experiments, Hiebsch and McCollum (1987) concluded that most crop mixtures utilise land area and time with about the same efficiency as pure stands of the components. This was presumably because complementarity did not occur in the systems examined.

The ATER approach is useful when the area of land left unused after harvesting the shorter duration sole crop could be utilised by another crop; the presence of the longer duration component generally precludes this in the intercrops. However, in the case of cropping systems on alfisols in the SAT, it is usually impossible to grow a second crop without irrigation, and so the low ATER values reported here have little practical significance. In fact, if water supplies permitted a second crop to be planted after groundnut harvest, the presence of the pigeonpea in the line and dispersed systems would not necessarily preclude this also being carried out in the intercrop.

Chapter 4: PHYSICAL INTERACTIONS

In this chapter, data concerning the capture and use of physical resources are presented and discussed. Light, water and microclimatic results are considered in relation both to the growth and development of pigeonpea and groundnut, and overall system productivity. The discussion reviews the relative importance of competition for light and water and microclimatic modifications for productivity, and considers the interactions between these variables.

4.1 LIGHT

The productivity of perennial systems, including agroforestry, may be improved relative to annual systems because larger quantities of light, water or nutrient resources are captured during the annual cycle or are used with greater efficiency. Productivity is likely to be improved if canopy duration, fractional interception and/or the efficiency of conversion of radiation to dry matter is increased. The principles involved and previous relevant research were reviewed in Section 1.4.2. The main aim in quantifying and analysing light interception was to determine to what degree these factors may have contributed to the observed treatment differences in crop growth and development. The initial aim was to examine the pattern of canopy development in all treatments and to determine the nature and extent of any temporal and spatial complementarity in the line and dispersed planting arrangements. Cumulative light interception was also examined in relation to productivity to establish the relative efficiency of conversion to dry matter in the various treatments examined.

The difficulties encountered in establishing the quantity of radiation intercepted by the pigeonpea component of these systems provide a good illustration of the practical problems which must be overcome when partitioning radiation interception in mixed crop canopies.

4.1.1 Solarimeter placement and calculation of intercepted radiation

In the line planting, partitioning of light interception between the two crop canopies was relatively straightforward; measurements were made using tube solarimeters of the type described by Green and Deuchar (1985). These were calibrated against a Kipp solarimeter on several occasions and were regularly cleaned to remove dust that would have resulted in an overestimate of radiation interception by the plant canopy. The solarimeters were not filtered, and so radiation interception is quoted in terms of total solar shortwave radiation comprising wavelengths in the range 0.3 - 3.0 μm .

The groundnut canopy never exceeded 30 cm in height and there was a discrete gap beneath the pigeonpea canopy, which began at a height of approximately 50 cm. Solarimeter tubes were placed both above (A1) and below (B1) the groundnut canopy in the mixed crop treatments (Fig. 2.5) in order to partition radiation interception between the pigeonpea and groundnut component. Interception by the pigeonpea canopy was assumed to be the difference between incident radiation and that recorded by tubes placed in the same orientation as tube B1 but above the groundnut canopy (tube A1). The pigeonpea canopy did not extend beyond tube A1 and solarimeter measurements after groundnut harvest at positions B1, B2 and B3 confirmed that there was no shading from the pigeonpea canopy beyond position B1. Therefore, the estimates of light interception calculated from tube A1 were divided by three in order to express light interception by pigeonpea in terms of the line planted system as a whole on a unit area basis.

Fractional radiation interception was calculated as:

$$f = 1 - (S_t/S) \quad \text{equation 4.1}$$

where S represents incident radiation, as measured by solarimeters placed at a height of 2 m (at the same angle as those below the canopy), and S_t is transmitted radiation

measured below the canopy.

The placement of solarimeter tubes in the dispersed planting was as shown in Figure 2.5. Constraints of instrumentation made it impossible to examine both the spatial variation in light interception with distance from the pigeonpea trees and the relationship between dry matter production per unit land area and intercepted radiation. Unlike the line planting, the tube positioning required for each of these studies differed. Ideally, solarimeters would have been placed both above and below the pigeonpea canopy at positions 1 and 2, but the limited number of tubes available necessitated some degree of compromise. The relationship between light interception and dry matter production took priority as this was the fundamental factor required for comparison with the other systems (see Section 3.2). The mean calculated value of light interception from sites 1 and 2 (Fig. 2.5) covered one quarter of the area between adjacent pigeonpea plants and represented the maximum possible range of distances from trees.

The principle adopted to measure interception by pigeonpea (i.e. by comparison of radiation fluxes recorded by tubes placed above the groundnut canopy with the incident radiation) was as described for the line planting. Unfortunately, there were insufficient tubes to place instruments above both positions B1 and B2 (Fig. 2.5). On the assumption that the pigeonpea canopy would not extend beyond position A1 for most of the growing season, the 'above groundnut' tubes were located only at this position. However, the pigeonpea canopy developed rapidly during the second year, causing the groundnut at position 2 to be shaded by the pigeonpea canopy for an undefined period before final harvest. When the groundnut was harvested, the values recorded at sites B1 and B2 were identical, indicating that both sites were equally shaded by the pigeonpea canopy.

In order to calculate radiation interception in the dispersed planting, it was necessary to make certain assumptions. In 1989 it was assumed that the pigeonpea covered only the solarimeters located at site 1 throughout the measurement period, whereas in 1990 the pigeonpea canopy was assumed to cover the solarimeters at both

positions 1 and 2 throughout the measurement period. Other methods of estimating light interception in the dispersed planting and the potential errors arising from each approach are discussed in Section 4.1.5

4.1.2 Percentage light interception

4.1.2.1 1989

Sole crops

Figure 4.1a shows the seasonal timecourses for percentage intercepted shortwave radiation for each sole crop in 1989. The groundnut canopy developed rapidly to reach 40 % radiation interception at the time of 50 % flowering (36 DAS); by 66 DAS interception had reached 80 % and remained above this level for 27 days. The maximum leaf area index (L) recorded at 70 DAS was 2.7 (Fig. 3.5). Thereafter interception and L declined rapidly as a result of leaf senescence, to reach 13 % at final harvest.

In the sole pigeonpea, there was an initial lag phase which extended up to 45 DAS for groundnut when interception did not exceed 20 %. This was followed by a rapid increase in interception to 40 % at 60 DAS, 60 % at 70 DAS and 80 % at 80 DAS. Interception values for pigeonpea were maintained above 80 % until 125 DAS, and this was followed by a gradual decline to 57 % when the pigeonpea was harvested. The high population of sole pigeonpea in 1989 caused seasonal mean interception values to be higher than in either of the mixed crop treatments. Unfortunately, the relatively small plot size and limited number of pigeonpea plants made it impossible to obtain regular destructive samples in order to monitor concurrent changes in L.

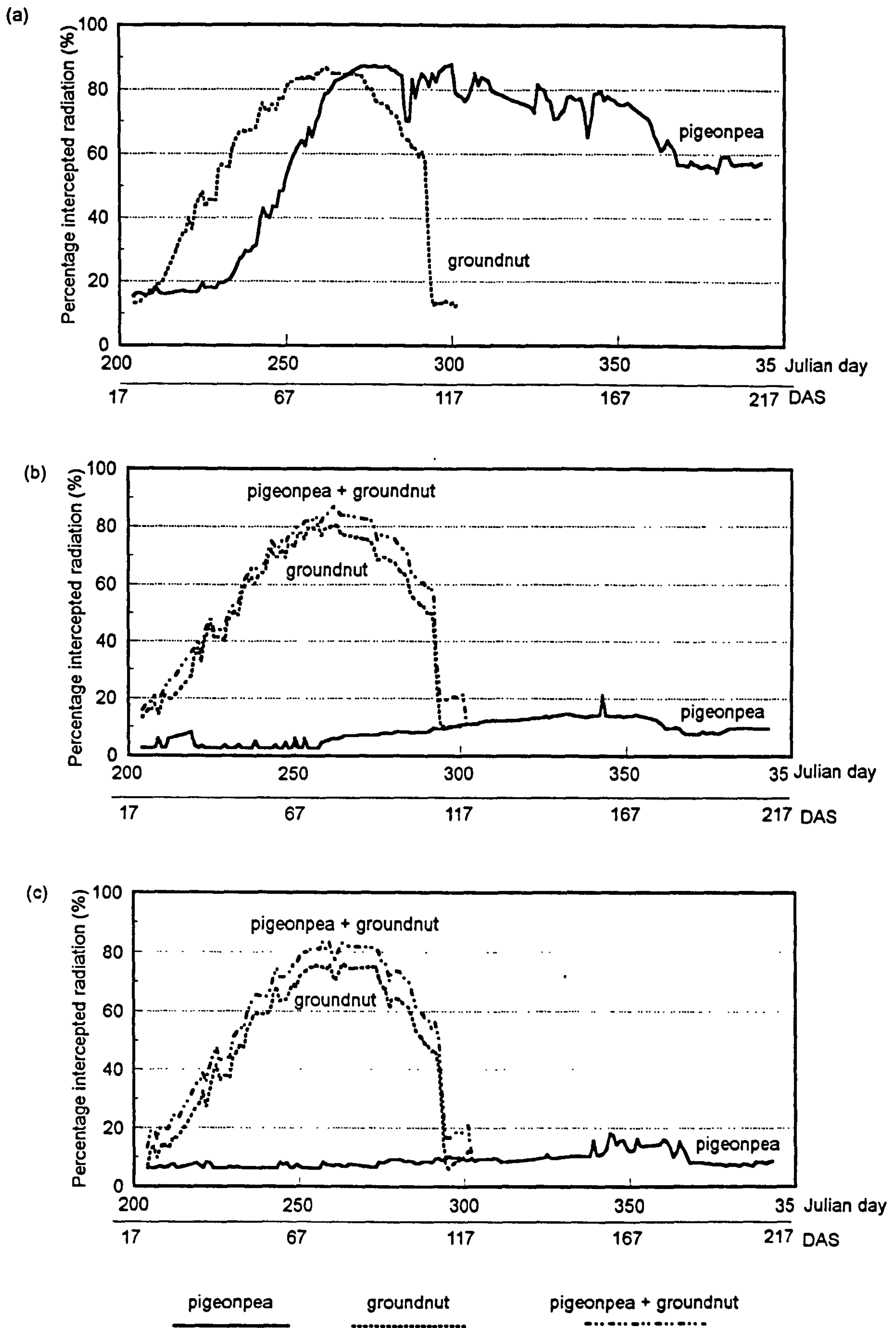


Figure 4.1: Seasonal timecourses for percentage intercepted shortwave radiation, 1989; mean daily values are shown ($n=6$) for (a) the sole crops, (b) the line treatment and (c) the dispersed treatment.

Line planting

Figures 4.1b and c show the daily mean percentage interception values for each component of the line and dispersed plantings in 1989, and also for the entire system. The timecourses for dispersed and line planted groundnut were similar to the sole crop, although there was a slight reduction in f values relative to the sole crop. In the line planting system, groundnut intercepted 28 % of the incident radiation at 50 % flowering (36 DAS), less than half of the corresponding value for the sole crop. Fractional interception reached 40 % by 40 DAS, and was maintained at 70 - 80 % between 65 - 92 DAS; this was followed by a rapid decline to 12 % by groundnut harvest at 119 DAS. The maximum L for groundnut of 2.59 was slightly lower than in the sole crop, but also occurred at 70 DAS.

Maximum fractional interception for the entire line planted system varied between 80 and 83 % between 68 and 91 DAS, but declined rapidly prior to groundnut harvest. The pigeonpea, with its population of 0.5 plants m^{-2} , intercepted less than 10 % of the incident radiation for the first 115 DAS, reached a maximum of 14 % between 169 and 171 DAS and decreased to 9 % at harvest (206 DAS).

Dispersed planting

The estimates of interception by pigeonpea in 1989 were based on the assumption that the tubes located at position 1 (Fig. 2.5) were shaded throughout the groundnut growing season, but those at position 2 were never shaded by the pigeonpea canopy. The potential difficulties arising from this assumption are discussed in Section 4.1.3. The timecourses for radiation interception by both crop components were similar to the line planting since interception by groundnut reached 27 % at 50 % flowering and values between 70 and 80 % were maintained between 67 and 95 DAS, before decreasing to 13 % by groundnut harvest. The maximum L value for groundnut was 2.54, as compared with 2.59 in the line planting. Maximum interception for the entire system exceeded 80 % between 69 and 90 DAS. The pigeonpea intercepted less than 10 % of the incident radiation up to 143 DAS, reached a maximum of

18 % at 160 DAS and then decreased to 10 % by harvest.

4.1.2.2 1990.

Sole crops

Figure 4.2a shows the seasonal timecourses for mean daily percentage radiation interception for the sole crops in 1990. The occurrence of more extensive foliar disease than in 1989 was probably a major contributory reason for the relatively low values for L , percentage radiation interception and crop biomass recorded in groundnut in 1990. The sole groundnut intercepted 50 % of the incident radiation by 50 % flowering (35 DAS), rising to a maximum of approximately 80 % at 62 DAS; this was maintained until 83 DAS, before declining to 50 % interception at final groundnut harvest (111 DAS). The maximum L value for groundnut of 2.19 was reached at 60 DAS, 10 days earlier than in 1990.

During the period prior to the fodder cut, when the pigeonpea in all treatments was pruned to a height of 50 cm (up to 20 DAS for groundnut), interception by the pigeonpea exceeded 30 %. The sole pigeonpea intercepted 20 % of the incident radiation 14 days after this fodder cut and thereafter interception increased to a maximum of over 60 % between 140 and 165 DAS for groundnut; this was followed by a gradual decline to 37 % at pigeonpea harvest on Julian Day 25, 1991, 79 days after harvesting the groundnut.

Maximum interception by the sole pigeonpea was 25 % lower than in 1989, primarily because the pigeonpea population was reduced to 0.44 plants m^{-2} 48 days prior to groundnut planting in 1990. As severe competition between the trees was expected to result in some mortality in 1990, the population was reduced to maintain an even stand and an optimum population for comparing productivity with the mixed crop treatments. The lower percentage interception values obtained indicate that, although pigeonpea shows extensive plasticity in the relationship between population

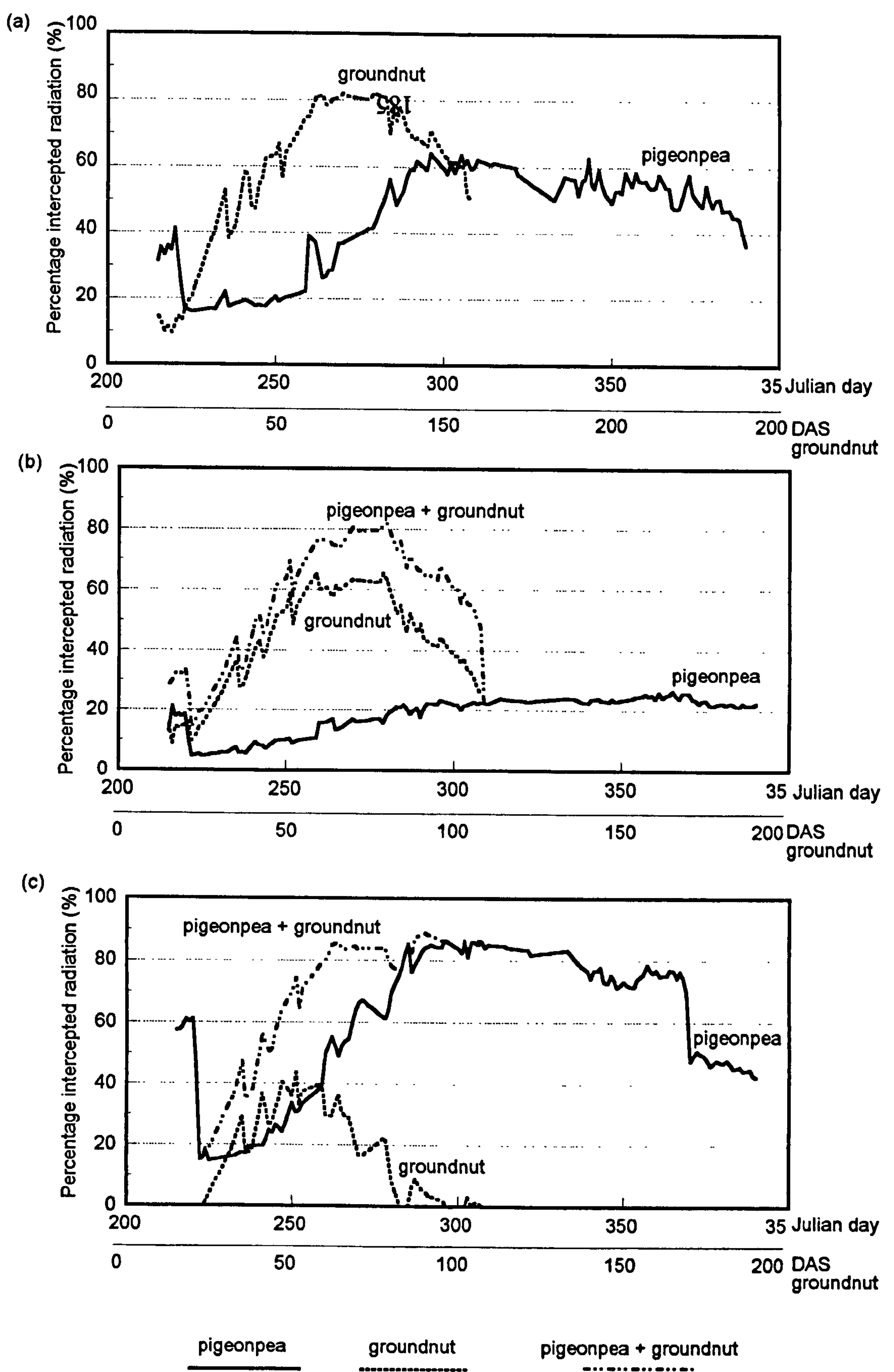


Figure 4.2: Seasonal timecourses for percentage intercepted shortwave radiation, 1990; mean daily values are shown ($n=6$) for (a) the sole crops, (b) the line treatment and (c) the dispersed treatment.

and productivity (Rao and Willey, 1983), the reduction to 0.5 plants m² was below the optimum for the second year of growth.

Line Planting

Interception by groundnut in the line planting system was substantially lower than in the sole crop; 20 % of the incident radiation was intercepted by 28 DAS, only three days later than the sole crop, whereas interception at 50 % flowering was only 37 % (Fig. 4.2b). A maximum of 60 - 65 % interception was achieved between 57 - 80 DAS, and this was followed by a rapid decline to 26 % at final harvest. Interception by the line-planted pigeonpea was much lower than in the sole crop, reaching 10 %, 28 days after the fodder cut at 48 DAS, and remaining at 20 - 25 % between 82 DAS and final harvest.

Dispersed planting

The interception values for pigeonpea in the dispersed treatment in 1990 are based on the assumption that its canopy shaded the solarimeters at positions 1 and 2 (Fig. 4.2c) throughout the entire measurement period. On this basis, radiation interception by groundnut was much lower than in the sole and line planted treatments. 20 % interception was reached at 33 DAS, eight days later than in the sole groundnut, but the maximum interception of 35 - 40 %, attained between 53 and 59 DAS was only half that in the sole treatment. Although radiation interception reached a maximum at 50 DAS, L continued to increase from 0.93 at 50 DAS to 1.45 at 70 DAS.

Interception by the pigeonpea increased rapidly after the fodder cut at 20 DAS; 20 % interception was reached 22 days after the fodder cut (42 DAS for groundnut) and a maximum exceeding 80 % was maintained between 88 and 136 DAS. Maximum interception was 20 % higher than in the sole pigeonpea and although attained 28 days later, was maintained for a similar period (48 d). Interception declined to 43 % by pigeonpea harvest.

Alternative methods for estimating radiation interception by the pigeonpea in the dispersed planting in 1990 are described in the appendix. The two methods described were based upon estimated mean radiation interception by groundnut, calculated indirectly from the routine growth analysis data. The values obtained from both methods (Table a1.5) fell between those based on the assumption adopted for the presentation of data throughout this chapter (that solarimeter positions 1 and 2 were shaded throughout the measurement period) and the assumption that position 1 alone was shaded throughout.

In the absence of additional data concerning the structure of the pigeonpea canopy, it is not possible to estimate the area of shade that would have been cast on the groundnut, or how this varied diurnally and seasonally. The radiation regime in agroforestry systems has been studied in some detail and descriptive models have been developed (e.g. Jackson and Palmer, 1989, Nygren *et al.*, 1993). However, these models are complex and require detailed information. For example, the extent of the shaded area and shadow intensity is dependent on canopy structure, tree height, latitude, time of year and row orientation. In addition, the models are often valid only for clear sky conditions, and cannot be used when there is a high proportion of diffuse radiation, as in the current study.

4.1.3 Cumulative light interception

4.1.3.1 1989

Table 4.1 shows cumulative intercepted shortwave radiation for all treatments between groundnut sowing on 2 July 1989 and the first pigeonpea harvest on 31 January 1990. Cumulative total dry matter (TDM) is also presented for the same period. At harvest, the pigeonpea was cut to a height of 50 cm from the ground. The TDM values for pigeonpea shown in Table 4.1 do not include the dry matter accumulated in the 50 cm of stem above ground level or the root biomass. Timecourses of cumulative intercepted radiation for the sole, line and dispersed treatments are shown in Figure 4.3.

Sole groundnut

The sole groundnut intercepted more radiation (943 MJ m^{-2}) than in the intercrops (857 and 675 MJ m^{-2} in the line and dispersed treatments respectively), but the seasonal radiation conversion coefficient (e) was only 0.36 g MJ^{-1} for the sole groundnut; thus, although 28 % more radiation was intercepted by the sole groundnut than in the dispersed planting, only 11 % more TDM was produced.

Sole pigeonpea

The sole pigeonpea at its initial optimum population of 9 plants m^{-2} in 1989, intercepted more radiation (1960 MJ m^{-2}) than any other treatment, and more than seven times that achieved by the pigeonpea component of the line or dispersed plantings. When the groundnut component is taken into account, interception by the sole pigeonpea was 1.7 times the total for the line planting system (1131 MJ m^{-2}) and twice that for the dispersed arrangement (955 MJ m^{-2}). The radiation conversion coefficients (e) for this period were 0.42 g MJ^{-1} for sole pigeonpea, as opposed to 0.54 and 0.56 g MJ^{-1} for the line and dispersed planted pigeonpea. Consequently, TDM production by the sole pigeonpea was only about five times greater than in the other treatments, less than would have been expected if the radiation conversion coefficient had been conservative.

Line and dispersed plantings

Total interception in the line treatment was 1131 MJ m^{-2} , 18 % greater than in the dispersed system. The difference between these treatments was largely due to the lower radiation interception by the groundnut in the dispersed planting (675 MJ m^{-2}) relative to the line planting (857 MJ m^{-2}). The conversion coefficient (e) for groundnut in the line planting was similar to that for the sole crop (0.34 g MJ^{-1} over the entire season) but was higher in the dispersed groundnut (0.45 g m^{-2}) so that the reduction in light interception in the latter treatment did not result in a proportional reduction in TDM.

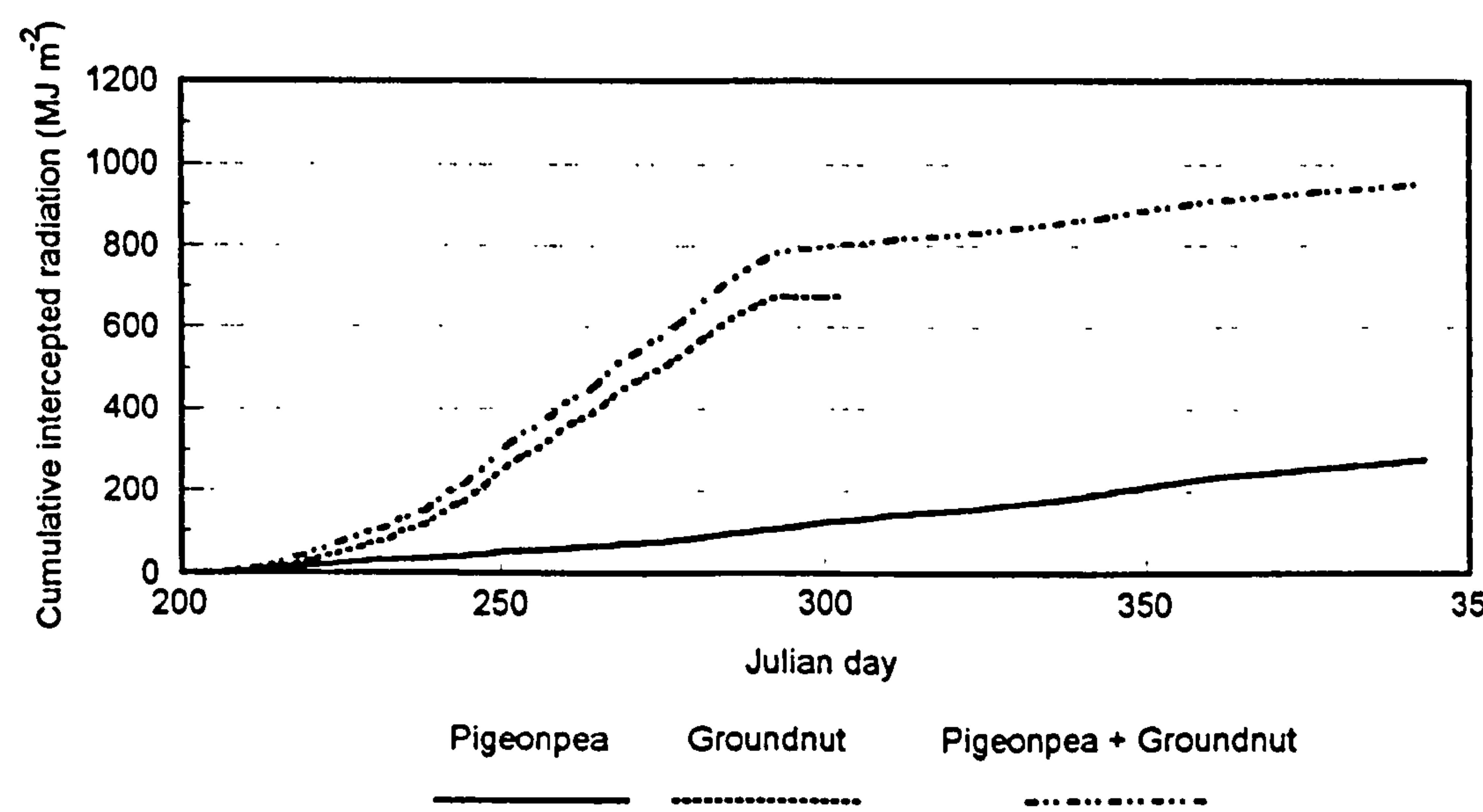
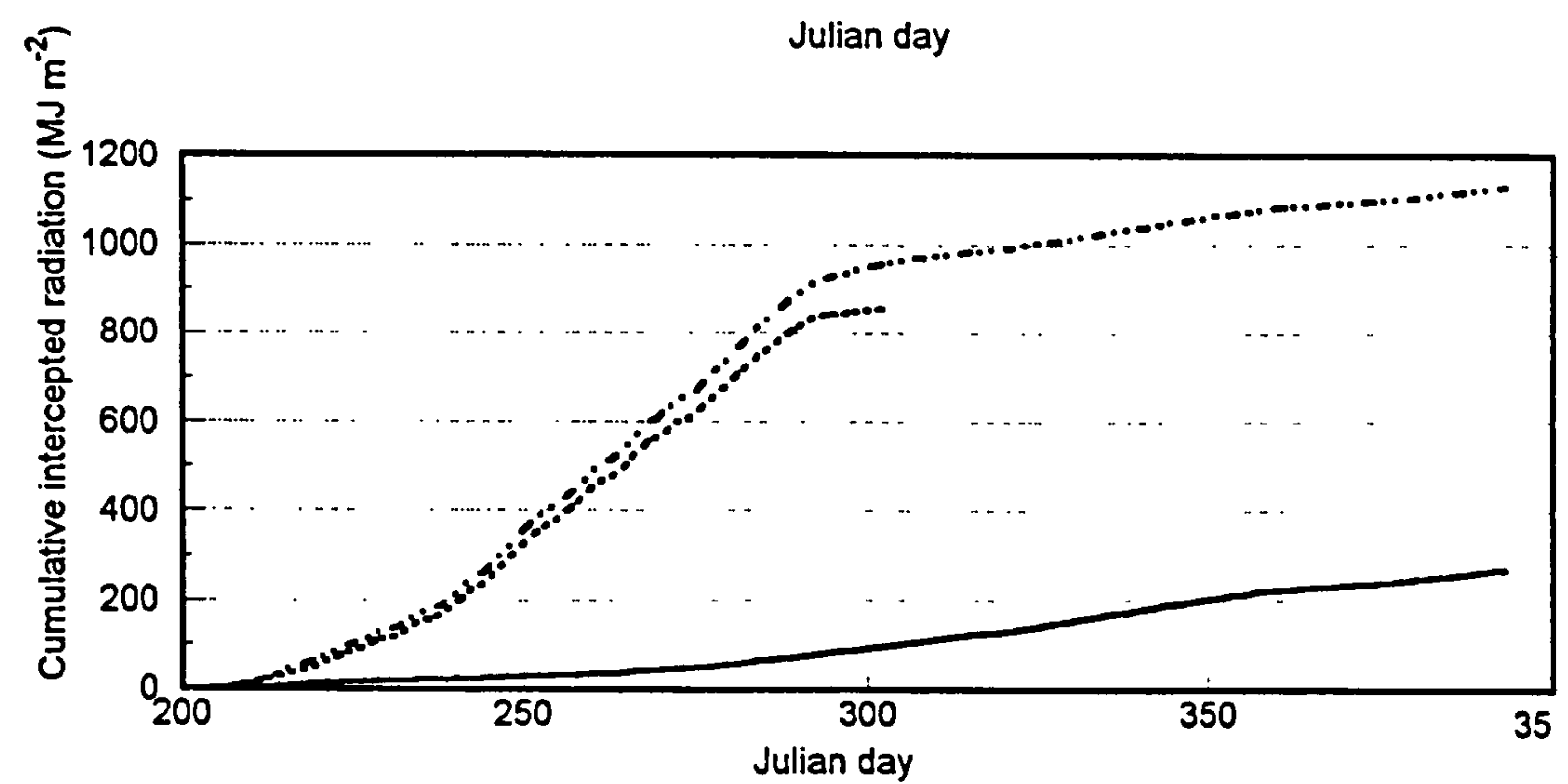
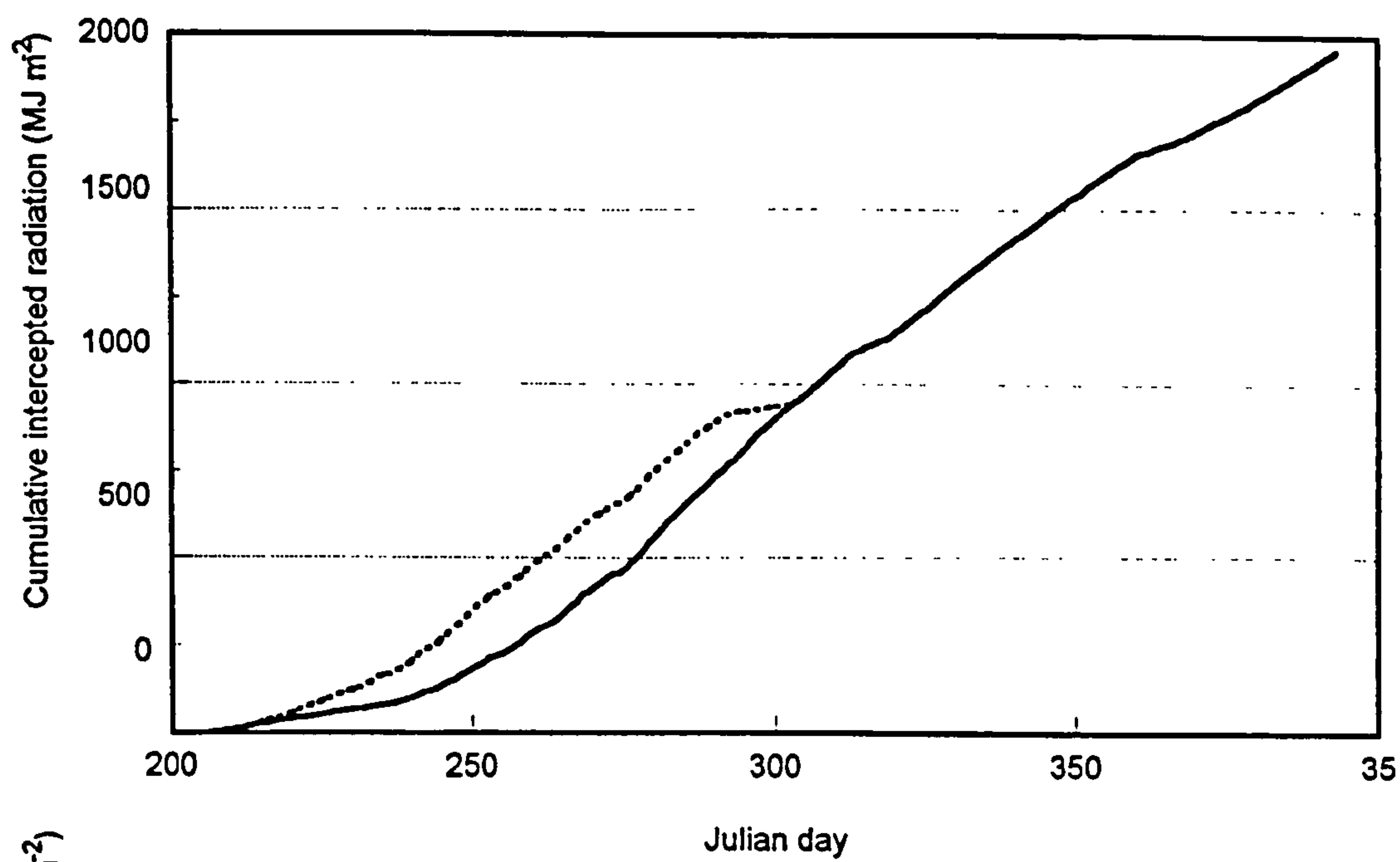


Figure 4.3: Cumulative intercepted radiation, 1989; daily treatment mean values are shown for (a) the sole crops, (b) the line treatment and (c) the dispersed treatment.

Table 4.1: Cumulative intercepted total shortwave radiation and total dry matter production between groundnut sowing and harvest for each crop component in 1989

	Pigeonpea		Groundnut		Pigeonpea + Groundnut	
	Radiation (MJ m ⁻²)	TDM (g m ⁻²)	Radiation (MJ m ⁻²)	TDM (g m ⁻²)	Radiation (MJ m ⁻²)	TDM (g m ⁻²)
Sole	1960	816	943	339		
Line	271	147	857	290	1131	437
Dispersed	279	156	675	303	955	459

Table 4.2: Cumulative intercepted total shortwave radiation and total dry matter production between groundnut sowing and harvest for each crop component in 1990

	Pigeonpea		Groundnut		Pigeonpea + Groundnut	
	Radiation (MJ m ⁻²)	TDM (g m ⁻²)	Radiation (MJ m ⁻²)	TDM (g m ⁻²)	Radiation (MJ m ⁻²)	TDM (g m ⁻²)
Sole		355	888	252		
Line	487	209	795	182	1282	391
Dispersed	1552	452	300	168	1912	620

4.1.3.2 1990

Table 4.2 shows cumulative values for total intercepted shortwave radiation for all treatments between the third pigeonpea fodder cut on 8 August 1990 and the final pigeonpea harvest on 25 January 1991. Total dry matter production over the same time period is also shown. The TDM measurements for pigeonpea again exclude dry matter accumulated in the stem between ground level and 0.5 m and therefore underestimate the true productivity values. The timecourses for cumulative radiation interception are shown in Figure 4.4 for all treatments.

Sole groundnut

The radiation interception and conversion efficiency values for sole groundnut were considerably lower than in 1989, probably largely because of the greater incidence of foliar disease in 1990. The sole groundnut intercepted 888 MJ m⁻² of radiation, almost three times more than the groundnut in the dispersed treatment. However, the TDM production of the sole groundnut (252 g m⁻²) was only 1.5 times greater than in the dispersed planting due to the much higher e of the shaded groundnut in the latter treatment (0.56 g MJ⁻¹ between sowing and final harvest, as compared with 0.28 and 0.23 g MJ⁻¹ in the sole and line plantings respectively).

Sole pigeonpea

The sole pigeonpea population was reduced from 8.9 to 0.44 plants m⁻² on 1 June 1990, resulting in a spacing of 1.5 m between rows and 1.4 m within rows, which was as near as possible to that in the dispersed planting. In the dispersed treatment, one quarter of the area between adjacent trees was monitored by solarimeters (Fig. 2.5), on the assumption that this was representative of the entire system. As productivity estimates for groundnut were made for the same unit area, the quantitative relationship between radiation interception and dry matter accumulation could be examined. Unfortunately, insufficient solarimeters were available to make equivalent measurements in the sole pigeonpea stand, and so tubes were placed

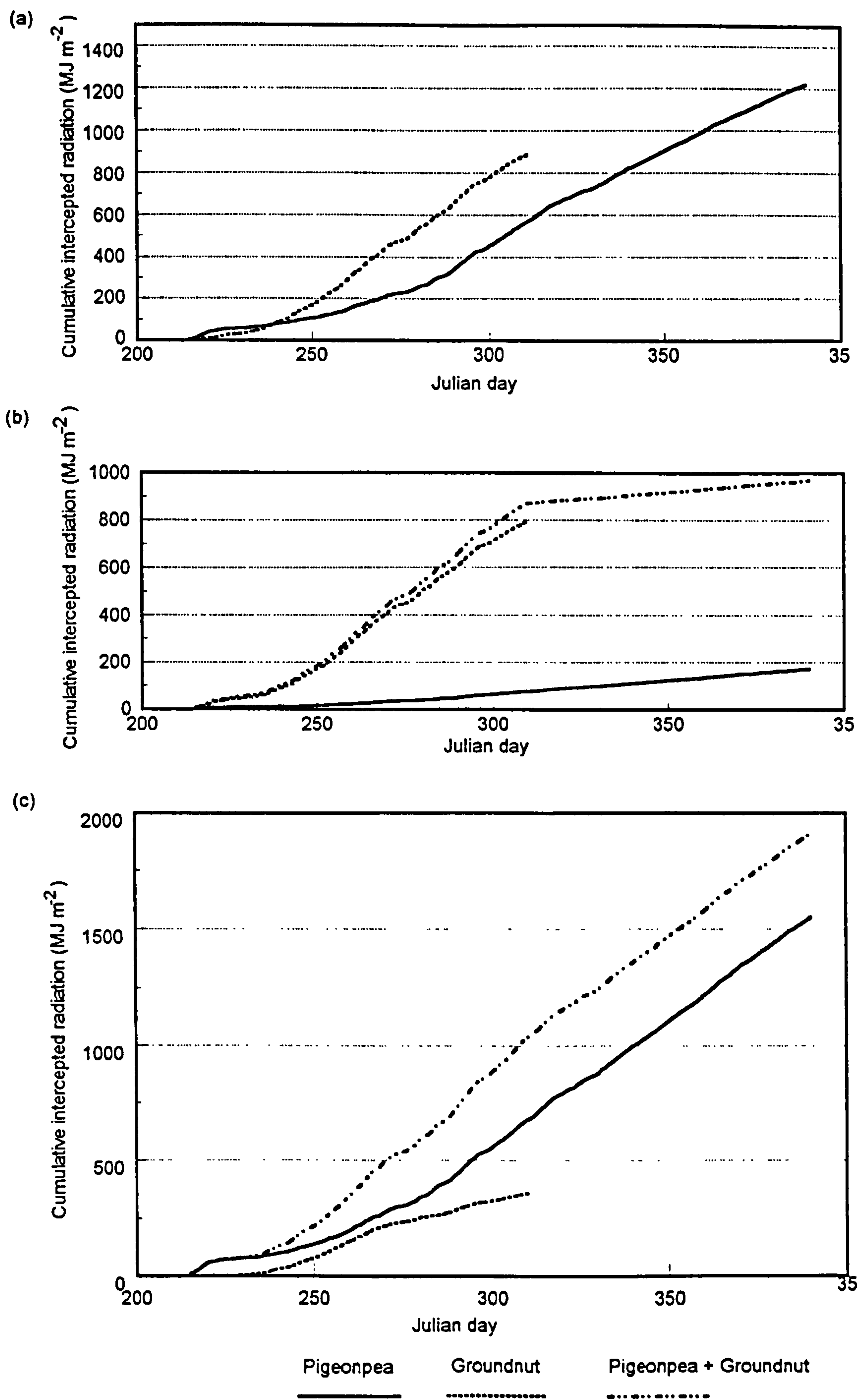


Figure 4.4: Cumulative intercepted radiation, 1990; daily treatment mean values are shown for (a) the sole crops, (b) the line treatment and (c) the dispersed treatment.

30 cm from the base of the pigeonpea trees at an angle of 45° to the row, similar to the positioning of tube B1 in the dispersed planting. The solarimeter readings from this treatment therefore cannot be used to provide representative estimates of interception on a unit area basis for the entire system because only the area of most intense shading close to the pigeonpea plants was monitored. Consequently, the estimated total accumulated intercepted radiation for the sole pigeonpea (823 MJ m⁻²) was calculated using the radiation conversion coefficient value for the line-planted pigeonpea (0.43 g MJ⁻¹) and TDM production between 8 August 1990 and 25 January 1991. The estimate obtained indicated that total interception by the sole pigeonpea was less than half that of the total for the dispersed system (1912 MJ m⁻²) and two thirds of the value for the line planted system (1282 MJ m⁻²).

Line planting

The groundnut in the line planting system intercepted 795 MJ m⁻², approximately 12 % less than in the sole crop. As the seasonal mean interception by the pigeonpea was approximately 23 %, the radiation incident upon the groundnut within this treatment would have been reduced by approximately 7.5 % as compared to the sole groundnut. The L value for the shaded groundnut rows (L_{max}) was lower than at other sites in the line planting, which would have contributed to the observed reduction in intercepted radiation.

Dispersed planting

The dispersed planting intercepted considerably more radiation than any other treatment over the period shown, primarily because of the greater interception by the pigeonpea component. The groundnut in this treatment was shaded by the pigeonpea throughout the season and intercepted 300 MJ m⁻² (Table 4.2), or 40 % of the corresponding value for sole groundnut. The pigeonpea in the dispersed planting intercepted more than three times as much radiation as the line planting system, and almost twice as much as the sole pigeonpea. These data suggest that the conversion coefficient for the pigeonpea in the dispersed planting was considerably lower than

in the other two treatments (0.29 g MJ^{-1}), causing TDM production to be lower than expected from the radiation interception values. However, two factors may have introduced errors into the estimates of e for the dispersed pigeonpea. Firstly, since the stem diameter of the dispersed pigeonpea was much greater than in the other treatments (Section 3.6), the correction necessary to allow for the dry matter accumulation in the stem below 0.5 m would have been higher. At final harvest, the TDM accumulated in this portion of the stem since planting was 0.62, 0.60 and 1.11 t ha^{-1} for the sole, line and dispersed plantings respectively. Therefore, TDM, and hence e , is likely to have been underestimated to a greater extent in the dispersed pigeonpea than in the line or sole planted pigeonpea.

Secondly, the estimates of radiation interception for the dispersed planting were based on the assumption that the pigeonpea canopy covered both solarimeter sites 1 and 2 (Fig. 2.5) between August 8 1990 and 25 January 1991. However, there would have been a period immediately after the fodder cut before this was achieved, when interception by pigeonpea would have been overestimated, thereby causing e to be underestimated. Nevertheless, because interception by groundnut was calculated by deducting pigeonpea interception (measured as the difference between incident radiation and radiation reaching solarimeter position A1) from interception by both canopies (measured as the difference between incident radiation and the mean interception recorded by solarimeters B1 and B2), the extent of the error over the entire system would have been reduced, because any overestimate in interception by the pigeonpea would have resulted in an underestimate of interception by groundnut. This was most apparent immediately after the fodder cut on 8 August 1990 when the deduction necessary to account for interception by the pigeonpea resulted in some negative values for groundnut interception; in the calculations of cumulative interception these values were recorded as zero.

4.1.4 Intercepted radiation and dry matter production in groundnut

The relationship between dry matter production and accumulated intercepted radiation is shown in Figure 4.5 for groundnut in 1990. In common with most

annual crops, dry matter bore an approximately linear relationship to intercepted radiation for much of the growing season (Gallagher and Biscoe, 1978). Linear regressions were fitted to the data obtained between 30 - 70 DAS to obtain values of e for this period; these are shown in Table 4.3, together with equivalent data from previous studies of groundnut conducted at Hyderabad during the rainy season. Values for e were also calculated for the entire period between sowing and final harvest (111 DAS) and these proved, as expected, to be lower than those for the period between 30 - 70 DAS (Table 4.3). A major factor in this difference was the consistent reduction in dry matter production per unit land area between 90 DAS and final harvest exhibited by groundnut in all treatments, which resulted largely from rapid leaf senescence during this period when new leaves were not being produced. In addition, much of the assimilate produced during this period would have been transported to the developing pods to support their growth; the pods characteristically possess a greater energy content per unit dry matter than other plant components (Squire, 1990; Azam-Ali, 1995). Older leaves also have inherently lower photosynthetic rates (Squire, 1990) and so, not only did L decline as the crop approached maturity, but the quantity of dry matter produced per unit of intercepted radiation would also have declined as the proportion of older leaves increased. Dead or senescent leaves may also be retained for some time in groundnut and these would have intercepted radiation without contributing to dry matter production, thereby reducing the *calculated* value of e relative to the *true* value for the remaining physiologically active leaves.

The data presented in Table 4.3 indicate that the conversion coefficient was increased by shade since the heavily shaded groundnut in the dispersed planting had an estimated e value of 1.1 g MJ^{-1} between 30 - 70 DAS, almost twice that for the sole crop (0.6 g MJ^{-1}). The value for groundnut in the dispersed arrangement was very similar to that for the heavily shaded groundnut rows at L_{max} in the line planting (1.0 g MJ^{-1}). However, the mean value for the line planting (0.8 g MJ^{-1}) was closer to that for the sole crop (0.6 g MJ^{-1}), probably because approximately two-thirds of the groundnut was unshaded when expressed on a unit area basis.

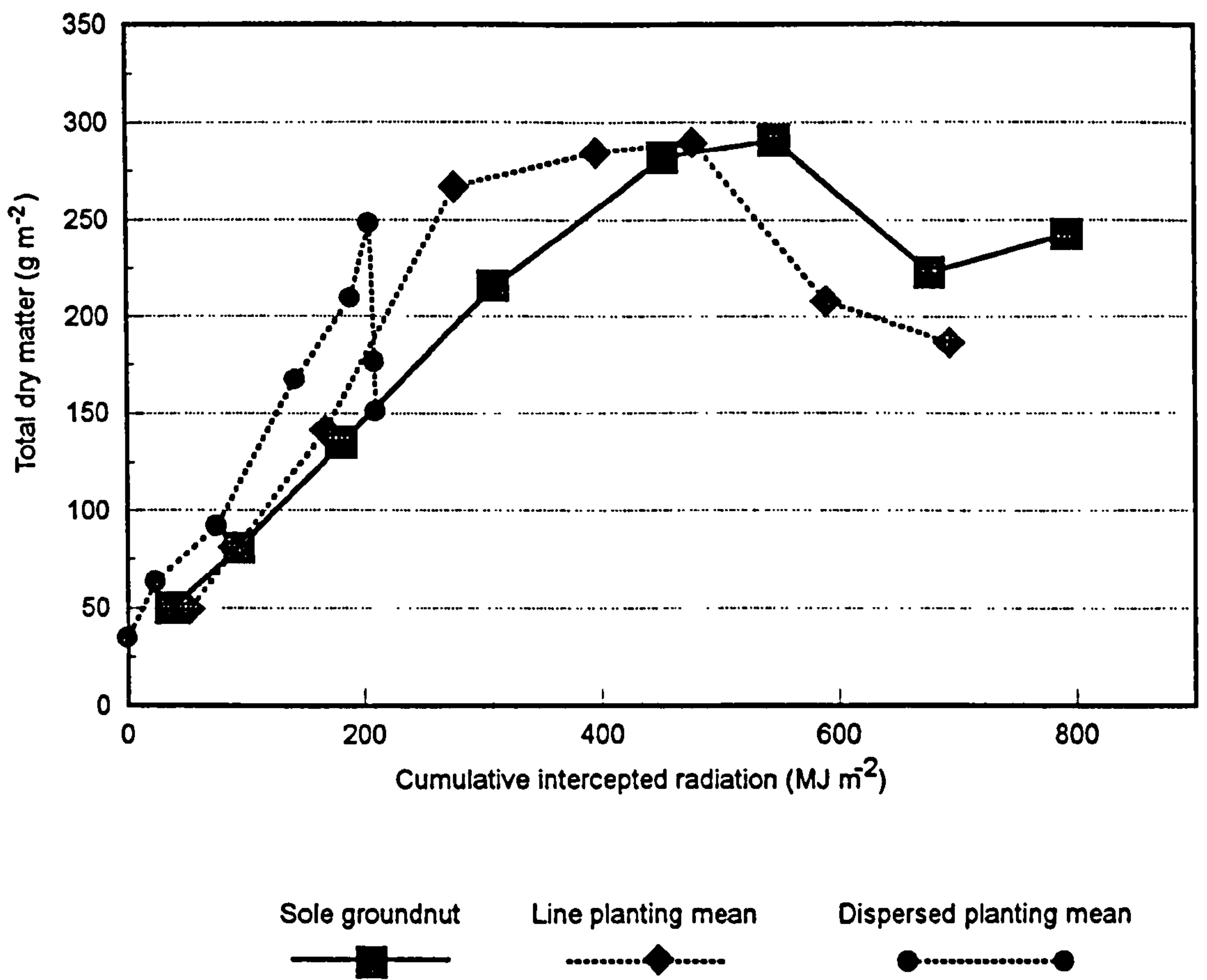


Figure 4.5: Relationship between intercepted radiation and dry matter accumulation; means for groundnut, 1990.

Table 4.3: Radiation conversion coefficient (e) for groundnut obtained at Hyderabad during the rainy season. Values were calculated using data for total intercepted shortwave radiation (0.3 - 3.0 μm); see text for details. * indicates that the energy equivalent was calculated from TDM at final harvest rather than for the time period over which e is shown

Author	Treatment	Mean intercepted radiation ($\text{MJ m}^{-2} \text{d}^{-1}$)	LUE (e) (g MJ^{-1})	Energy equivalent of TDM per unit of radiation intercepted ($\text{MJ MJ}^{-1} \times 10^{-3}$)	Time period (DAS)
Marshall (1995)	Sole, 1989	9.2	1.5		30 - 70
	Sole, 1990	13.7	0.6		30 - 70
	line planting mean, 1990	9.1	0.8		30 - 70
	Lmax, 1990	4.8	1.0		30 - 70
	Dispersed planting mean, 1990	4.8	1.1		30 - 70
	Sole, 1990	11.0	0.3	5.75	30 - harvest
	Line planting mean, 1990	8.0	0.2	4.70	30 - harvest
	Dispersed planting mean, 1990	2.6	0.6	7.28	30 - harvest
Ong <i>et al.</i> (1991)	Sole, 1985	7.6	0.5	7.06*	20 - 80
	Sole, 1986	5.8	0.6	7.97*	20 - 80
	Sole, 1987	5.2	1.07	13.3*	20 - 80
Harris <i>et al.</i> (1987)	Sole, 1983	5.5	0.5	23.6	29 - harvest
	Intercrop, 1983	4.4	0.7	15.8	29 - harvest
Stirling (1990)	Sole, 1985	12.4	1.0		49 - 92
	Bamboo shade	3.2	2.2		49 - 92

Calculations based on the biomass present at final harvest (Table 4.3) provide an e value for sole groundnut of 0.3 g MJ^{-1} , which is significantly higher than the mean for the line planted groundnut (0.2 g MJ^{-1}), reflecting the greater reduction in total dry matter between 80 DAS and final harvest in the line planting as compared to the sole crop (Fig. 4.5). There was also a considerable reduction in TDM in the dispersed planting relative to the sole crop by final harvest, but the higher initial value of e between 30 and 70 DAS was sufficient to ensure that e was still greater at final harvest (0.6 g MJ^{-1}) than in the other treatments.

Several workers have reported that e is increased in groundnut by partial shading (Stirling *et al.*, 1990; Ong *et al.*, 1991c; Marshall and Willey, 1983). However, since the e values for specific crops are also influenced by other environmental factors such as temperature and saturation deficit (Squire, 1990), it is not possible to establish a simple relationship for individual species that can be applied universally under differing experimental conditions. This may be demonstrated by comparing the e values for sole groundnut in 1989 and 1990. The productivity in these two years was considered in relation to rainfall distribution in section 3.7.1.1, where it was demonstrated that the more favourable conditions in 1989 resulted in an e value of 1.5 g MJ^{-1} , higher than in any treatment in 1990.

Table 4.3 also includes e values from other studies using groundnut cv. Kadiri-3 during the rainy season at Hyderabad. Total shortwave solar radiation (0.3 to $3.0 \mu\text{m}$) was recorded in all cases. It should be noted that Stirling *et al.* (1990) shaded groundnut by using bamboo screens which did not affect the spectral quality of the radiation reaching the crop.

Roots were not included in any of the estimates of dry matter used to calculate the e values shown in Table 4.3, but may contribute a substantial proportion (20 - 50 %) of the total dry weight, particularly in annual crops grown under dry conditions or in perennial crops (Squire, 1990). Azam-Ali *et al.* (1990) suggested that the omission of roots has little effect on the estimates of e for groundnut under wet conditions. The values shown in Table 4.3 span a considerable range despite the

broadly similar environmental conditions but numerous other factors must be considered, including the period over which e is calculated and harvest index; attack by pests or diseases or periods of drought may also reduce e values considerably.

Plants organs vary in their energy content per unit of dry weight, and in the case of groundnut, the seed contains a large proportion of lipids which have a relatively high energy content (Ashley, 1984). When the proportion of dry matter attributable to the pods varies, e values expressed on a dry weight basis may be misleading. For this reason, approximate values for the quantity of chemical energy produced per unit of intercepted radiation are also given in Table 4.3, wherever possible. TDM values for groundnut were converted into energy equivalents by multiplying the reproductive yield by a conversion factor of 23.41 kJ g⁻¹ and the vegetative yield (with its lower lipid content) by 17.51 kJ g⁻¹, as described by Azam-Ali (1995). In this study, the harvest index of the groundnut in 1990 was higher in the line planting (0.52) than in either the sole crop (0.47) or the dispersed planting (0.38). As discussed in Chapter 3, the relatively low harvest index in the dispersed planting occurred because fewer pods were initiated. The energy equivalent (expressed as MJ MJ⁻¹ of intercepted radiation) for the sole groundnut was 5.75×10^{-3} MJ MJ⁻¹ as compared with 7.28×10^{-3} MJ MJ⁻¹ in the dispersed planting (Table 4.3). Since a smaller proportion of the total dry matter in the dispersed planting was attributable to the pods, the magnitude of the difference in the conversion coefficients for groundnut between the dispersed and sole treatments was lower when expressed as energy equivalents rather than in terms of total dry matter. Even though the harvest index was higher in the line planted groundnut than in the sole crop, this was insufficient to compensate for the overall difference in total dry matter. The efficiency of conversion of intercepted radiation was 4.70×10^{-3} MJ MJ⁻¹ for the line planted groundnut, as compared to 5.75×10^{-3} MJ MJ⁻¹ in the sole crop.

Care should be taken when comparing e values calculated on the basis of intercepted total shortwave radiation rather than PAR. The photosynthetic pigments of crop plants absorb 80 - 85 % of the intercepted PAR (Szeicz, 1974) and typically transmit a relatively small proportion of green wavelengths at approximately 550 nm, but are

otherwise almost opaque to the visible wavelengths (Fitter, 1981). Because leaves absorb PAR in preference to other wavelengths in the range 0.3 - 1.5 μm , the shortwave radiation received by groundnut plants situated below the pigeonpea canopy would have been severely depleted in terms of PAR. Thus, direct comparison of the e values for sole and intercropped groundnut may be misleading since the values for the intercropped groundnut might have been higher relative to the sole crop if expressed in terms of PAR interception. Total shortwave radiation interception may be converted to PAR interception using the following equation (Marshall and Willey, 1993):

$$\ln (1-f_p) = 1.4 \ln (1-f_t) \quad \text{equation 4.2}$$

where f_p and f_t represent the fractional interception of PAR and total shortwave radiation respectively.

Thus

$$f_p = 1 - \exp^{(1.4 \ln(1-f_t))} \quad \text{equation 4.3}$$

This relationship was used to estimate PAR interception in the dispersed planting (Table 4.4). As incident PAR was not measured directly, it was assumed to comprise 50 % of the total shortwave radiation incident upon the crop (Monteith, 1973; Szeicz, 1974).

Table 4.4 indicates that the fraction of PAR incident on the groundnut in the dispersed planting was reduced to 0.38. As with all other calculations described in this section, interception by the pigeonpea was based on the assumption that the solarimeters at sites 1 and 2 (Fig. 2.5) were shaded throughout the measurement period in 1990. The PAR content of the total incident shortwave radiation is almost independent of solar angle because the proportion of PAR in diffuse radiation increases as its proportion in direct radiation decreases (Monteith, 1973). However, because fractional interception varies with solar angle, mean daily values of f_t were used to calculate the values shown in Table 4.4.

Table 4.4: Radiation interception in the dispersed planting during the groundnut growing season, 1990

	Total shortwave radiation		PAR	
	Fraction of incident radiation (f)	Quantity of incident radiation (MJ m ⁻²)	Fraction of incident radiation (f)	Quantity of incident radiation (MJ m ⁻²)
Total incident between groundnut sowing and harvest		1505	0.50	753
Sole groundnut: interception	0.627	943	0.75	566
Dispersed planting: pigeonpea interception	0.504	759	0.62	467
Dispersed planting: incident on groundnut.	0.496	746	0.38	286

4.2 WATER

This section presents the results of measurements of rainfall, tree and crop transpiration, stored soil moisture and soil surface evaporation. From this information, an approximate water balance was calculated for each of the systems examined. The relationship between productivity and dry matter accumulation is also examined. Detailed water balance measurements were only carried out in 1990 when there were significant differences in growth and development between the various pigeonpea planting arrangements.

4.2.1 Transpiration

4.2.1.1 *Pigeonpea*

4.2.1.1.1 *Calibration*

During a previous study of transpiration by pigeonpea at ICRISAT Center, heat balance equipment was calibrated against gravimetric measurements using pot grown plants (see Section 2.3.2.1). In that study the heat balance measurements were found to accurate be accurate to within $\pm 8\%$ on plants with stem diameters between 15 - 20 mm. The stem diameters of pigeonpea trees examined in the current study were generally within this range, but an attempt was made to confirm these results by removing several pigeonpea plants from the field in 1990 and transplanting them into large pots for calibration studies. Unfortunately, none of these survived and the study was abandoned due to shortage of time. The ability of the sap flux measurements reported here to provide accurate estimates of transpiration rates was therefore not unequivocally established in the present study. However, a number of other workers have found using small stems of various species, that the heat balance method is capable of estimating the true transpiration rate to within $\pm 10\%$ or better (e.g. Baker and van Bavel, 1988; Steinberg *et al.*, 1989).

4.2.1.1.2. *Seasonal trends in pigeonpea transpiration*

The heat balance technique was used (cf. Section 2.3.2.1) to establish the diurnal and seasonal trends in transpiration by pigeonpea in the line and dispersed plantings. Measurements were made between February 1990 and final harvest in January 1991, but data are presented here only for the period between July 19 1990 and final grain harvest on 25 January 1991 (Fig. 4.6). Prior to this, the transpiration rates were low ($< 30 \text{ g h}^{-1}$) and the data inconsistent, probably because the equation used to calculate the convective transfer of heat through the stem assumes that conductive heat losses are negligible as compared with convective heat transfer, or can be reliably corrected for. However, as transpiration decreased, the conductive heat loss becomes increasingly large relative to the convective transfer, introducing potentially significant errors. In addition, the accumulation of small errors incurred during the temperature measurements may also become important (Ong *et al.*, unpublished). For these reasons, transpiration rates recorded during the early morning and evening were sometimes erratic. In order to minimise errors in temperature measurement, the datalogger was kept in a shaded position and care was taken to ensure that the thermocouple leads were kept away from the heater so that they could not act as conductors.

Because of the errors associated with measurements at low transpiration rates, the night-time values obtained during this study were also considered to be suspect. This may be an important omission because night-time transpiration may contribute a significant proportion of the total crop water use in some species. For example, Green *et al.* (1989) indicated that night-time transpiration may contribute 20 % of the total in kiwifruit. Unreliable transpiration values were also occasionally obtained during the day, mainly during the rainy season when water penetrated the styrofoam insulation; this problem could be avoided by applying additional silicon rubber sealant to the appropriate area.

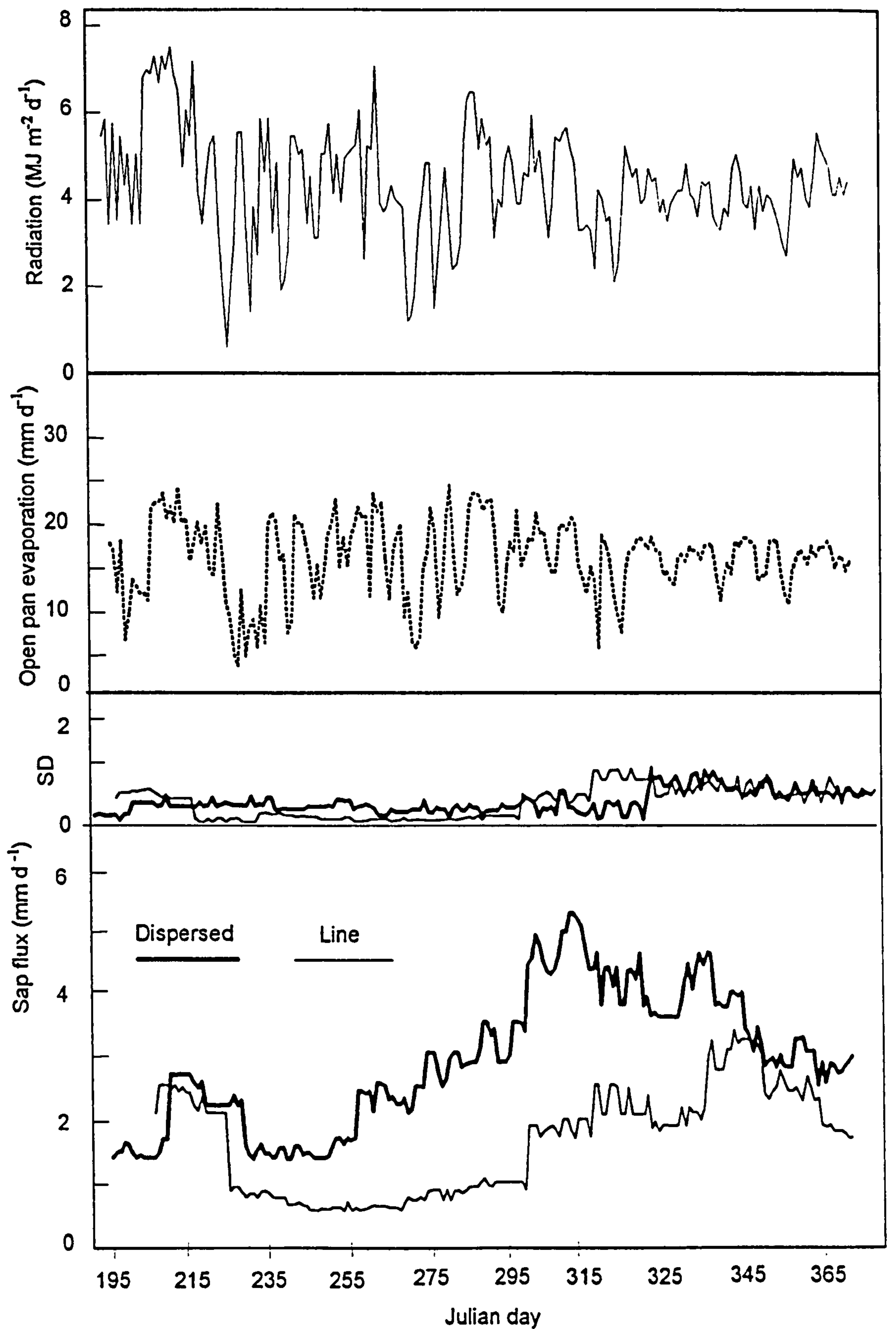


Figure 4.6: Daily mean values for incident radiation, open pan evaporation and pigeonpea sap flux in the line and dispersed treatments, 1990. SD represents the standard deviation for transpiration values ($n=3$).

Figure 4.6 shows the seasonal timecourses for daytime mean sap fluxes in both the line and dispersed pigeonpea. The data represent 12 hour totals from 0700 to 1900 h. The day to day fluctuation in transpiration clearly reflected the concurrent changes in solar radiation and open pan evaporation. The principles behind these relationships were introduced in Section 1.4.1 and will be discussed further in Section 4.4.

The fodder cut at Julian day 220 was followed by a marked reduction in the transpiration rate of pigeonpea in both the line and dispersed treatments, but thereafter transpiration increased progressively with time in both treatments. The transpiration rate of the dispersed pigeonpea was consistently greater than in the line treatment between JD 220-230 and reached a maximum sap flux of 5.3 mm d⁻¹ at JD 314, when the corresponding flux for the line planting was 1.9 mm d⁻¹; thereafter a period of leaf senescence and abscission during grain fill was accompanied by falling transpiration in this treatment. The line planting maintained a green leaf canopy for longer, and attained a maximum sap flux of only 3.3 mm d⁻¹ 45 days later than in the dispersed planting, by which time the sap flux had decreased to 4.0 mm d⁻¹ in the latter.

The more rapid increase in sap flux in the dispersed planting between the fodder cut at JD 220 and the time of maximum transpiration (JD 314 and 359 for the line and dispersed plantings respectively) may be described mathematically by the following exponential relationships (Fig. 4.7):

$$E_d = 0.01 e^{0.01t} \quad \text{equation 4.4}$$

where E_d is the daily transpiration rate of the line planted pigeonpea at t days after Julian day 230 ($r^2 = 0.86$), and:

$$E_w = 0.03 e^{0.02t} \quad \text{equation 4.5}$$

where E_w is the daily transpiration rate of the dispersed planted pigeonpea at t days

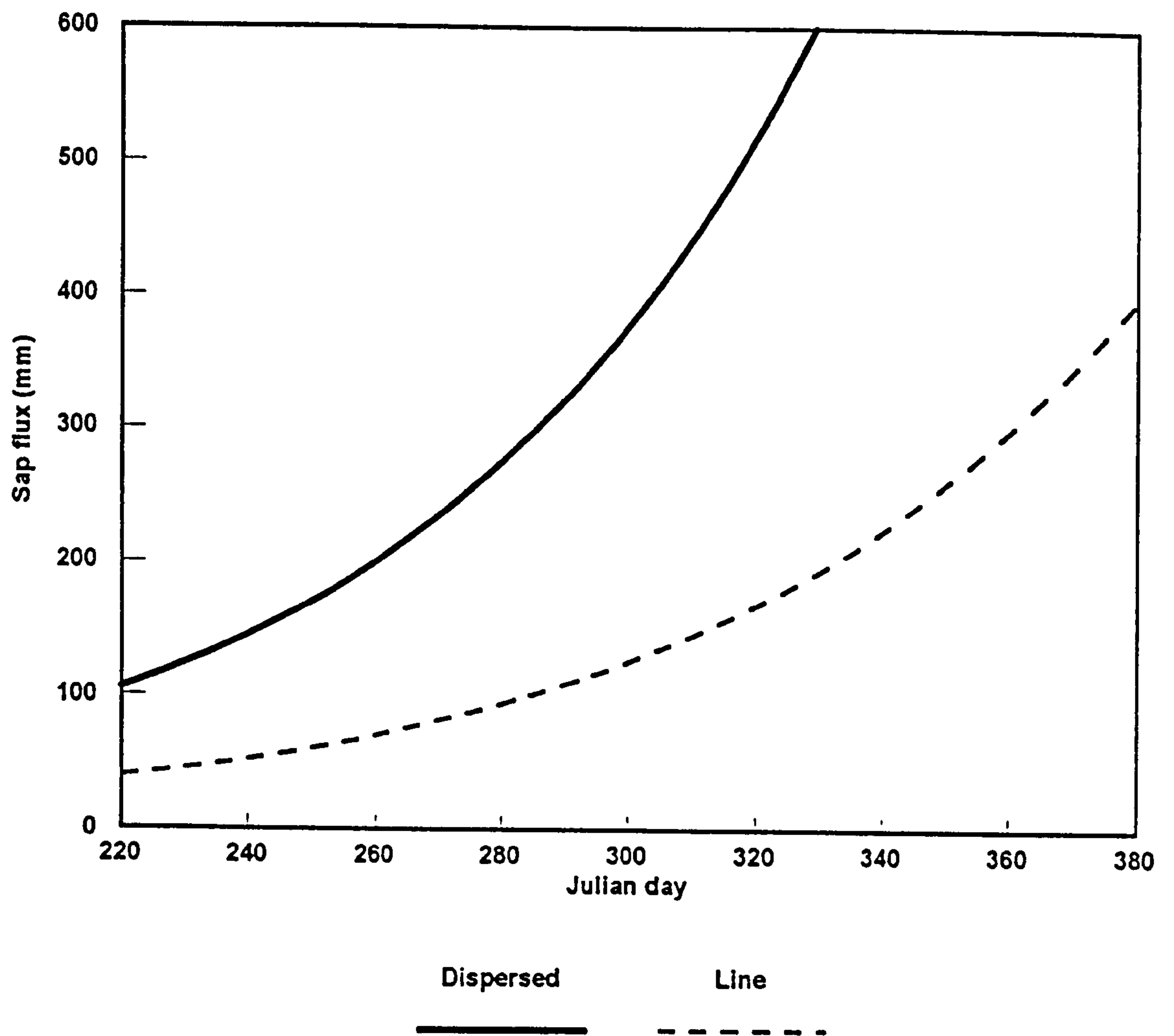


Figure 4.7: Exponential curves fitted to the data for mean daily sap flux between the fodder cut (Julian day 220) and the time of maximum recorded sap flux, 1990 for the line and dispersed planted pigeonpea (Eq. 4.11 and 4.12).

after Julian day 230 ($r^2 = 0.92$).

Under moist conditions, transpiration often increases proportionately to leaf area index (Squire, 1990) and may equal open pan evaporation when the canopy intercepts most of the incident radiation. This usually occurs when L is between 2.5 and 4.0, but is also influenced by the extinction coefficient. The value of L required for 95% radiation interception varies considerably between pigeonpea genotypes with different growth habits and may range between 3.9 - 6.0 (Lawn *et al.*, 1990). Estimates based on simultaneous measurements of L and fractional interception suggest that the L value required for 95 % interception in pigeonpea cultivar ICP 8094 is 4-5. Although L reached approximately 3, maximum sap fluxes recorded in the dispersed treatments were only about one third of open pan evaporation.

4.2.1.1.3 *Diurnal trends in pigeonpea transpiration*

Ong *et al.* (unpublished) reported that transpiration by pigeonpea was largely determined by irradiance during the rainy season at Hyderabad, but partial stomatal closure reduced transpiration rates when water was limiting. Stomata typically demonstrate a diurnal cycle of opening and closure and, in the absence of other limiting factors, tend to increase in aperture with increasing incident radiation. Maximum stomatal aperture often occurs at a photon flux density of about $400 \mu \text{mol m}^{-2} \text{s}^{-1}$ PAR in C3 species, but the saturation value for complete stomatal opening varies between species and the radiation conditions normally experienced within specific environments (Jones, 1992). However, many other environmental and internal factors such as saturation deficit, temperature, available soil water and leaf water status also influence stomatal aperture (Section 1.4.3).

Figure 4.8 shows the diurnal variation in transpiration by the line and dispersed pigeonpea and the corresponding hourly values for saturation deficit and incident shortwave radiation on three representative dates in 1990. The timecourse shown in Figure 4.8a was recorded 14 days prior to the first pigeonpea grain harvest, at which time there was little difference in transpiration between the two treatments, although

the values were slightly lower in the dispersed treatment from 1300 h onwards. This is consistent with the fact that there was little difference in growth rate or productivity during the period up to the first grain harvest.

The relatively high saturation deficits recorded on JD 217 (Fig. 4.8a) are typical of dry season values. Despite the high evaporative demand, the recorded sap fluxes were low in both treatments. These timecourses were recorded during the grain filling period when many of the leaves had been lost, and so the relatively low leaf area index and high proportion of senescent leaves were probably the major factors limiting transpiration. It is also possible that the stomata on the remaining green leaves may have responded directly to the prevailing high saturation deficit by closing, a phenomenon which has previously been observed in groundnut during periods of soil or atmospheric drought to conserve moisture (Black and Squire, 1979). Under dry conditions, transpiration is also influenced by the quantity of stored water in the soil and the ability of the root system to extract this, which in turn affects canopy conductance by reducing leaf water status, leaf expansion and stomatal conductance, and may also exert direct effects on the stomata through hormonal communication between the roots and stomata (Jones, 1992). It seems unlikely that water supply was the major limitation to transpiration in the present study because there was no time lag between the increase in saturation deficit in the morning and the associated increase in transpiration. Unfortunately, the absence of successful measurements of soil moisture content or total crop water use, during this period preclude confirmation of this supposition.

The diurnal timecourses shown in Figure 4.8b were recorded during the rainy season, three days prior to the fodder cut on Julian day 220. Transpiration followed a similar timecourse in both treatments, although the values were consistently higher in the dispersed arrangement. The relatively low leaf area index and saturation deficit probably limited canopy transpiration, despite the plentiful supply of water. Under such rainy season conditions, the diurnal trends in stomatal conductance would largely have been controlled by radiation.

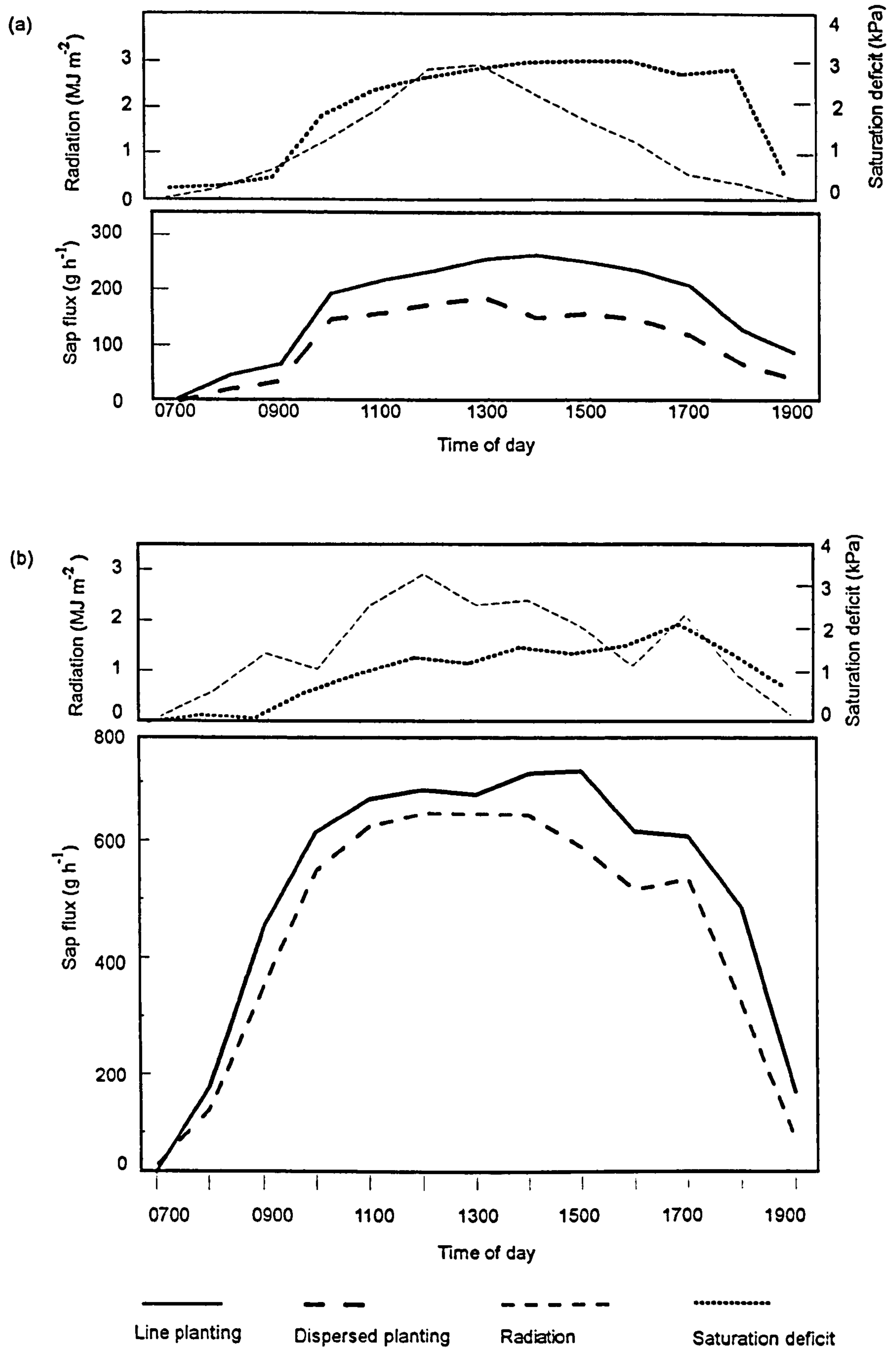


Figure 4.8: Diurnal timecourses for incident radiation, saturation deficit and transpiration in the dispersed and line planted arrangements of pigeonpea, 1990; (a) January 17 (JD 17), (b) August 5 (JD 217) and (c) October 8 (JD 281).

(c)

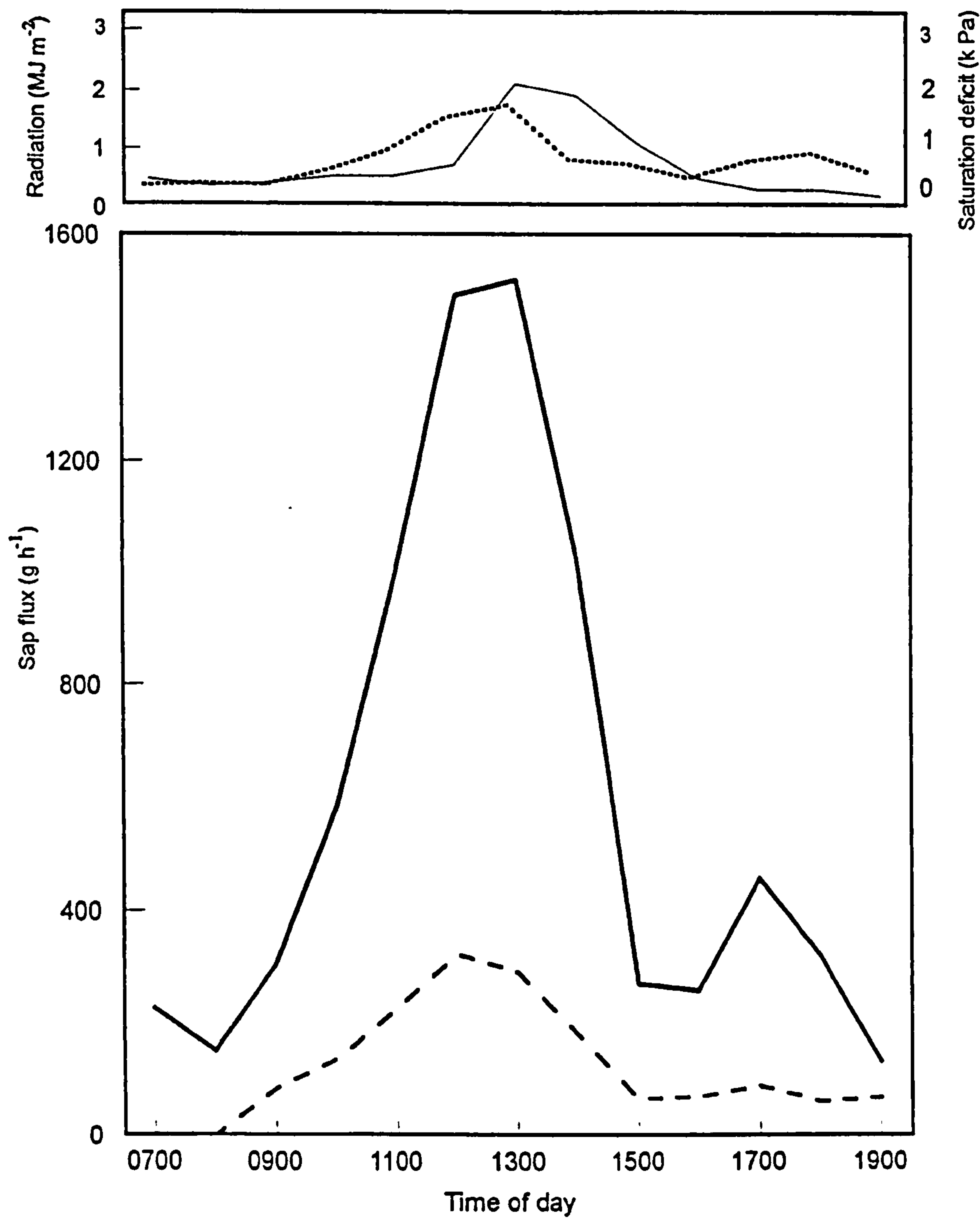


Figure 4.8c shows diurnal trends recorded towards the end of the 1990 rainy season (Julian day 281), on a day with heavy cloud cover during the afternoon. Concurrent fluctuations in saturation deficit and transpiration are apparent. The canopy of the dispersed pigeonpea was considerably larger than in the line planting by this time and the transpiration rate at midday was approximately five times greater than in the line planting. The higher L in the dispersed planting is likely to have been a major reason for this.

4.2.1.1.4 *Accumulated transpiration*

Figure 4.9 shows the cumulative values for daily transpiration between the fodder cut on August 8 1990 (JD 220) and the final grain harvest on January 25 1991 (JD 25). During this period, the line planted pigeonpea transpired 262 mm of water, approximately half of that in the dispersed planting (517 mm). The water use ratio (ratio of net uptake of carbon dioxide for photosynthesis to the net loss of water by transpiration, ϵ_w) calculated using equation 1.9 was similar in the line and dispersed pigeonpea (8.0 and 8.7 kg ha⁻¹ mm⁻¹ respectively). Thus, the dispersed planting, which transpired twice as much water, also produced approximately twice as much dry matter as the line planting over the same period (Table 4.5).

As ϵ_w is inversely proportional to saturation deficit (cf. Section 1.4.3), the values obtained tend to be higher during the rainy season; those shown in Table 4.5 are means calculated over an extended period which included both the wet and dry seasons. Odongo *et al.* (1995) have previously reported ϵ_w values for pigeonpea (cv. ICP 8094) of 5.4 kg ha⁻¹ mm⁻¹ in the dry season and 26.2 kg ha⁻¹ mm⁻¹ in the rainy season at ICRISAT Center, while Sadar Singh *et al.* (1981) obtained a post-rainy season value of 7.6 kg ha⁻¹ mm⁻¹ for cultivar ICP-1.

4.2.1.1.5 *Relationship between accumulated intercepted radiation and transpiration*

Canopy conductance (effectively the product of the leaf conductance and leaf area index) has a major influence on transpiration by crops. Canopy conductance can vary

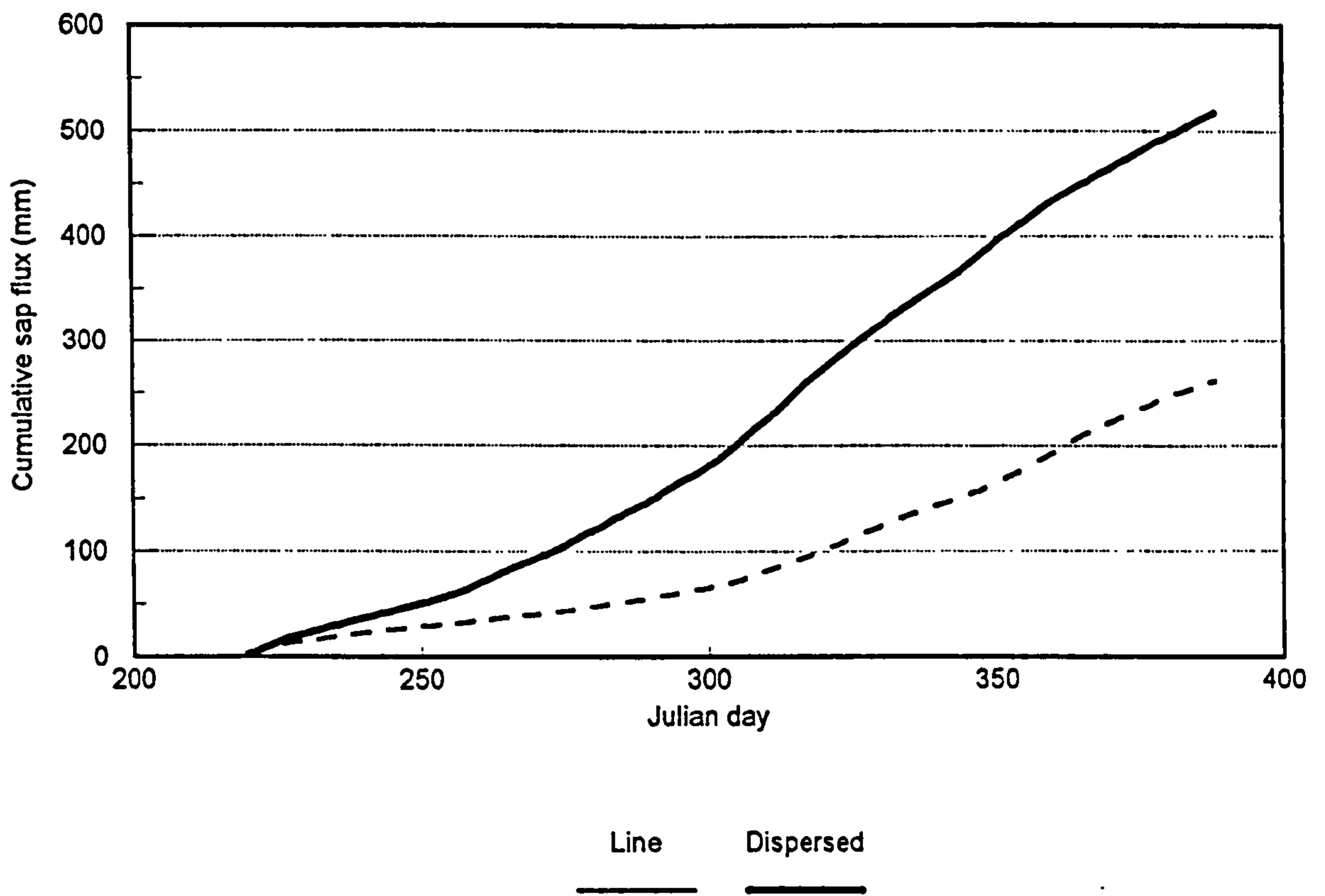


Figure 4.9: Daily values for cumulative sap flux in the dispersed and line planted treatments of pigeonpea between the fodder cut on August 8, 1990 (JD 220) and final grain harvest on January 25, 1991 (JD 25).

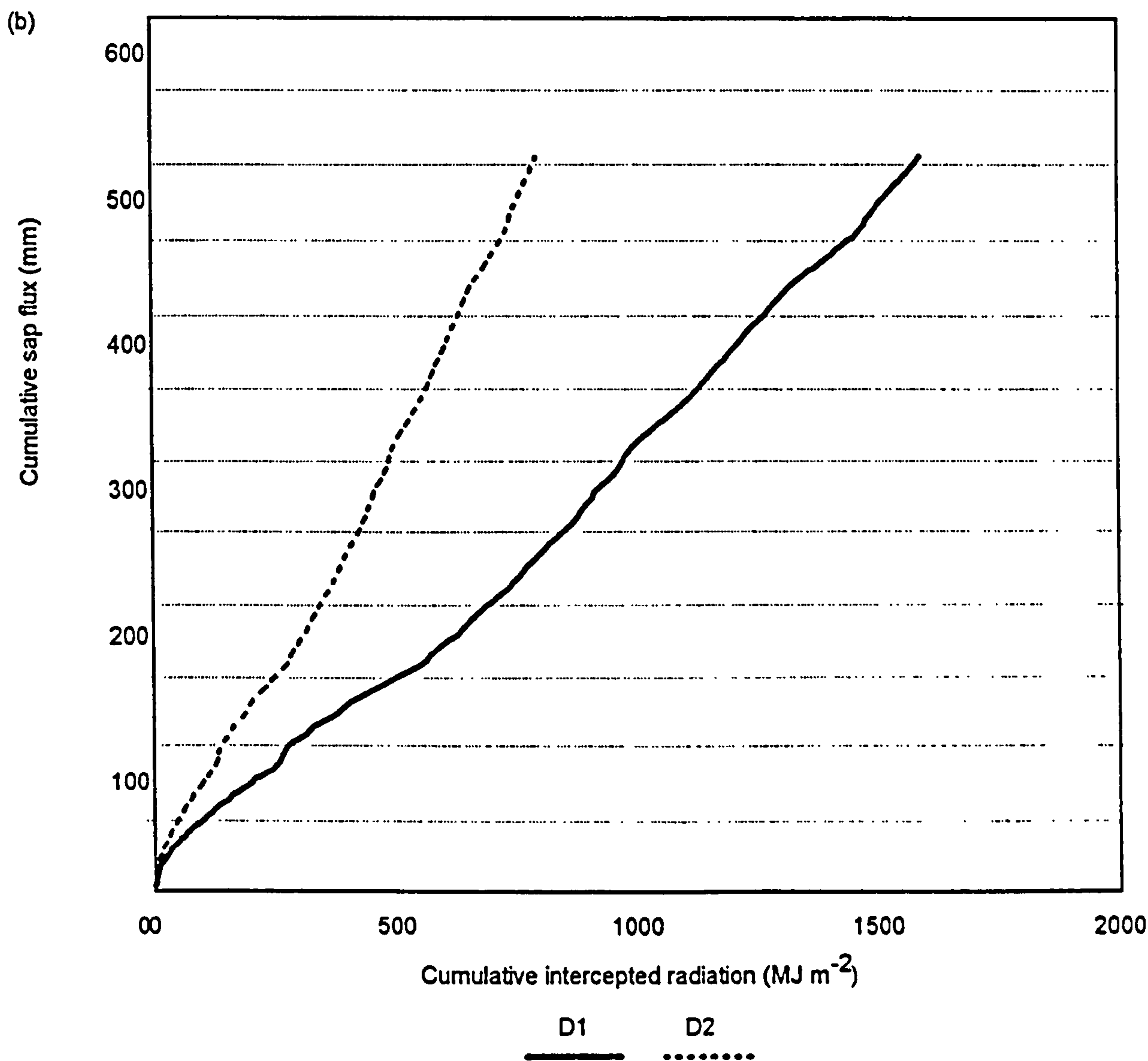
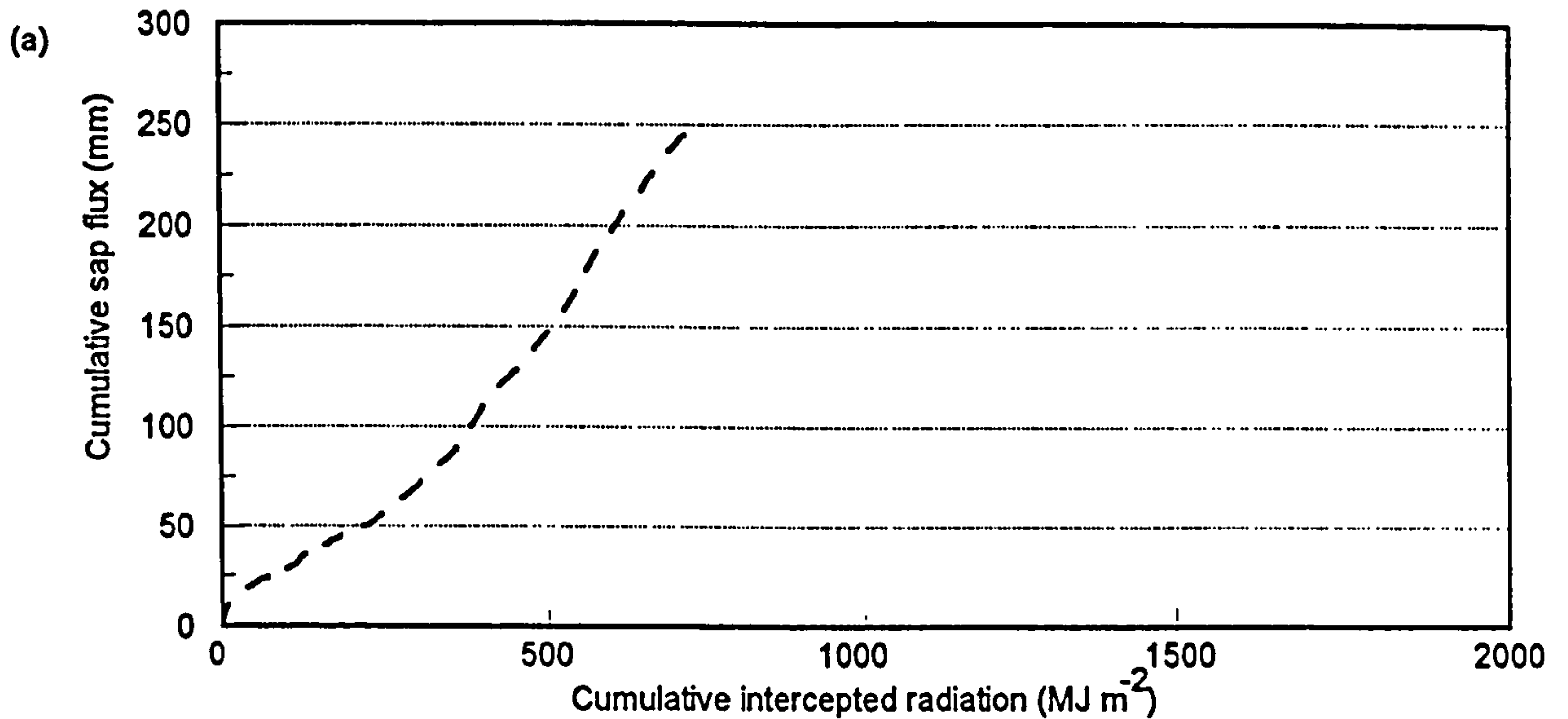


Figure 4.10: Relationship between cumulative sap flux and intercepted radiation between August 13 (JD 225) 1990 and final grain harvest on January 25 (JD 25) 1991; (a) line planted and (b) dispersed treatment. Relationship D1 assumed that the pigeonpea canopy covered both solarimeter positions 1 and 2 (Fig. 2.5) throughout the entire period, while D2 assumed that only position 1 was covered.

Table 4.5: Water use ratios (ϵ_w) for pigeonpea for the period between August 8 1990 and final harvest on January 25 1991

	Dry matter production (t ha ⁻¹)	Cumulative sap flux (mm)	Water use ratio (kg ha mm ⁻¹)
Line	2.09	262	8.0
Dispersed	4.51	517	8.7

Table 4.6: Values used in equation 2.12 to estimate the transpiration of groundnut in 1990. Values in brackets are the standard deviations of the ten day means

DAS	Saturation deficit (kPa)			Leaf temperature (°C)			Estimated daily transpiration (mm)		
	Sole	Line	Disp.	Sole	Line	Disp.	Sole	Line	Disp.
30	0.46 (0.16)	0.59 (0.19)	0.64 (0.18)	25.28 (1.84)	25.25 (1.73)	24.74 (1.78)	1.28	1.18	0.81
40	0.48 (0.48)	0.48 (0.55)	0.71 (0.61)	25.15 (2.80)	25.24 (2.35)	24.63 (2.60)	1.64	1.71	1.21
50	0.76 (0.22)	0.72 (0.12)	0.64 (0.11)	27.57 (1.69)	27.46 (1.24)	27.12 (1.13)	2.70	2.87	2.13
60	1.02 (0.08)	1.01 (0.07)	0.91 (0.07)	27.87 (0.63)	29.08 (0.53)	29.02 (0.44)	3.70	5.10	3.31
70	0.58 (0.29)	0.47 (0.21)	0.47 (0.26)	27.51 (1.21)	27.63 (1.14)	27.23 (1.23)	4.14	3.85	3.53
80	0.54 (0.26)	0.59 (0.27)	0.58 (0.25)	27.91 (1.78)	29.22 (1.67)	28.44 (1.75)	3.49	3.38	3.04
90	1.34 (0.69)	1.14 (0.59)	1.22 (0.68)	29.20 (0.86)	29.02 (1.19)	29.59 (1.30)	1.36	0.76	0.86
100	0.97 (0.39)	0.82 (0.35)	0.97 (0.69)	28.09 (1.14)	29.28 (1.22)	28.32 (1.38)	0.55	0.25	0.19

considerably for a given value of L due to differences in leaf conductance or orientation (Squire, 1990). In order to examine the contribution of leaf conductance to changes in canopy conductance, it is useful to express transpiration in relation to intercepted radiation. Under moist conditions, transpiration approaches potential evaporation when leaf conductance is high as most of the solar energy intercepted by the crop canopy is used to evaporate water (Mathews *et al.*, 1988). However, as the canopy ages and begins to senesce, canopy conductance decreases due to reductions in both L and stomatal conductance, and the rate of evaporation per unit of intercepted radiation also decreases. This relationship was examined for pigeonpea by plotting cumulative transpiration against the values for intercepted radiation derived from the solarimeter measurements.

The relationship obtained for the line planted pigeonpea between five days after the final fodder cut (August 13 1990, JD 225) and final harvest is shown in Figure 4.10a. No data are available for the period between the fodder cut and JD 230 because of the need to reinstall and stabilise the solarimeters and heat balance equipment. A linear regression line fitted over the period indicates that 2.04 MJ of radiation were intercepted for each kg of water transpired ($r^2 = 0.97$), although transpiration per unit of intercepted radiation was lower during the first 100 days after the fodder cut than during the period preceding final harvest. Thus, between JD 225-324, 421 mm of rain were received and 3.03 MJ of radiation were intercepted per kg of water transpired ($r^2 = 0.98$), but this value decreased to 1.49 MJ kg⁻¹ ($r^2 = 0.997$) between Julian day 325 and final harvest, when only 17 mm of rainfall was received. The mean daily open pan evaporation over each of these periods was 4.1 mm.

Canopy conductance should not have been rate-limiting for transpiration during the first 100 days after the fodder cut because the pigeonpea was well supplied with water, healthy and growing rapidly. During the latter stages of the season, some reduction in stomatal conductance might have been expected due to the declining availability of water and the increasing proportion of senescent leaves. However, these effects appear to have been compensated for by other factors, in view of the

increased gradient of the relation between accumulated transpiration and intercepted radiation towards the end of the season. Transpiration was probably sustained despite the lower mean daily temperature because the atmospheric saturation deficit was higher, thereby maintaining the leaf to air vapour pressure difference which drives transpiration.

The absence of direct measurements of intercepted radiation by pigeonpea in the dispersed planting precluded a similar analysis for this treatment. However, Figure 4.10b indicates the large differences in the predicted relationship between cumulative transpiration and cumulative radiation interception calculated using the two extreme estimates of radiation interception for the dispersed planting described in Section 4.1.4. The first assumed that the pigeonpea covered the solarimeters located at positions 1 and 2 throughout the measurement period, while the second assumed that only position 1 was shaded.

The relationship between transpiration and intercepted radiation was examined for the period between groundnut harvest (Julian day 311) and pigeonpea final harvest (Fig. 4.11) in both treatments. During this period, when direct measurements of radiation interception by pigeonpea were available from the below-groundnut solarimeters at positions 1 and 2 (Fig. 2.5), 2.7 MJ of radiation were intercepted per kg of water transpired ($r^2 = 0.997$) in the dispersed planting, as compared to 1.5 MJ kg^{-1} in the line planting. As the pigeonpea in both treatments was of the same age and subject to similar environmental conditions, the differing relationship between transpiration and intercepted radiation is surprising. The main contributory factors may have been differences in rainfall interception by the canopy, or in leaf and boundary layer resistances between the two treatments. This observation is considered further in relation to the available microclimatic measurements in Section 4.4. Experimental error may have been an additional contributory factor since it was difficult to keep the solarimeter tubes at ground level clean during the post-rainy season. If tubes were not completely clean in the dispersed planting, this would have decreased the quantity of radiation that they detected, thereby causing the true quantity of radiation intercepted by the pigeonpea canopy per unit of transpired

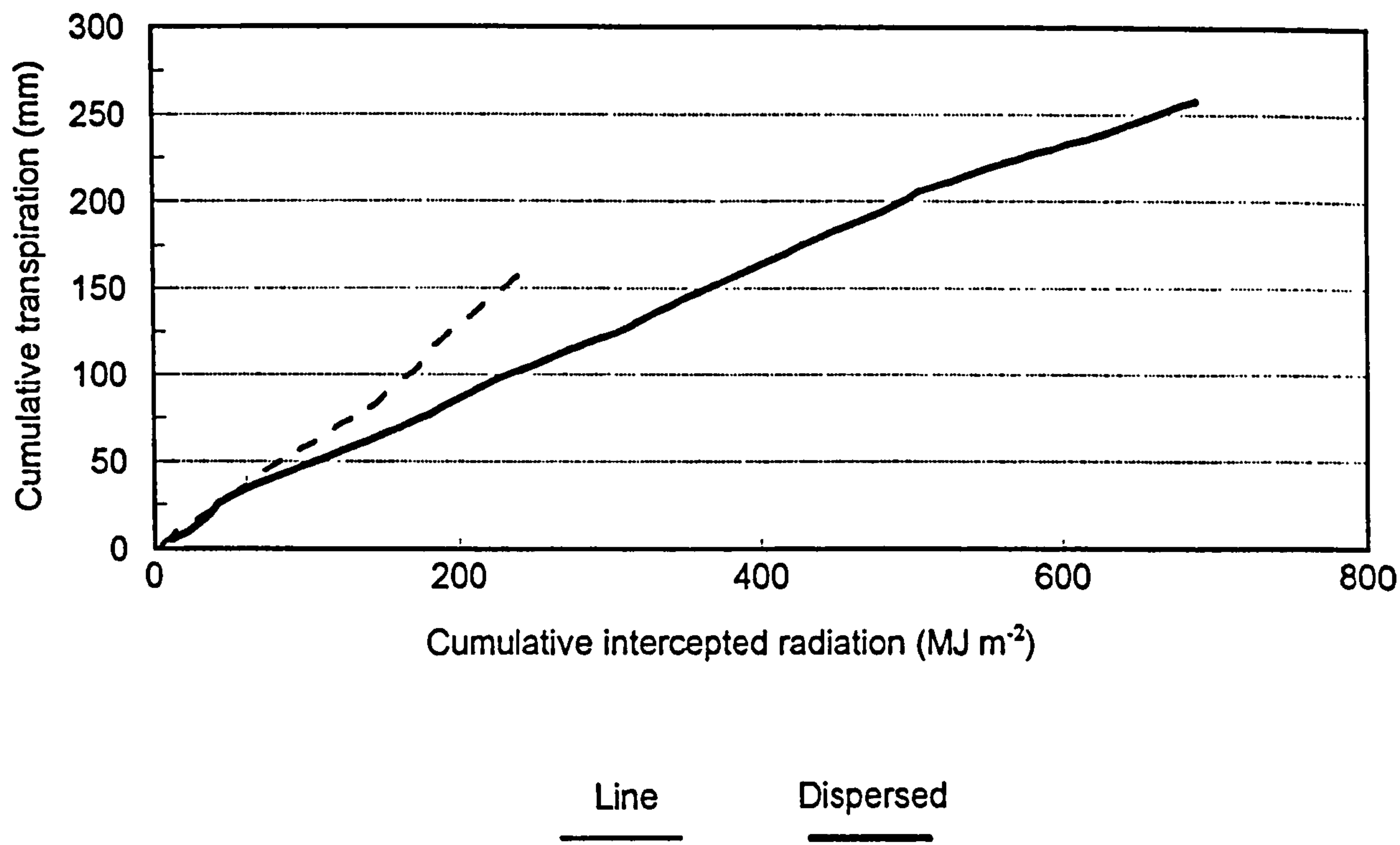


Figure 4.11: Relationship between cumulative sap flux and intercepted radiation in pigeonpea between groundnut harvest (JD 311, 1990) and final pigeonpea grain harvest (JD 25, 1991).

water to be overestimated and resulting in the observed discrepancy between the two treatments.

4.2.1.2. *Groundnut*

In order to obtain accurate measurements of diffusive resistance, it is essential that the leaf surfaces are dry. This makes it extremely difficult to make porometry measurements during periods of frequent rainfall, as in the present experiment. Due to the large number of other regular measurements that are required for porometric estimation of transpiration, and the additional problems concerned with supply and maintenance of a porometer in good working order, it proved impossible to estimate groundnut transpiration using the method described in Section 2.3.2.2. Transpiration by groundnut was therefore estimated using equation 2.12, although this approach relied on a number of assumptions and estimates derived from other sources.

The hourly records of leaf temperature and saturation deficit were used to estimate values for v_i , v_b for inclusion in equation 2.12. v_i and v_b were calculated from the daytime mean values for leaf temperature and saturation deficit (0900-1700 h; Table 4.6). Ten day means for each variable were calculated from the daytime means recorded for the 10 d period centred around each estimate of L (Fig. 3.9). A limited number of complete diurnal trends for stomatal resistance were obtained by diffusion porometry, and the mean values for three successful days (45, 61 and 75 DAS groundnut) were used to obtain an estimate of the seasonal mean stomatal resistance (0.87 s cm^{-1}).

Boundary layer resistance (r_b) is approximately proportional to windspeed and only slightly influenced canopy characteristics. The influence of r_b on transpiration under field conditions is usually small relative to L , r_i and v_i-v_b , but depends on stomatal resistance and the absolute level of r_b . For example, if the stomata are fully open and r_i is therefore low, changes in r_b may markedly affect transpiration per unit leaf area. Azam-Ali (1984) studied factors influencing transpiration by groundnut and concluded that, for similar locations and windspeeds, a single-site value of r_b is

probably adequate. Because very few estimates of r_b were obtained in the present study, the mean value obtained by Azam-Ali (1984) at ICRISAT Center between January and March (0.34 s cm^{-1}) was used. This might have resulted in a slight underestimation of r_b , because data from the ICRISAT meteorological station indicate that mean wind speed between March and May tends to be higher than during the rainy season.

The groundnut canopy was considered as a single layer for the purposes of estimating transpiration in the present study, although two or more separate layers would normally be defined and measured as soon as significant shading of the older leaves in the canopy began. Azam-Ali (1984) distinguished two canopy layers from 59 DAS onwards when working with groundnut cultivar TMV-2, which has a bunched growth habit, but this shading effect is less marked in cultivar Kadiri-3 due to its semi-spreading habit.

For each 10 day period between 25 and 105 DAS, the mean daily transpiration rate was estimated using the fixed values of r_i and r_b , the appropriate 10 day means for v_i and v_b , and the L values obtained from the growth analysis. The values for cumulative transpiration calculated in this way are shown in Figure 4.12. The sole and line planted groundnut transpired similar total quantities of water (189 and 191 mm respectively), whilst the dispersed groundnut transpired approximately 20 % less (151 mm at 100 DAS). These values do not take account of transpiration between emergence (7 DAS) and 25 DAS or between 105 DAS and final harvest at 111 DAS, and so the total water use is likely to have been underestimated. However, this underestimation is likely to have been small because transpiration would have been limited by the low L values prior to 25 DAS and progressive canopy senescence after 105 DAS. Variation in L had the greatest influence on the estimates of canopy transpiration obtained in this way. Thus, the seasonal changes in L values (Fig. 3.9) would have resulted in a 23-fold variation in daily transpiration for given values of v_i and v_b , whereas the observed range of values for $v_i - v_b$ (2.2-3.3 kPa) would have produced only a 1.5-fold variation in daily transpiration for specific L values.

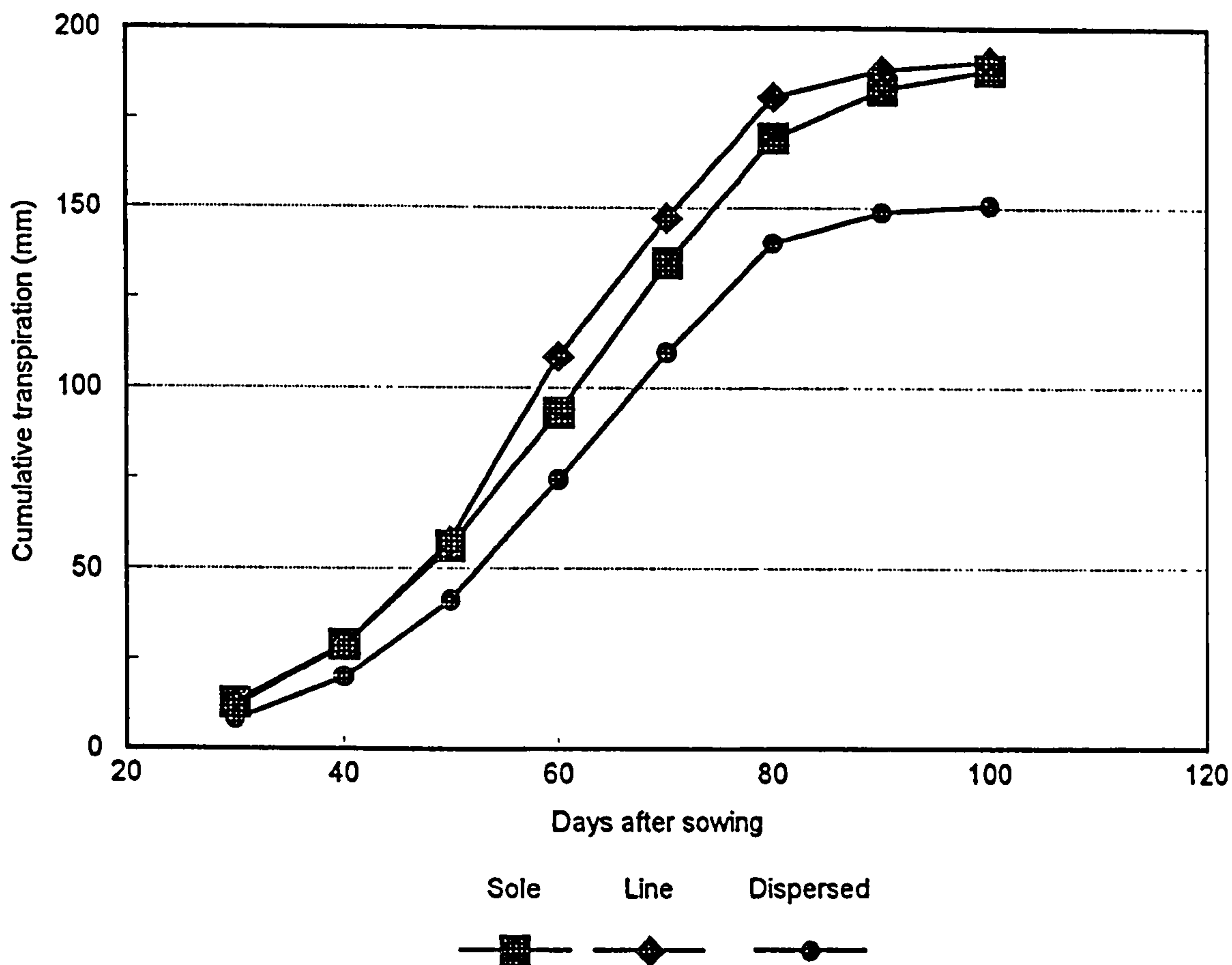


Figure 4.12: Cumulative transpiration by groundnut estimated using the method described in Section 4.2.1.2.

The estimated values for seasonal total transpiration by groundnut comprise 35, 36 and 24 % of the rainfall received during the period between sowing and harvest (522 mm) in the sole, line and dispersed treatments respectively, or 22, 23 and 15 % of the total annual rainfall recorded from May 1 1990 (834 mm).

More accurate estimates of transpiration by groundnut might have been obtained using hourly values of v_i and v_s . Total daily transpiration could have been estimated from the area under the curve showing the mean diurnal variation in transpiration for consecutive ten day periods. However, this increased level of sophistication in the analysis was not considered justified, due to the considerable uncertainties in the values used in the denominator of equation 2.12.

The values for cumulative transpiration and dry matter production in groundnut are shown in Table 4.7. The values of water use ratio calculated at 80 DAS (before the observed decline in TDM) and at final harvest were similar in all treatments, falling within the range 1.0-1.8 g kg⁻¹. In healthy, well watered non-senescent crops, saturation deficit is the primary factor influencing ϵ_w for a given leaf area. Because ϵ_w is often inversely related to saturation deficit (D), the product of ϵ_w and D is frequently conservative, whilst ϵ_w is variable. Thus, $\epsilon_w D$ can be used to compare between different experimental sites, season or treatments (Squire, 1990). $\epsilon_w D$ values were calculated using the appropriate daytime mean saturation deficit for each treatment (0700 - 1800 h).

Unfortunately, no published values for either ϵ_w or $\epsilon_w D$ in groundnut during the rainy season at Hyderabad are available for comparison. Although previous studies of ϵ_w in groundnut cultivar Kadiri-3 have been reported (e.g. Ong *et al.*, 1987; Mathews *et al*), all have involved stands grown on drying soil. As ϵ_w increases sharply when water is limited (Turner, 1986), it is not surprising that the reported values of $\epsilon_w D$ (2.9-5.0 g kPa kg⁻¹) were considerably higher than those shown in Table 4.7. The extensive occurrence of foliar disease in the current study may also have reduced ϵ_w below its potential for the prevailing environmental conditions.

Table 4.7: Relationship between transpiration and dry matter production in groundnut, 1990; D represents saturation deficit

		Sole	Line	Dispersed
80 DAS	TDM (g m ⁻²)	291	290	246
	Cumulative transpiration at 85 DAS (mm)	170	181	140
	ε _w (g kg ⁻¹)	1.7	1.6	1.8
	ε _w D at 85 DAS (g kPa kg ⁻¹)	1.2	1.1	1.0
Final harvest	TDM (g m ⁻²)	252	198	152
	Cumulative transpiration at 105 DAS (mm)	189	191	151
	ε _w (g kg ⁻¹)	1.3	1.0	1.2
	ε _w D (g kPa kg ⁻¹)	1.1	0.8	0.8

Hebbar *et al.* (1994) measured ϵ_w between 32 - 60 DAS in 14 groundnut cultivars grown in a greenhouse under well watered conditions and obtained a mean value of 2.0 g kg⁻¹, with a range of 1.2 - 2.7 g kg⁻¹. These values are similar to those shown in Table 4.7. However, Hebbar *et al.* did not measure saturation deficit, and cultivar Kadiri-3 was not included in their study. Transpiration by groundnut in the present study was not estimated directly from ϵ_w values reported elsewhere, because of the lack of previous estimates of ϵ_w for cv. Kadiri-3 in the rainy season.

4.2.2 Stored soil moisture

4.2.2.1 1989

On seven occasions between November 11 1989 and February 2 1990, a Troxler neutron moisture meter (neutron probe) was used to measure volumetric soil moisture content at 15 cm depth intervals in each of the 48 access tubes. The intention was to quantify changes in stored soil moisture for each treatment during the early part of the dry season, prior to the first pigeonpea grain harvest. Unfortunately, severe malfunction of the neutron probe caused considerable variation in the standard counts both within and between sampling dates (values ranged from 733 to 918). Although limited variation in the standard counts obtained may be expected during the course of the day due to changes in temperature, a sudden shift of more than 1.5 % as compared with the previous four readings is generally indicative of an abnormality in function or handling of the probe (Troxler International Ltd., 1983). There are several possible explanations for the observed variation in standard count. The most likely is that damage or premature ageing of one or more of the electronic components had occurred because the probe was in almost constant daily use and was subject to transportation over rough terrain. Another possibility is that the flow of moist air through the instrument (which is not sealed) resulted in the accumulation of condensation which affected measurements (Greacen, 1981). However, the instrument was stored in warm dry conditions when not in use in order to avoid this problem.

Unfortunately, facilities were not available to repair the neutron probe prior to the pigeonpea grain harvest in January 1990, and a replacement probe was not available on a regular basis to continue measurements. Tests on three consecutive dry days using the faulty probe and two other Troxler probes confirmed the erratic and severe nature of the fault, which made it impossible to draw any meaningful conclusions from the measurements made during the soil drying cycle. The results obtained suggest that there was no progressive reduction in stored soil moisture over the measurement period (Fig. 4.13).

Daniel *et al.* (1989) also studied depletion of soil moisture under perennial pigeonpea growing on a vertisol at ICRISAT Center, and their results may provide some indication of the type of response that might have been expected in the present study, despite the greater moisture retention properties of vertisols as compared with alfisols. These workers found that soil moisture depletion was greatest at depths of 30-45 cm during the first year of pigeonpea growth and between 30-60 cm during the period of maximum growth, during flowering and early pod development.

4.2.2.2 1990

4.2.2.2.1 Calibration

A fully functional neutron probe was available in 1990 and was used to measure soil moisture content using all 48 access tubes on nine occasions between August 17 1990 and February 6 1991. During calibration (Section 2.3.3), soil moisture was recorded at nine depths on six occasions, producing 432 data points. Volumetric water content calculated from the gravimetric samples was plotted against the corresponding count ratio readings obtained from the neutron probe to determine the calibration equation. Because the soil profile was relatively uniform (Section 3.5.5.), it unnecessary to produce separate calibration equations for each 15 cm soil depth increment. The data were plotted for various different increments and the highest correlation between count ratio and volumetric soil content was obtained using only

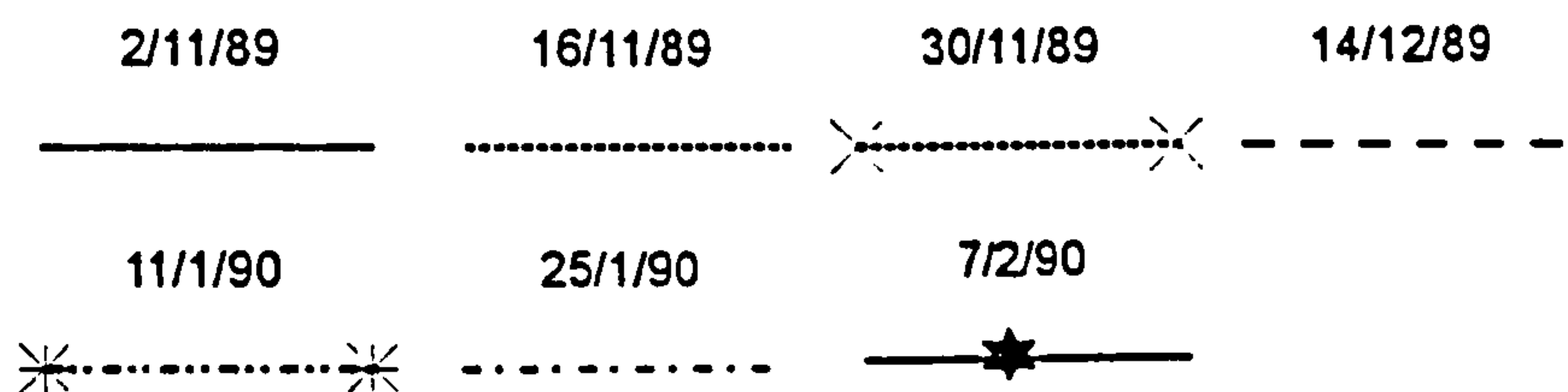
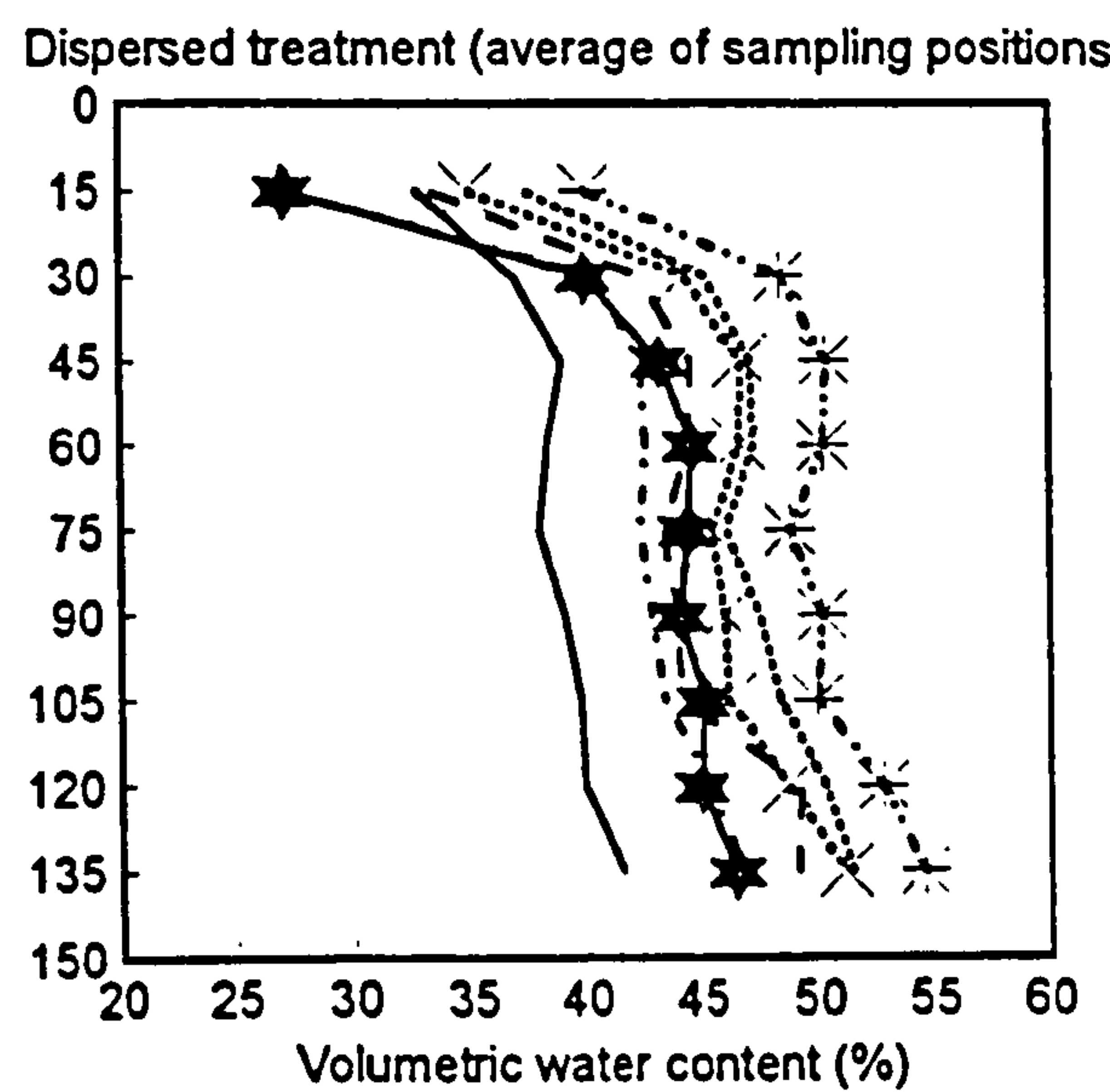
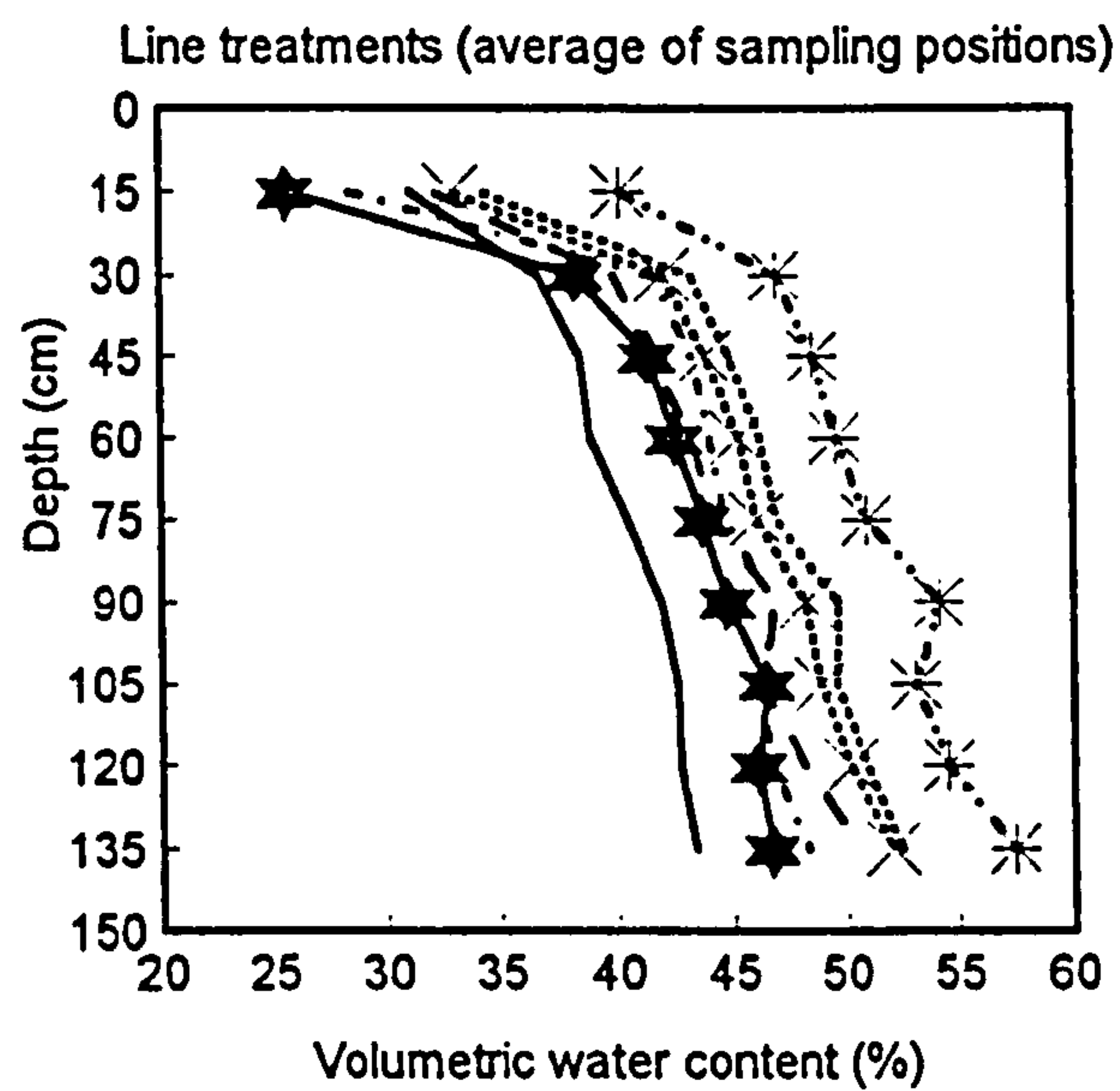
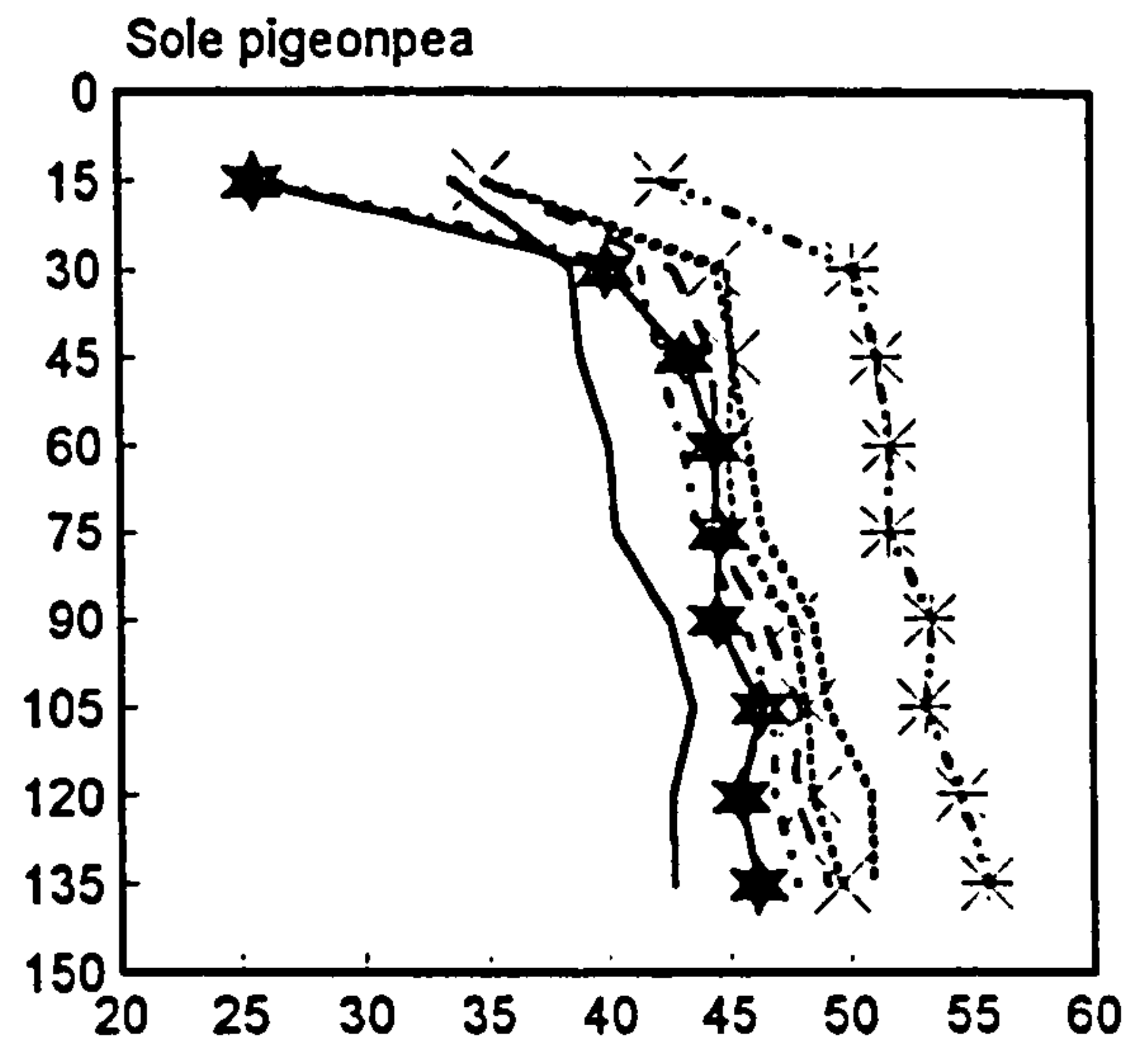
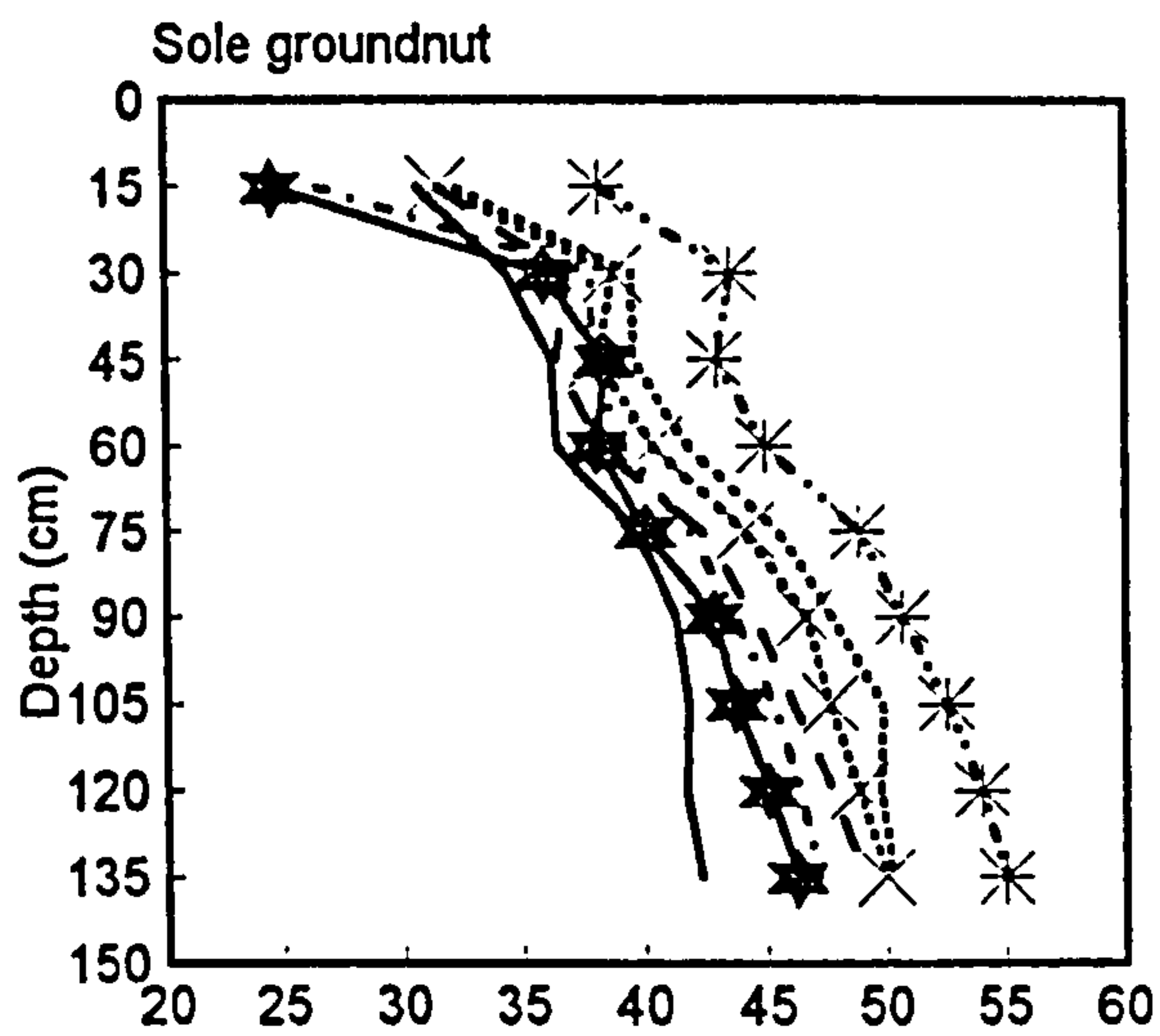


Figure 4.13: Neutron probe measurements of stored soil moisture, 1989.

two depth intervals, 0-60 cm and 60-135 cm. The equations obtained for the 0-60 and 60-135 horizons are respectively:

$$V = -0.1354 + C (0.4582) \quad \text{equation 4.6}$$

$$V = -0.2273 + C (0.5436) \quad \text{equation 4.7}$$

where V is the volumetric soil water content and C is the count ratio reading from the neutron probe. For each 15 cm depth interval, volumetric water content was calculated using a conversion factor of 150.

Despite the removal of obviously spurious values from the count ratio vs. volumetric water content data, the r^2 values were low (0.51 and 0.61 for the 0-60 and 60-135 cm depth increments) indicating a lack of precision in the data. The precision refers to the dispersion of the observations and may be reduced by the random errors arising from site heterogeneity, changes in the characteristics of the instrument electronics, nuclear delay and use of an inappropriate calibration equation (Williams and Sinclair, 1981).

4.2.2.3 *Soil moisture content profiles*

Figure 4.14 shows the treatment mean profiles of soil moisture content on four representative sampling dates during the drying cycle. The first sampling date was during the rainy season (30 DAS groundnut), while the remaining measurements were made between groundnut harvest and the final pigeonpea grain harvest.

As expected, the profiles for sole groundnut showed a marked decrease in soil moisture content between the first and second measurement dates on August 17 and November 28 1990 (53.4 mm accumulated difference between 0-150 cm; Fig. 4.14b). The depletion in soil moisture continued more slowly over the remainder of

the drying cycle, presumably due to soil surface evaporation and deep drainage. Total soil moisture depletion to the maximum measurement depth was 90.3 mm between August 17 1990 and January 23 1991.

In all other treatments, soil moisture content continued to decrease throughout the profile over the entire measurement period. Daniel (1989) reported similar rates of soil water depletion in the 30-150 cm horizons by perennial pigeonpea in the second year of growth. The decline during the drying cycle in the total quantity of water present in the soil profile between 0 and 150 cm is shown in Figure 4.15, while a summary of the data together with the associated standard errors is presented in Table 4.8. The data clearly indicate that there was little difference in the rate of water extraction between the three treatments containing pigeonpea, but that the sole pigeonpea crop exhibited the greatest extraction (133 mm), while the sole groundnut extracted the least water (88 mm).

By January 1991, the dispersed pigeonpea had developed a more extensive root system than the line planting (Section 3.5.5) and had transpired approximately twice as much water as the line planting between August 1990 and January 1991 (Table 4.5), suggesting that a greater quantity of water was extracted in the dispersed treatment. This observation apparently conflicts with the neutron probe data, which indicate that the dispersed and line plantings extracted 118 and 111 mm respectively. However, the neutron probe data may be misleading because, although the roots extended to a depth of at least 2.0 m (Section 3.5.5), changes in soil moisture could only be measured to 1.5 m. An unknown proportion of the water transpired by the dispersed pigeonpea during the drying cycle was therefore extracted from depths below 1.5 m.

Root distribution and transpiration were not measured in the sole pigeonpea. However, as biomass productivity was lower than in the line or dispersed plantings between August 1990 and the final grain harvest (Table 3.27), the sole pigeonpea

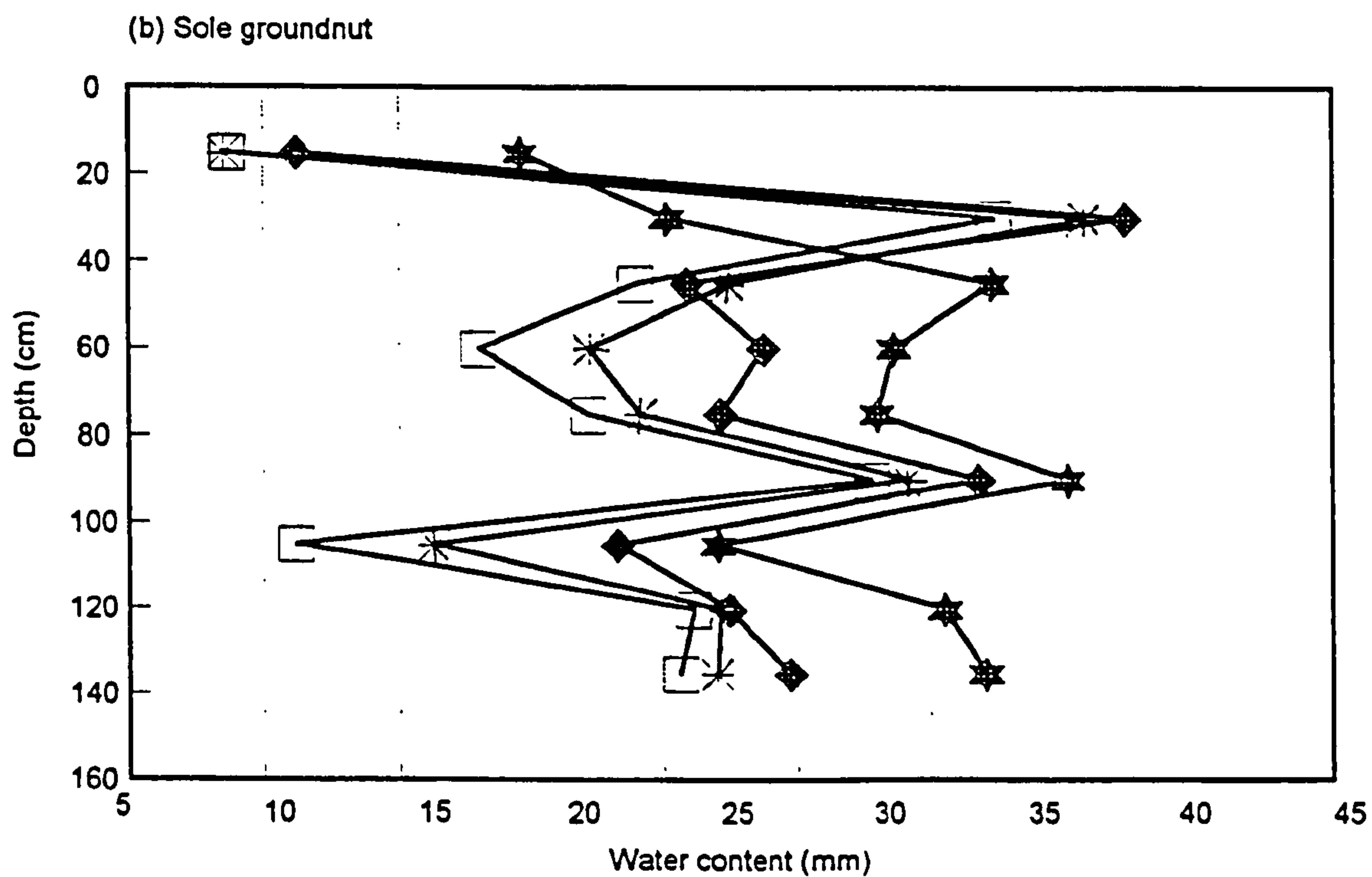
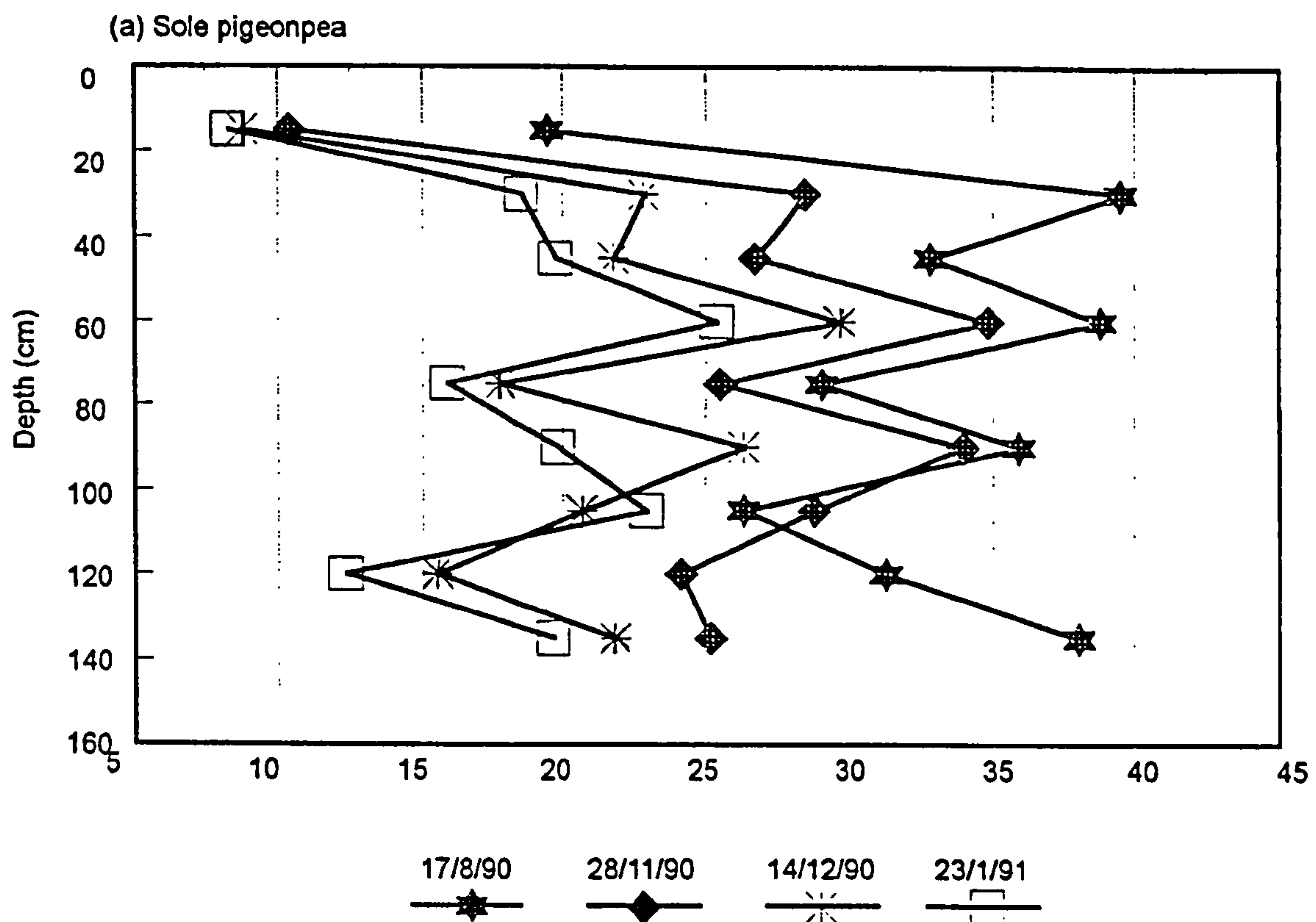
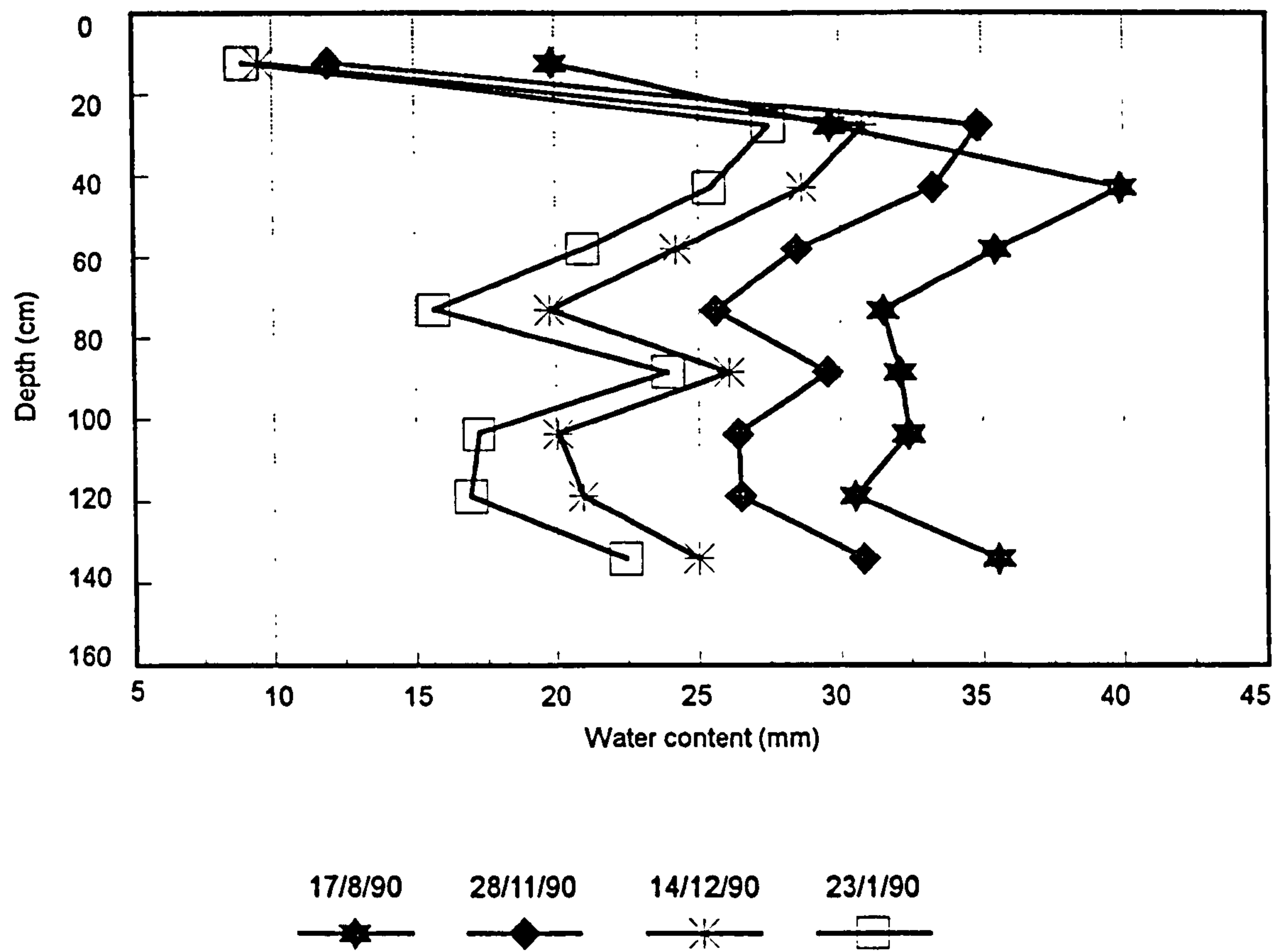
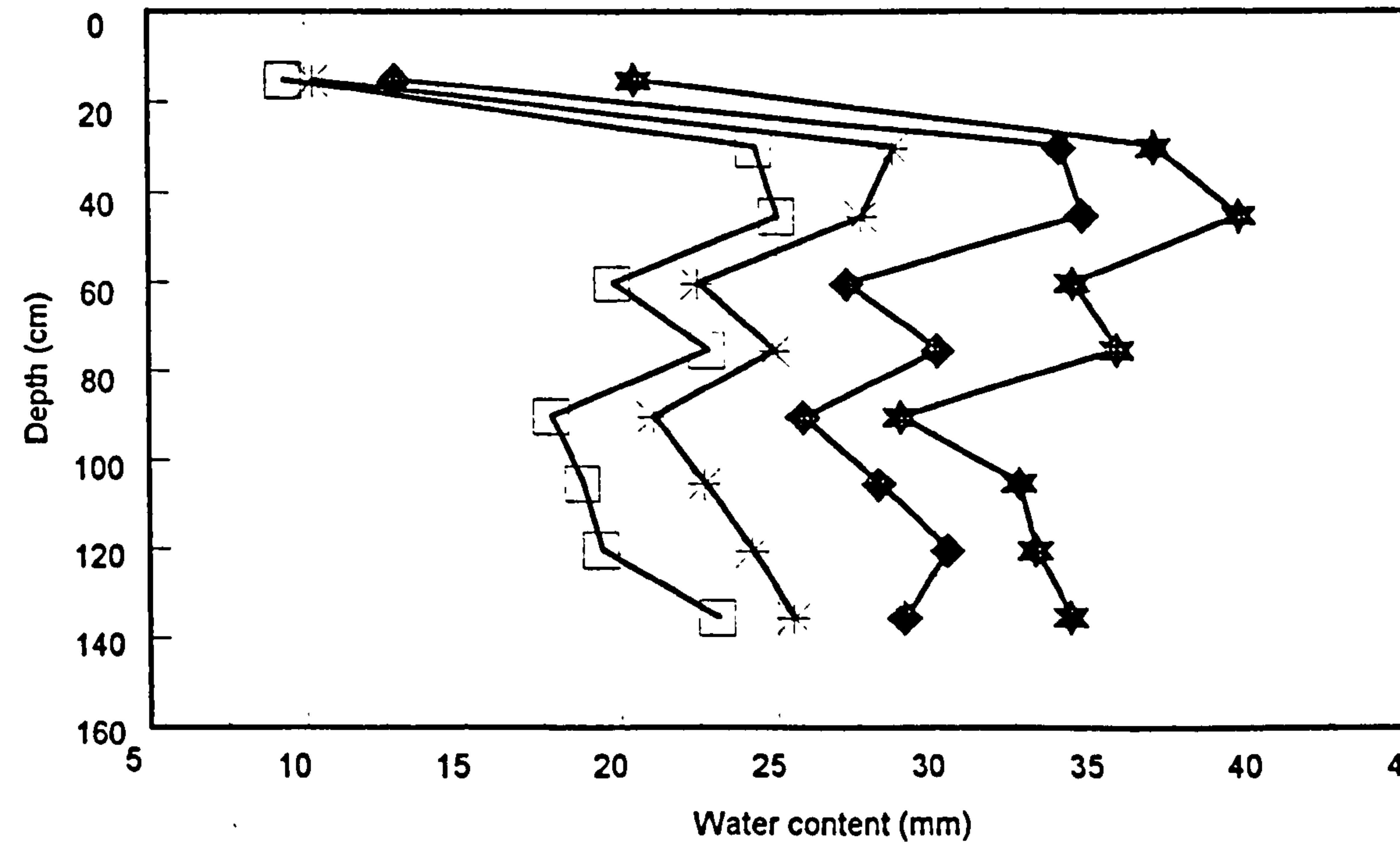


Figure 4.14: Stored soil moisture, 1990 -1991. Values calculated from neutron probe measurements and the calibration equations shown in Section 4.2.2.1

(c) Line treatment (average of all sampling positions)



(c) Dispersed treatments (average of all sampling positions)



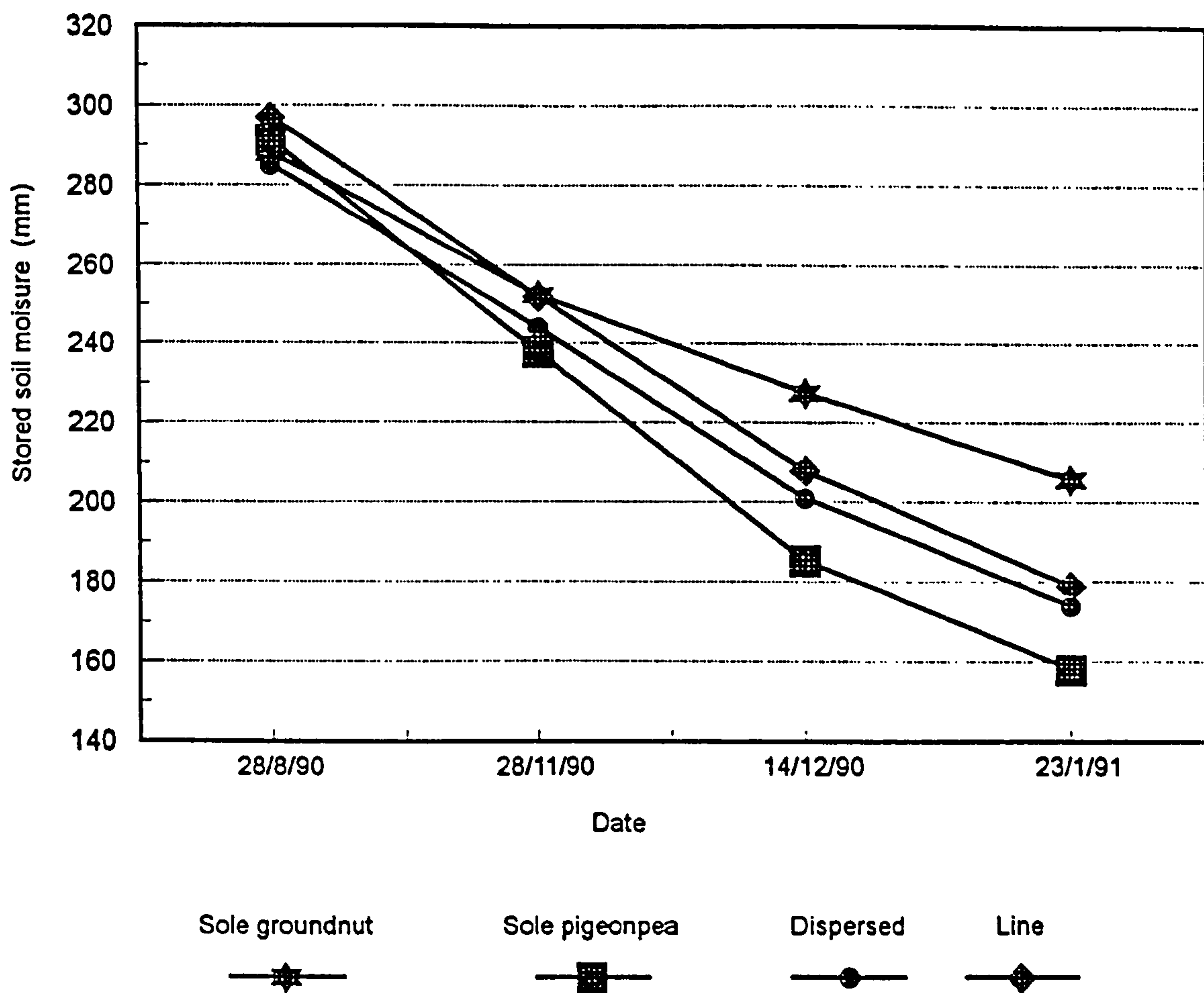


Figure 4.15: Total stored soil moisture content in the 0-150 cm horizons during the 1990-1991 drying cycle. Values were calculated from neutron probe measurements and the calibration equations shown in Section 4.2.2.2.1.

Table 4.8: Stored soil moisture between August 28 1990 and January 23 1991 calculated using a field-calibrated Troxler neutron moisture meter; (a) effective standard errors (SED) for comparing soil moisture between the dates shown in Figure 4.14 at 15 cm depth intervals and (b) treatment mean values for total soil moisture (mm) between 0-150 cm and the corresponding SED values

(a)

Depth (cm)	15	30	45	60	75	90	105	120	135
SED	7.38	6.39	4.95	6.86	7.91	5.71	7.08	7.32	6.35

(b)

Date	Sole groundnut	Sole pigeonpea	Line planting	Dispersed planting	SED
28/8/90	288	291	285	297	32.9
28/11/90	252	237	244	252	27.6
14/12/90	228	185	201	208	26.9
23/1/91	206	158	174	179	30.9

would have been expected to extract the smallest quantity of water for transpiration. However, the neutron probe measurements showed a greater depletion of soil moisture than in the line or dispersed plantings. A possible explanation is that the sole pigeonpea produced a shallower root system, resulting in a greater proportion of water being extracted from the 0-150 cm horizons, rather than from depths below 150 cm. The root distribution of the sole pigeonpea may have differed greatly from that of the line and dispersed plantings due to its initially high population and the absence of an intercrop.

4.2.3 Runoff

Installation and testing of runoff equipment were not completed until August 17 1990, after which there were intermittent malfunctions of the data-logging equipment. Consequently, only two rainfall events occurred when significant runoff was recorded (5 and 8 September 1990). On 5 September, 16 mm of rainfall was received, of which 13 % was lost as runoff from the sole pigeonpea plots and none from the other treatments. On 8 September, 24.9 mm of rainfall was received at a higher intensity and 20 % was lost as runoff in the sole pigeonpea plots, 4 % from the sole groundnut and none from the line or dispersed treatments. As there were no further measurements with which to confirm these initial observations, the values obtained were not included in subsequent water balance calculations. The data obtained suggest that, when a groundnut crop is present, significant runoff occurs most readily in the sole pigeonpea plots, but that after groundnut harvest the presence of the pigeonpea would be expected to reduce runoff relative to the bare soil of the sole groundnut plots. If data could have been obtained more regularly, it would have been possible to establish the proportion of rainfall lost as runoff in relation to the intensity of rainfall events for each of the treatments.

4.2.4 Soil surface evaporation

Squire *et al.* (1984) found that the measured values of evaporation from soils (E_s) with partial or complete canopy cover were in close agreement with those estimated using the empirical formula:

$$E_s = f_i E_p / (t + 1) \quad \text{equation 4.8}$$

where f_i is the fraction of the incident radiation reaching the soil, E_p is the potential evaporation and t is the number of days without significant rainfall. Values of E_s were calculated on a daily basis.

For the purposes of this calculation, it is not necessary to partition total shortwave radiation interception between the pigeonpea and groundnut canopies and so f_i was calculated using radiation data provided by the 'below groundnut' solarimeters (Fig. 2.5). For the line planting, the analysis was as follows:

$$f_i = (1 - ((fB1 + fB2 + fB3)/3)) \quad \text{equation 4.9}$$

where $fB1$, $fB2$ and $fB3$ represent the fraction of the incident radiation intercepted by the vegetation canopies at locations B1, B2 and B3 (Fig. 2.5a). For the dispersed planting:

$$f_i = (1 - ((fB1 + fB2)/2)) \quad \text{equation 4.10}$$

where $fB1$ and $fB2$ represent the fraction of the incident radiation intercepted by the canopy at positions B1 and B2 (Fig. 2.5b). Interception by the sole pigeonpea was calculated on the assumption that the single tube position employed was representative of the entire system. This is analogous to the assumption adopted in the dispersed planting that tube positions A1 and A2 (Fig. 2.5b) were both covered by the pigeonpea canopy for the entire period between August 8 1990 and the final pigeonpea grain harvest. This approach was used to estimate soil surface evaporation

in the sole, line and dispersed pigeonpea between 2/7/89 (groundnut planting) and 31/1/90 (pigeonpea harvest), and between 19/7/90 and 25/1/90 (second pigeonpea grain harvest).

For the period between 31/1/90 and 19/7/90, the micrometeorological data were incomplete and somewhat erratic. Mean fractional interception was therefore estimated from dry matter production and the radiation conversion coefficient for line planted pigeonpea calculated between 8/8/90 and 25/1/91 of 0.43 g MJ^{-1} (Table 4.2). As total dry matter production was recorded between 31/1/90 and 8/8/90, it was necessary to deduct the dry matter that would have been accumulated between 19/7/90 and 8/8/90. As transpiration was measured between 19/7/90 and 8/8/90, the mean ϵ_w values for the period between 8/8/90 and 25/1/91 (8.0 and $8.7 \text{ kg ha}^{-1} \text{ mm}^{-1}$ for the line and dispersed plantings; Table 4.5) were used to estimate TDM production by the pigeonpea. The values obtained (0.23 , 0.38 and 0.37 t ha^{-1} for the sole, line and dispersed pigeonpea) were deducted from the TDM production between 31/1/90 and 8/8/90 (Table 3.27) to provide estimates of TDM production between 31/1/90 to 9/7/90. Total shortwave radiation interception between 31/1/90 and 19/7/90 (114 , 144 and 221 MJ m^{-2} for the sole, line and dispersed treatments) was then divided by the total incident radiation (3338 MJ m^{-2}) to determine mean fractional interception. The values obtained were 0.03 , 0.04 and 0.07 for the sole, line and dispersed planted pigeonpea respectively.

In the sole groundnut, the soil surface was bare between 29/10/89 and 19/7/90 and between 7/11/90 and 25/1/90. Daily evaporation from the soil surface during these periods (E_s) was estimated as Reddy (1983);

$$E_s = E_p \{ [1 + ((5 - E_p)/16)(t_r/E_p)^{0.5} \exp[(-t_r + a)/0.02K] \} \quad \text{equation 4.11}$$

where E_p is the open pan evaporation for a given day, t_r is the number of days since the last rainfall event, a is the number of days following a rain event during which the available soil moisture in the top 10 cm of soil can meet potential evaporative demand ($a = 1$ for Alfisols at ICRISAT Center) and K is the maximum available

soil moisture capacity of the soil in the root zone (120 mm for Alfisols at ICRISAT Center).

This model assumes that evaporation occurs at the potential rate until the moisture content of the top 10 cm of soil reaches the permanent wilting percentage. Thereafter, the actual evaporation rate is calculated from the potential evaporation rate, the availability of water in the top 10 cm of soil and soil characteristics. Soil evaporation tends to decrease more rapidly in coarse textured soils than in fine textured soils. Unlike the model developed by Ritchie (1972), Reddy's model allows for the fact that the exponent of time in the second phase of drying is not controlled by a constant soil-dependent factor, but changes with time.

This model showed close agreement between measured and estimated values of E_s when tested over a wide range of soils and climates. Reddy also produced a model to predict evaporation from systems with partial or complete canopy cover which takes account of soil properties not included in the Squire model (Eq. 4.8). However, Reddy's model requires calculation of a crop growth stage coefficient based on both LAI and light interception measurements. Squire's model was therefore considered more appropriate for the present study because of the absence of regular direct measurements of L in pigeonpea.

Table 4.9 shows the estimates of soil evaporation over the entire experimental period obtained using equations 4.14 and 4.15 as appropriate. Between groundnut emergence and harvest in 1989, there was little difference in soil surface evaporation between treatments containing groundnut because of the slow initial growth of the pigeonpea. However, between groundnut harvest in 1989 and the emergence of the second groundnut crop in 1990, the estimates of E_s were high and invariably exceeded rainfall, suggesting that stored moisture extracted from the soil profile was lost by evaporation. There were only six significant rainfall events prior to 5/5/89 and consequently more than 80 % of the total E_s between 29/10/89 and 19/7/90 occurred after 5/5/89. As expected, E_s was greatest from the bare soil of the sole groundnut treatment (590.6 mm) and lowest in the sole pigeonpea (383.5 mm),

Table 4.9: Estimates of soil surface evaporation (mm) obtained using Squire’s model (Eq. 4.15) unless otherwise stated

	Sole groundnut	Sole pigeonpea	Line planting	Dispersed planting	Rainfall (mm)
Groundnut growing season 1989 (10/7/89 - 29/10/89)	87.8	122.9	87.8	90.3	813
30/10/89 - 19/7/90	590.5 (Reddy)	383.5	380.0	404.7	308
Groundnut growing season 1990 (20/7/90 - 7/11/90)	101.4	152.4	99.8	79.9	517
8/11/90 - 25/1/91	73.6 (Reddy)	23.6	40.2	12.7	23
1989-1990 total 10/7/89 - 31/1/90	184.2	133.9	110.7	111.0	828
1990-1991 total 1/2/90 - 25/1/91	761.0	548.5	497.1	476.6	838

which maintained the highest mean leaf area index. During the groundnut growing season in 1990, E_s was 152.4 mm in the sole pigeonpea, whose population had been reduced to 0.44 plants m^{-2} , approximately 1.5 times greater than in the sole groundnut treatment (101.4 mm). The dispersed pigeonpea intercepted the greatest quantity of radiation due to its rapidly growing canopy and consequently lost least water by soil evaporation (79.9 mm). Between groundnut harvest in 1990 and the final pigeonpea grain harvest, the large proportion of bare soil in the line planting caused soil evaporation (40.2 mm) to be approximately three times greater than in the dispersed treatment (12.7 mm); the sole pigeonpea was intermediate between these two values (23.6 mm). E_s from the bare soil of the sole groundnut was 76.6 mm, approximately three times rainfall during this period. There was little difference in total E_s between the line and dispersed plantings in either 1989-1990 or 1990-1991 because of the very low fractional radiation interception in both treatments between February and July.

Figure 4.16 shows the daily estimates of E_s between groundnut emergence in 1990 (Julian day 207) and the final pigeonpea grain harvest (Julian day 25, 1991). The data show that E_s was greatest in the sole pigeonpea treatment, approaching open pan evaporation on several occasions, until the groundnut crop was removed from the other treatments on Julian day 311. Thereafter, E_s was much greater from the bare soil of the sole groundnut plots.

4.3 MICROCLIMATE

Microclimate reflects the interaction between the environment and the crop, and may be defined in terms of the fluxes of energy (mainly sensible and latent heat) and mass (most importantly water) close to the ground. The principal objectives of the temperature and saturation deficit measurements conducted in this study were to investigate the nature and extent of the microclimatic changes experienced by groundnut crops grown together with pigeonpea, and assess their possible contribution to the observed treatment effects on groundnut growth and development. An initial assumption was that shading by the pigeonpea would reduce leaf

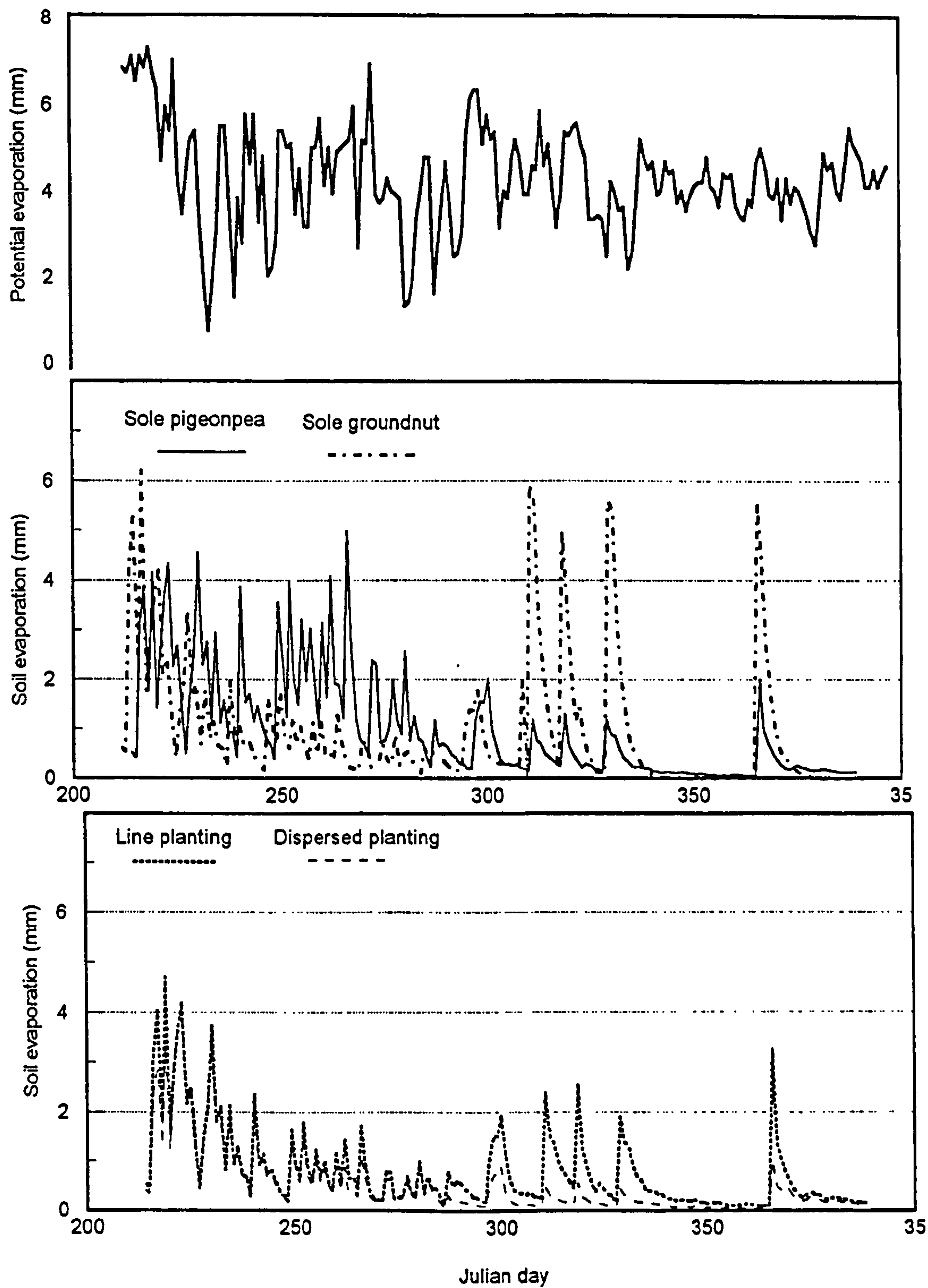


Figure 4.16: Daily values for potential evaporation and soil surface evaporation between groundnut emergence and pigeonpea grain harvest, 1990-1991.

temperature and both water vapour and CO₂ fluxes in groundnut. The pigeonpea canopy was expected to reduce windspeed above the groundnut crop, thereby increasing the boundary layer resistance to CO₂ and water vapour fluxes and reducing the heat flux away from the canopy. The combined effect of shading and increased aerodynamic resistance on groundnut growth and development rate would depend upon the relative magnitude, interactions and feedback responses between these energy balance components (Section 1.4.1). Because the pigeonpea canopy had little effect on groundnut growth and development in 1989, the majority of the data presented here are drawn from the 1990 field season.

4.3.1 Wind speed

The results shown in Figure 4.17 indicate that windspeed was reduced by approximately 50 % in all treatments containing pigeonpea relative to the sole groundnut after Julian day 240. Although no further quantitative analysis was carried out due to the lack of replication (Section 2.6.4), the tree arrangement appeared to have little effect on the degree of wind speed reduction.

4.3.2 Soil and leaf temperature

Table 4.10 summarises the seasonal mean values for leaf, soil and air temperatures. The data indicate that shading by pigeonpea had no significant effect on the seasonal mean leaf temperature of groundnut as compared with the sole crop. The daily mean values for the difference between leaf and air temperatures (Figs. 4.18-4.19) confirm the absence of any consistent treatment effects. However, the differences between the leaf and air temperatures for shaded groundnut at positions MLmax and MDmax (Fig. 2.5) were 1-4 °C lower than at MLmin and MDmin respectively between Julian day 280-300 (80-100 DAS) (Fig. 4.18). This corresponded to a period of low rainfall, high incident solar radiation and relatively high saturation deficit during which time the groundnut canopy was beginning to senesce. The higher leaf temperatures in the less shaded crop may also be explained by the fact that the senescent leaves were unable to transpire sufficiently rapidly to dissipate the

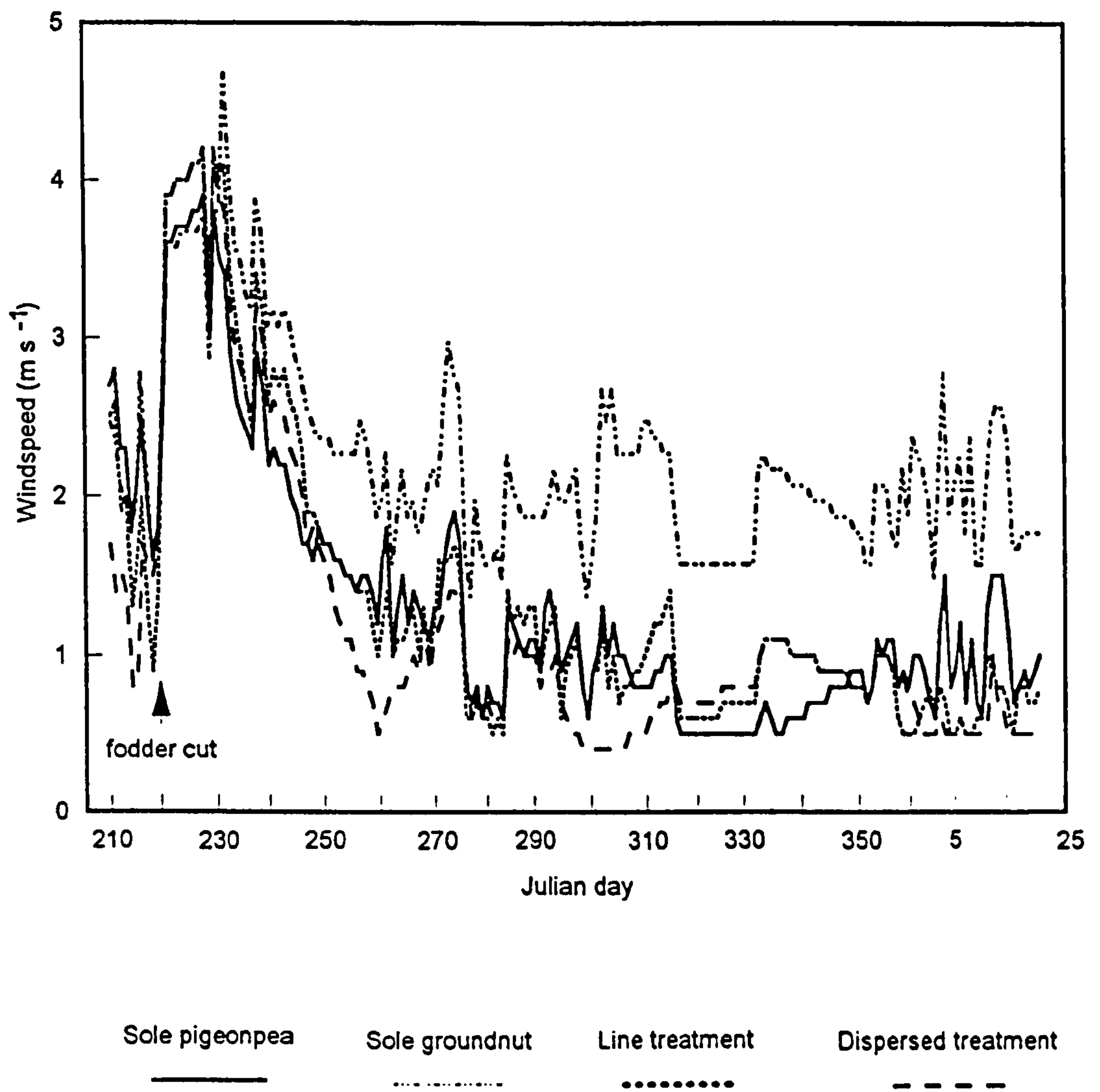


Figure 4.17: Mean daily windspeed in all treatments between groundnut emergence and pigeonpea grain harvest, 1990-91.

Table 4.10: Seasonal mean values for saturation deficit and soil, leaf and air temperature during the groundnut growing season, 1990.
SD represents the standard deviation

	Soil temperature (°C)		Leaf temperature (°C)		Air temperature (°C)		Saturation deficit (kPa)	
	Day	Night	Day	Night	Day	Night	Day	Night
Sole	27.0	25.2	27.6	22.1	26.9	22.0	0.82	0.17
SD	1.8	2.1	2.1	2.8	1.8	2.8	0.28	0.14
Line mean	26.4	25.9	28.1	22.9	26.9	23.1	0.76	0.17
SD	2.0	2.6	2.2	2.9	1.9	2.7	0.26	0.13
Disperse d mean	26.6	24.3	27.3	19.8	26.4	21.9	0.74	0.14
SD	1.9	1.9	2.2	1.1	1.8	2.3	0.27	0.12
Lmax	25.8	24.9	27.5	22.9	26.6	22.8	0.79	0.19
SD	1.9	2.6	2.0	2.9	1.7	2.8	0.24	0.13
Lmin	27.0	26.1	28.8	23.0	27.1	22.5	0.76	0.16
SD	2.2	2.7	2.8	3.0	2.1	2.9	0.29	0.13
Dmax	26.8	23.5	27.1	21.7	26.7	21.5	0.84	0.15
SD	2.0	2.0	2.2	2.4	1.8	2.6	0.31	0.13
Dmin	26.4	24.4	27.5	21.7	26.1	21.7	0.65	0.14
SD	1.9	1.9	2.4	2.4	1.8	2.4	0.24	0.12

additional radiation (Eq. 1.5). At location MLmin, which was not shaded by pigeonpea, leaf temperatures were generally 1-4 °C higher than in the sole crop between 50-100 DAS, possibly because the shelter-belt effect of the pigeonpea rows reduced windspeed and hence the transfer of latent and sensible heat from the groundnut canopy.

The effect of temperature on groundnut development is well established (Leong and Ong, 1983; Ong, 1985). Thermal time was calculated (Eq. 1.1) to determine whether the relatively small leaf temperature differences between treatments were sufficient to affect groundnut growth and development. Cardinal temperatures for cv. Kadiri-3 ($T_b = 10\text{ }^{\circ}\text{C}$, $T_o = 36.5\text{ }^{\circ}\text{C}$ and $T_m = 46\text{ }^{\circ}\text{C}$) were obtained from the controlled environment studies of Mohamed *et al.* (1984) and a K value of 2.76 was used (Ong *et al.*, 1991c). Prior to emergence, the temperature of the meristematic tissue below the soil surface determines developmental rate, and for this reason soil temperatures (5 cm depth) were recorded between 0-7 DAS and used in the thermal time calculations (Table 4.11). As expected, the treatment differences between thermal time values (Θ) were small. The highest Θ values were recorded at location MLmin, although this corresponded to an overall difference in development of only 2.7 days by 80 DAS as compared with the sole crop, and 1.3 days when compared to MLmax. Leong and Ong (1983) have previously reported that the thermal time to first flowering was 538 °Cd when cv. Kadiri-3 was grown in a controlled environment greenhouse under irrigation, which corresponds closely to the 50% flowering values shown in Table 4.11. The slightly higher Θ values at MLmin may have originated from a reduction in windspeed between the pigeonpea rows, which would have increased the boundary layer resistance (r_b) and reduced sensible heat transfer (conduction, convection and turbulent transfer) and latent heat transfer from the groundnut canopy. It appears that the shade imposed by the pigeonpea canopy had little effect on the rate of primordial initiation in groundnut and that the observed decrease in leaf area index and stem and pod dry weights resulted from reductions in the rate and/or duration of growth in the shaded groundnut that could not be attributed to effects on tissue temperature on development.

Table 4.11: Thermal time (Θ ; °Cd) values for sole groundnut in 1989 and for groundnut in all treatments in 1990. 0-7 represents the period between sowing and emergence, FLW from sowing to 50% flowering and 80 from sowing to 80 DAS

DAS	1989	1990						
	Sole	Sole	Line	Disp.	MLmax	MLmin	MDmax	MDmin
0-7	124	106	102	104	97	108	102	105
FLW	545	539	544	541	537	551	532	531
80	1224	1206	1238	1198	1227	1248	1157	1166

Table 4.12: Vapour pressure deficit factor values (Z) for groundnut, 1990

DAS	Sole groundnut	MLmax	MLmin	MDmax	MDmin
13-20	0.87	0.87	0.89	0.89	0.87
21-40	1.00	1.00	0.99	1.00	0.98
41-60	0.98	0.97	0.97	1.00	0.98
61-80	0.98	0.98	0.97	1.00	0.98
81-100	0.93	0.94	0.89	0.95	0.88
101-111	0.85	0.90	0.76	0.91	0.79

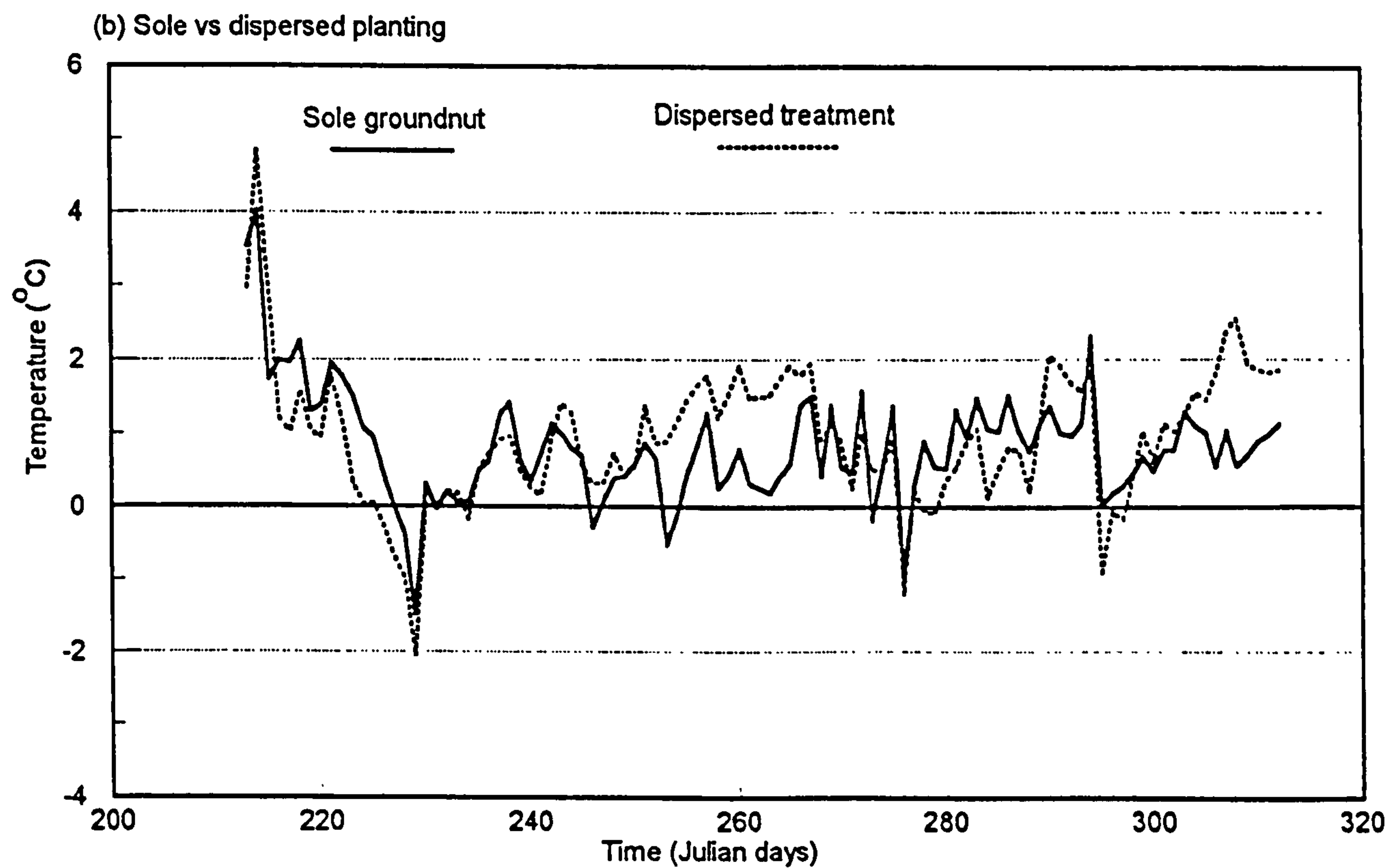
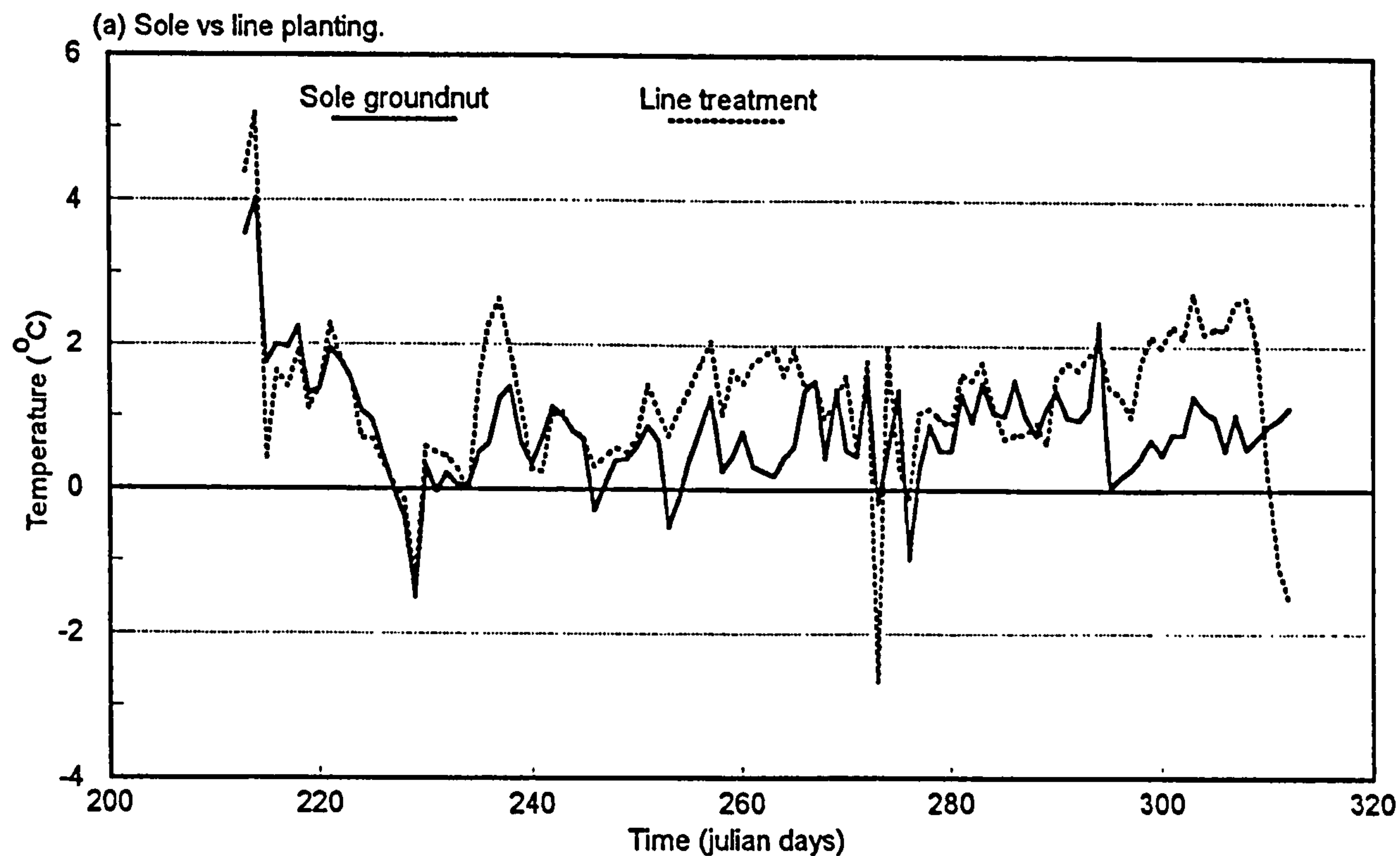


Figure 4.18: Daily mean values for leaf minus air temperature in groundnut, 1990.

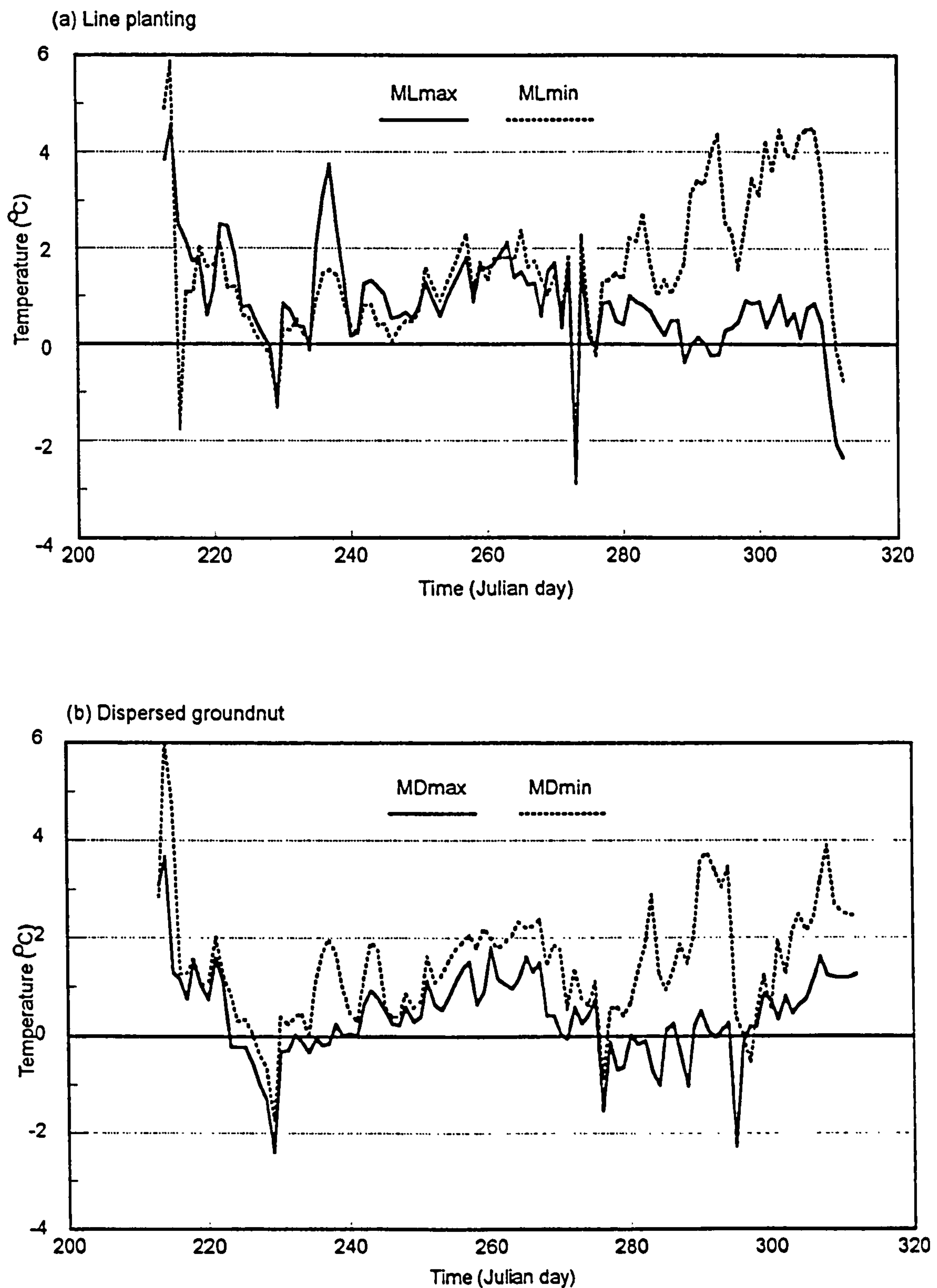


Figure 4.19: Daily mean values for leaf minus air temperature in groundnut, 1990. Comparison of measurement positions within the line and dispersed treatments.

The major determinants of day-time differences in soil temperature between and within treatments would normally be expected to be variation in fractional interception by the crop canopy and aerodynamic resistance to the transfer of sensible and latent heat, on the assumption that there would have been little variation in net longwave radiation under the prevailing cloudy conditions during the rainy season. However, there was no systematic variation in soil temperature between or within treatments at any stage of the season (Fig. 4.20) despite the observed large differences in radiation interception between measurement sites.

4.3.3 Saturation deficit (SD)

There was no significant difference in the seasonal mean saturation deficit values either between treatments or locations within the line and dispersed plantings (Table 4.10). The 10 day treatment mean values for D from 14 DAS to groundnut harvest are shown in relation to incident solar radiation, rainfall and relative humidity in Figure 4.21. Although the treatment differences were not significant (and reached a maximum of 0.2 kPa), D was generally lower in the line and dispersed treatments than in the sole crop; this effect became more apparent as the season progressed and shading by the pigeonpea canopy increased. In the line planting (Fig. 4.22a), D was lower at position MLmax than at MLmin (with the difference ranging from 0.05 to 0.5 kPa), whereas in the dispersed planting there was no significant positional variation in D between MDmax and MDmin, which were both shaded by the pigeonpea canopy for much of the season (Fig. 4.22b).

Z values were calculated using equation 1.13, assuming that VPDo and VPDm values were 1 and 6 kPa respectively (after Ong, 1991c). Because leaf temperature was 1-2°C above air temperature for much of the day, calculations using D would have consistently provided underestimates of the leaf to air vapour pressure difference (VPD). The results (Table 4.12) indicate that VPD had a negligible effect on groundnut growth because values were below VPDo at all measurement locations for much of the growing season.

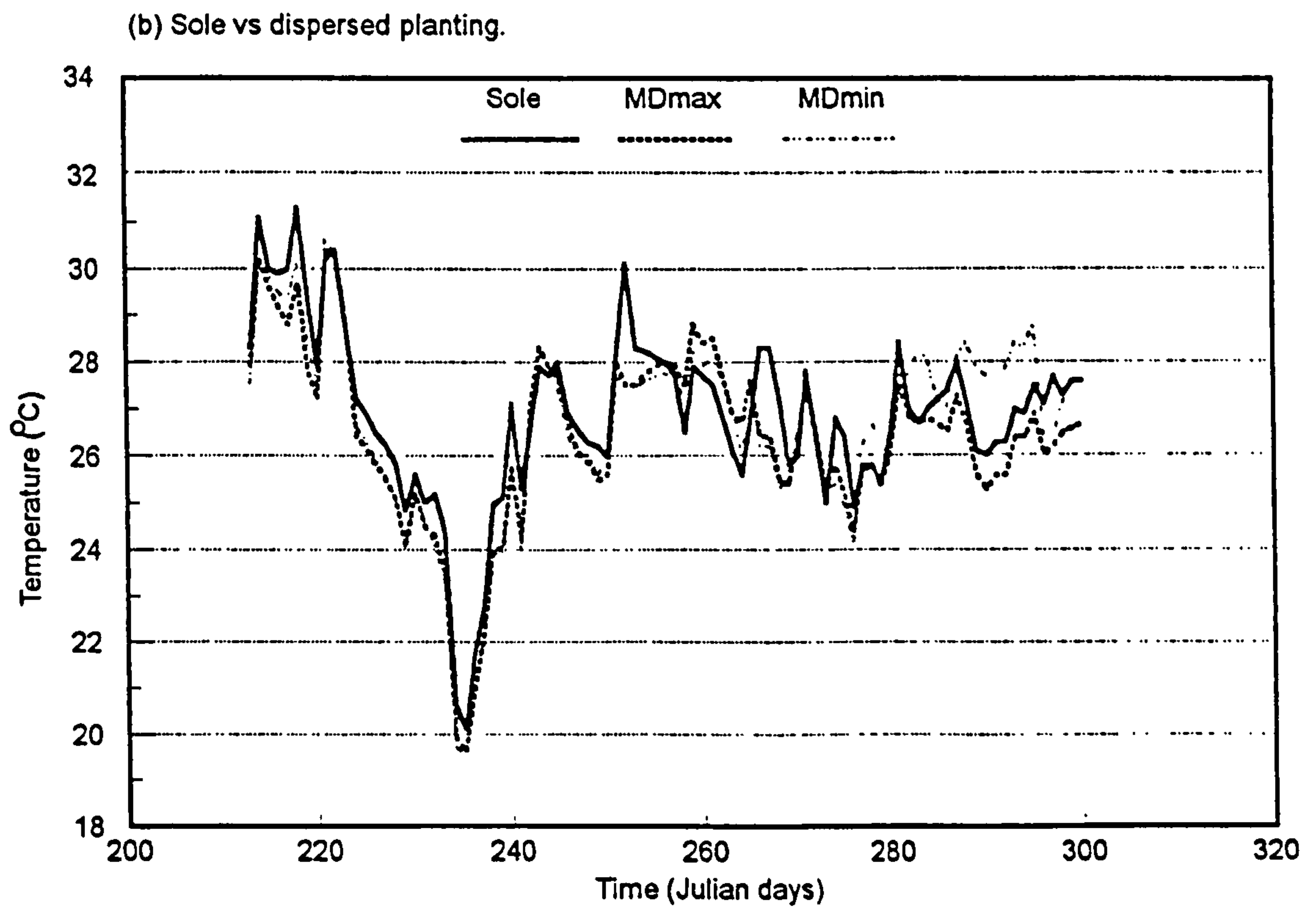
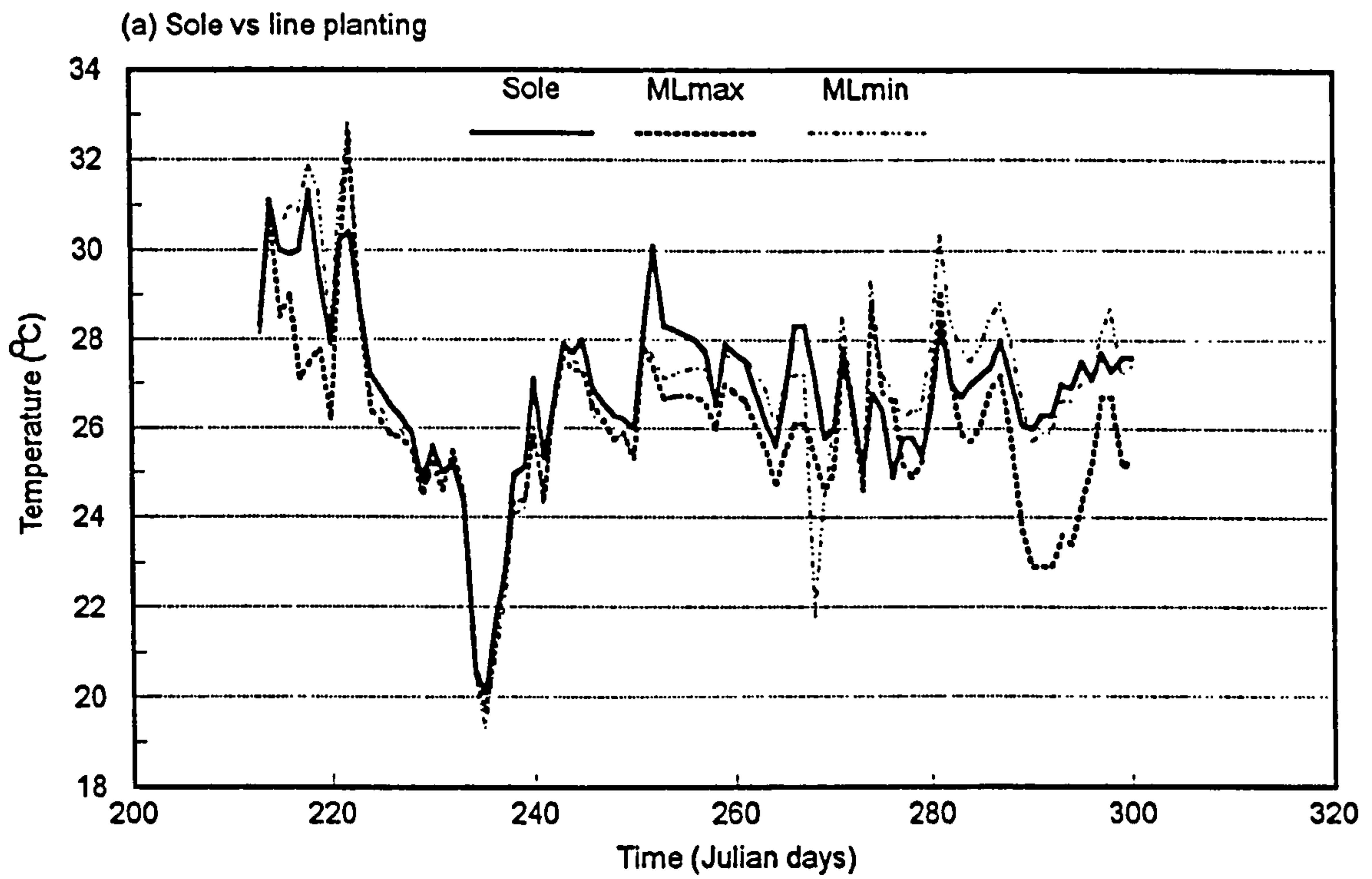


Figure 4.20: Mean day-time soil temperature (at 5 cm depth), 1990. Comparison of the sole groundnut with various measurement positions within the line and dispersed treatments.

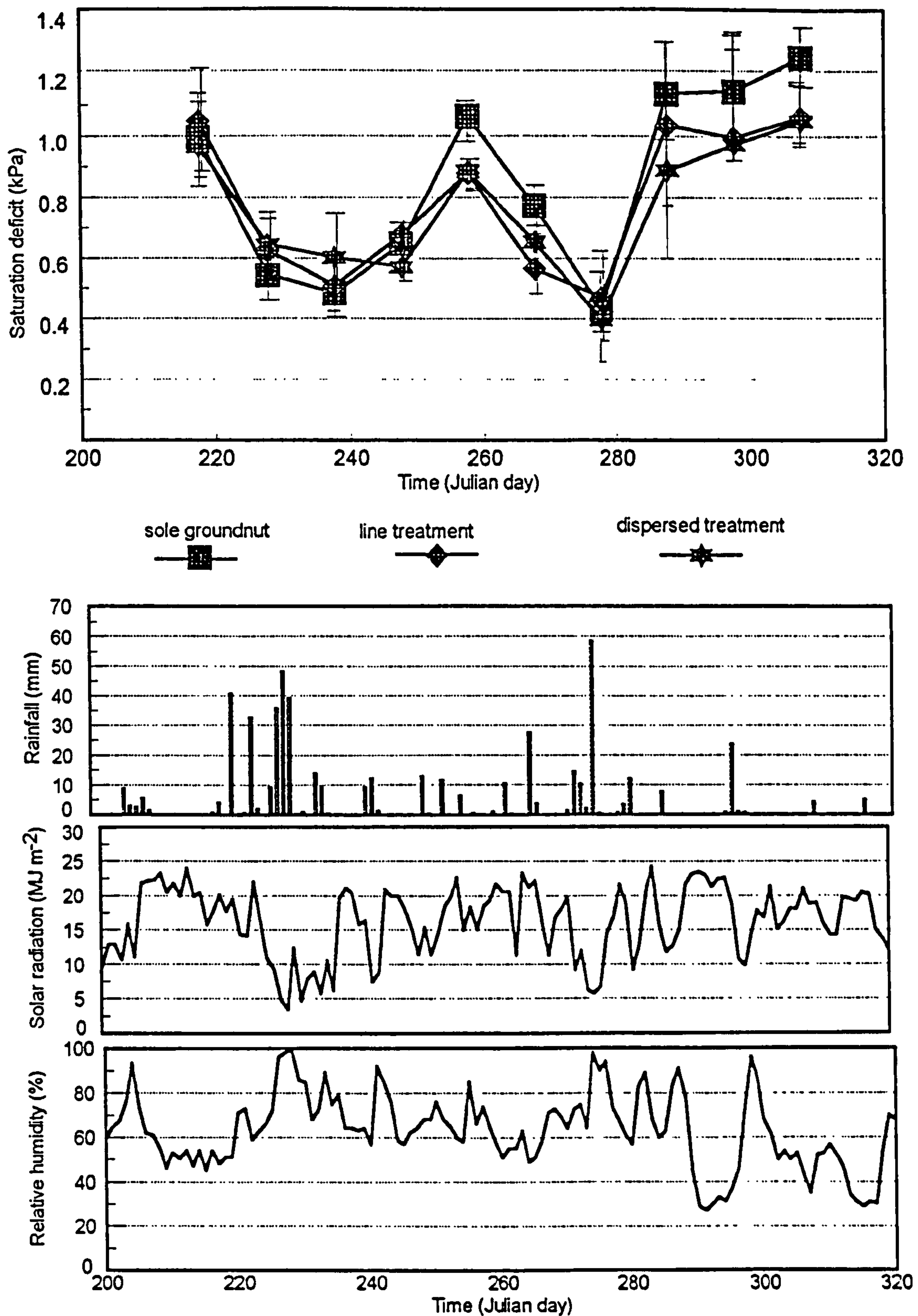


Figure 4.21: Day-time mean values for saturation deficit (D), daily totals for rainfall and radiation and daily mean values for relative humidity, 1990. The standard deviation is shown for each ten day mean value for D; relative humidity was measured daily at ICRISAT weather station.

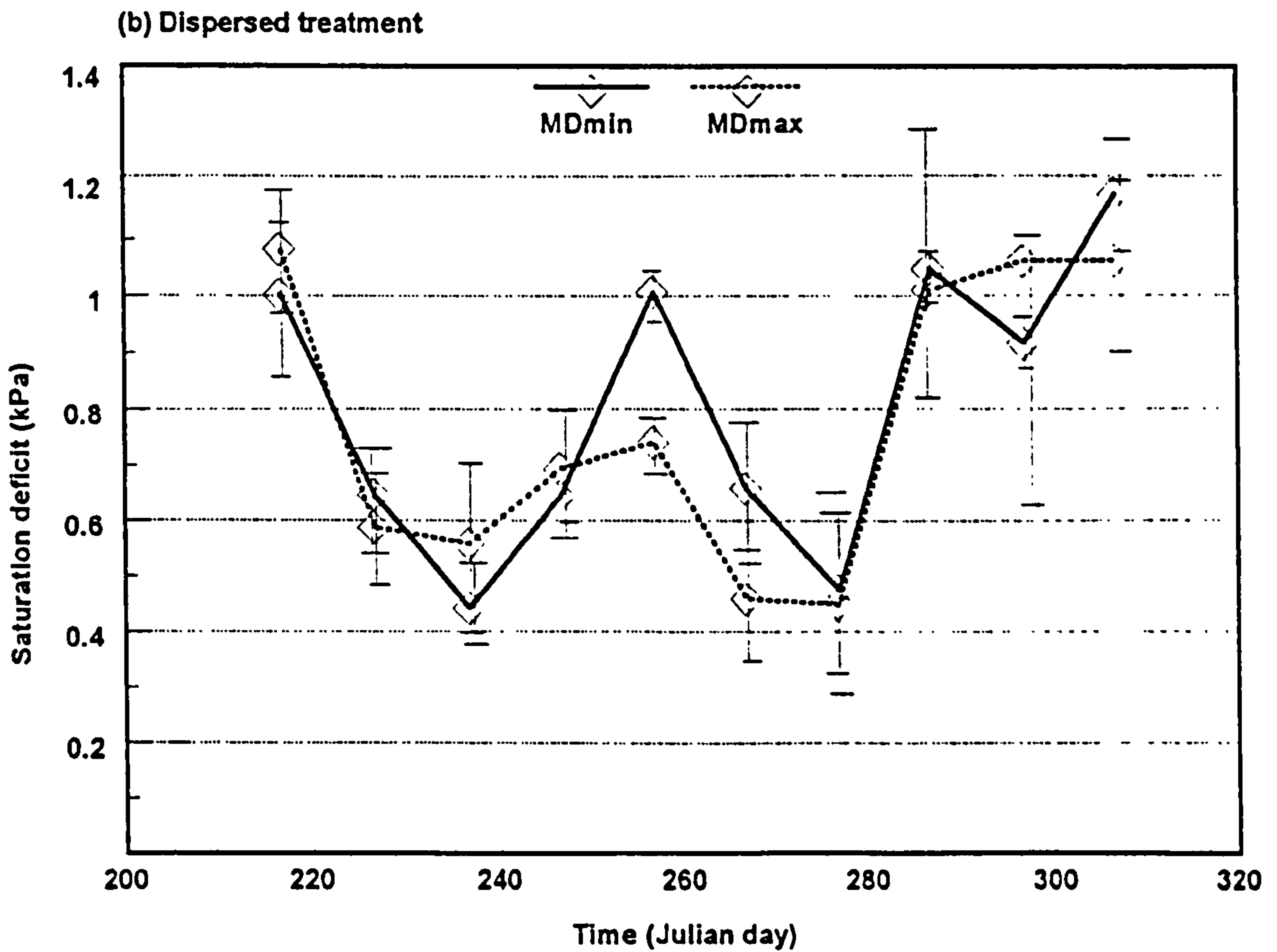
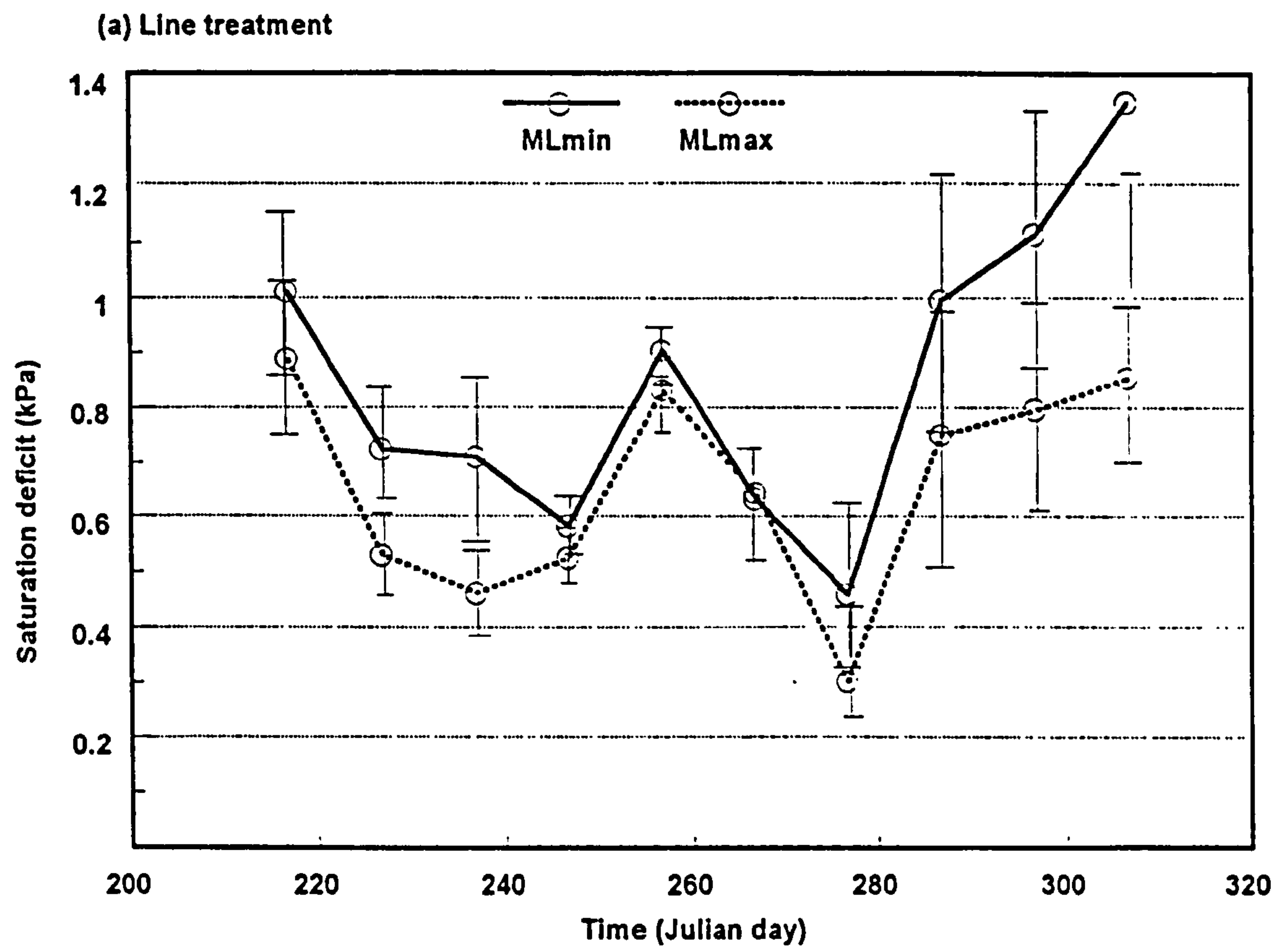


Figure 4.22: Ten day mean day-time saturation deficit values, with standard deviations, 1990. Comparison of measurement locations within the line and dispersed treatments.

4.4 DISCUSSION

4.4.1 Light

Increases in fractional interception (f), canopy duration (t) and/or the radiation conversion coefficient (e) may all contribute to increased productivity in intercropping or agroforestry systems (Eq. 4.9). The relative contributions of each of these factors (summarised in Table 4.13) for the period between groundnut planting and pigeonpea grain harvest in both 1989 and 1990 are considered below. The dry season data are not included here because the proportion of the overall total dry matter produced during this period was very low ($< 5\%$) and no direct physical measurements were made at that time. However, productivity and resource use over the entire experimental period, including the dry season, are discussed in Chapter 5.

4.4.1.1 1989

4.4.1.1.1 *Fractional interception*

Pigeonpea develops very slowly in its first year of growth, with the result that the sole groundnut had reached 60 % interception by 35 DAS, whilst the sole pigeonpea never exceeded 20 %. The more rapid canopy development of the groundnut caused radiation interception by the intercrop treatments to be greater than in the sole pigeonpea during the first 70 DAS, even though interception by the intercrop pigeonpea never exceeded 10 %. However, the sole pigeonpea canopy reached its maximum value of approximately 80 % at 70 DAS and remained above 55 % until grain harvest, whilst interception by groundnut declined rapidly. Interception by the intercropped pigeonpea did not exceed 20 % at any time.

Fractional interception by the sole pigeonpea between sowing and harvest was 0.54, as compared with 0.31 and 0.26 for the line and dispersed treatments respectively.

Table 4.13: Comparison of radiation interception, conversion coefficients and productivity for all treatments between (a) the start of interception measurements on 23 July 1989 and the pigeonpea grain harvest on January 31 1990 and (b) the pigeonpea fodder cut on August 8 1990 and the final grain harvest on January 25 1991. PPea and Gnut respectively represent the pigeonpea and groundnut components, W the total dry matter at final harvest, S the total incident shortwave radiation, f the seasonal mean fractional radiation interception, e the mean light conversion coefficient from sowing to harvest and t the canopy duration. The value of e for the sole pigeonpea in 1990 is taken from the line treatment

(a)

		W (g m ⁻²)	S (MJ m ⁻²)	f	e (g MJ ⁻¹)	t (d)
Sole	PPea	816	3249	0.54	0.47	212
	Gnut	339	1701	0.26	0.40	119
Line	PPea	147	3249	0.08	0.57	212
	Gnut	290	1602	0.24	0.37	119
	System	437	3249	0.31	0.43	212
Dispersed	PPea	156	3249	0.07	0.68	170
	Gnut	303	1574	0.19	0.49	212
	System	459	3249	0.26	0.54	212

(b)

		W (g m ⁻²)	S (MJ m ⁻²)	f	e (g MJ ⁻¹)	t (d)
Sole	PPea	355	2683	0.31	0.43	170
	Gnut	252	1505	0.33	0.28	111
Line	PPea	209	2683	0.18	0.43	170
	Gnut	182	1298	0.30	0.23	111
	System	391	2683	0.48	0.30	170
Dispersed	PPea	452	2683	0.58	0.29	170
	Gnut	168	746	0.11	0.56	111
	System	620	2683	0.69	0.33	170

This is in accordance with results from many annual crop systems which indicate that mixed cropping frequently does not increase the annual radiation interception relative to the longer duration sole crop (Squire, 1990; Keating and Carberry, 1993). However, previous studies indicate that radiation interception and productivity of pigeonpea could have been increased further in the first year by increasing its population, with little loss of groundnut yield. Odongo *et al.* (1995) examined a 1:4 row planting arrangement of pigeonpea/groundnut and found that groundnut yield was reduced to 64 % of the sole crop in the first year, but that there was no reduction in pigeonpea yield relative to a sole stand with a population of 8 plants m^{-2} . Overall biomass production by the intercrop was 72 % higher than that of the sole pigeonpea up to the first grain harvest, although radiation interception was only 91 % of the sole pigeonpea. Although interception by each component of the intercrop was not measured separately, the increase in the overall e value was almost certainly attributable to the groundnut component, which had an e value of 0.9 g MJ^{-1} in the sole crop, as compared with 0.2 g MJ^{-1} for the sole pigeonpea.

4.4.1.1.2 *Radiation conversion coefficient*

The seasonal e values (Table 4.13a) are relatively low because the majority of the leaf area was lost prior to harvest, resulting in a loss of TDM that was not taken into account. The e values for pigeonpea were increased in both the intercrops by 20-30 %. In the dispersed intercrop, the e value for the groundnut was also 20 % greater than in the corresponding sole crop, resulting in a slight increase in e of this system relative to the sole pigeonpea. Thus, the dispersed intercrop intercepted 52 % less radiation than the sole pigeonpea and produced 46 % less total dry matter.

4.4.1.1.3 *Tree-crop complementarity in light use*

In its first year of growth, the pigeonpea/groundnut cropping system provides an example of two-way complementarity of resource use, such that the component populations can be adjusted to provide maximum yield from one crop (in this case groundnut) and some additional yield from the other. The system provided an

example of temporal complementarity in light use, which occurs when the component crops make their major demands on resources at different times (cf. Section 1.4.2). The increased canopy duration (t) was clearly the factor responsible for the improved seasonal interception in the line and dispersed treatments relative to the sole groundnut. However, the sole pigeonpea was the most productive because its higher fractional interception over most of the growing season resulted in a seasonal fractional interception value over 20 % greater than in the other treatments. There are few published examples in which complementarity of resource use has resulted in greater light interception and productivity in an intercrop, as compared with the longer duration sole crop grown at optimum population (Natarajan and Willey, 1980; Willey *et al.*, 1986).

4.4.1.2 1990

4.4.1.2.1 *Fractional radiation interception*

In the line planting, total interception prior to groundnut harvest was similar to the sole groundnut, because interception by the pigeonpea was just sufficient to offset the reduction in interception by groundnut at L_{max} caused by shading. The main intercrop advantage occurred after groundnut harvest when the pigeonpea intercepted 64 % of its seasonal total.

In the dispersed planting, the pigeonpea canopy developed so rapidly that interception by the pigeonpea was similar to the sole groundnut up to 80 DAS, when the dispersed pigeonpea attained its maximum interception; thereafter interception exceeded that in all other treatments. The dispersed pigeonpea intercepted 62 % of its seasonal total after groundnut harvest, and it is interesting to note that interception during this period was very similar to that of sole pigeonpea grown at its optimum population in 1989.

The rapid canopy development of the dispersed pigeonpea reduced the quantity of radiation available to the groundnut throughout its lifecycle. The dispersed groundnut

reached a maximum interception of only 40 % of total shortwave radiation at 80 DAS, as compared to 60 % in the line planting and 80 % in the sole crop. The total shortwave radiation reaching the groundnut in the dispersed planting was reduced to only 50 % of that incident on the sole crop (Table 4.13b). In addition, the dispersed groundnut was able to intercept only 48 % of the shortwave radiation that penetrated through the pigeonpea canopy, whereas the sole crop intercepted 59 % of the total seasonal shortwave radiation because shading slightly reduced L (< 9 %) in the former treatment.

Under moist conditions, assimilate production by sole crops often outstrips the requirements of expanding leaves (Squire, 1990), and therefore the leaf area of the shorter component of intercrops is usually little affected. The current findings are in close agreement with those of Stirling *et al.* (1990) who reported reductions in L in groundnut of approximately 10 % when incident solar radiation was reduced by 46 % using bamboo shades. The stems and rapidly growing reproductive organs provide a greater demand for assimilates than the leaves (Squire, 1990), with the result that the reduced irradiation experienced by the intercropped groundnut may have limited assimilate production sufficiently to effect the considerable reductions in TDM observed throughout the growing season. Despite the substantial increase in e in intercropped groundnut, the decreased irradiance incident upon its canopy reduced seasonal f to only 0.11 (as compared to 0.33 in the sole groundnut) and resulted in a considerable yield reduction (34 %) relative to the sole stand. If the e value for the dispersed groundnut was identical to that in the sole crop, its maximum TDM would have been reduced to 100 g m⁻² (40 % of the sole crop yield) but overall productivity including the pigeonpea component would still have exceeded the other treatments.

The seasonal treatment mean quantity of PAR received by the groundnut in the dispersed treatment was 62 % of that in the sole crop, whereas the reduction in TDM at final harvest was 34 %. Stirling (1988) has previously reported that TDM production by groundnut was reduced by 26 % at final harvest when bamboo shades were used to reduce incident radiation by 46 % throughout reproductive growth

during a rainy season experiment at Hyderabad. In the current study, the total incident radiation was reduced even further and TDM at final harvest was reduced by an additional 8 %. The similarity of results from these two studies supports the supposition that light was the major factor limiting TDM accumulation by groundnut in the dispersed planting. In addition, similar changes in dry matter partitioning were observed by Stirling (1988). In both studies, fewer pods were initiated in the shaded plants but dry matter was partitioned to these organs over a longer period of time, causing a higher proportion of the pods to be filled at final harvest; harvest index was similar to the unshaded controls.

4.4.1.2.2 *Further examination of radiation conversion coefficients*

The e values for groundnut in all treatments were considerably lower in 1990 than in 1989 due to the high incidence of foliar disease, which reduced fodder (but not pod) yield at final harvest. Because of the late onset of disease, there was little difference between the two years in radiation interception by the sole groundnut. Therefore, whilst the e values for the intercrop systems were higher than in the sole pigeonpea in 1989-90, they were apparently lower in 1990-91 despite a substantial increase in the e value for groundnut in the dispersed planting relative to the sole crop.

Although the data presented in Table 4.13b indicate that e was considerably higher in the line planted pigeonpea (0.43 g MJ^{-1}) than in the dispersed pigeonpea (0.29 g MJ^{-1}), this may have been an artefact created by the overestimation of radiation interception in the latter treatment (cf. Section 4.1.2), which would in turn have caused e to be underestimated. Supporting evidence for this supposition is provided by the high e values obtained in 1989, when reliable measurements of radiation interception by pigeonpea were available for all treatments (0.42 , 0.54 and 0.56 g MJ^{-1} for the sole, line and dispersed pigeonpea respectively). The values of e and f for the dispersed pigeonpea (Table 4.13) are based on the assumption that the solarimeters at both positions 1 and 2 (Fig. 2.5) were covered throughout the period between August 8 1990 and final harvest, when in fact only position 1 may have

been covered for some of the period prior to groundnut harvest. The measurements made following groundnut harvest showed that the tubes at both positions were covered, and so the difference between the accumulated intercepted radiation calculated from measurements at position 1 at groundnut harvest, and the estimate based on coverage of both tubes provides a measure of the maximum accumulated overestimate of interception by the dispersed pigeonpea. This value of 337 MJ m⁻² amounts to 22 % of the estimated seasonal interception by the dispersed pigeonpea and, if included in the analysis, would raise the e value from 0.29 to 0.35 g MJ⁻¹. However, this overestimate does not fully account for the difference in e between the line and dispersed treatments, suggesting that there may have been a real decrease in e in the dispersed pigeonpea in 1990-91. There is no previous evidence that e decreases in the second year of growth in perennial pigeonpea; indeed Odongo *et al.* (1995) reported higher e values during the second year of growth for a range of sole and intercrop treatments of ICP-8094. As there was little difference in harvest index between the line and dispersed pigeonpea, the lower e value cannot be accounted for by a higher proportion of dry matter being partitioned to tissues with a higher energy equivalent in the latter treatment.

4.4.1.2.3 *Complementarity in radiation use*

In contrast to 1989, the pigeonpea/groundnut systems in 1990 showed one-way complementarity (Section 1.4), in which the pigeonpea was clearly the dominant component. Thus, the pigeonpea was responsible for the increased seasonal radiation interception by the line and dispersed treatments relative to the sole pigeonpea. The dispersed treatment appeared to exhibit both temporal and spatial complementarity in resource use because, not only was the crop duration increased greatly relative to the sole groundnut, but interception by the dispersed system exceeded that for the sole pigeonpea during the period when both crop components were competing for resources. However, a major difficulty in assessing the extent of any intercrop advantage was the sub-optimal population of pigeonpea in 1990-91. Previous studies of ICP-8094 have shown a substantial increase in productivity between the first and second year of growth; for example, Ranganathan (1993) and Odongo *et al.* (1995)

reported approximately two and three-fold increases. In order for the sole pigeonpea in the current study to have intercepted the same quantity of radiation as the dispersed treatment in 1990, an increase in productivity of only 10 % as compared with 1989 would have been required. It therefore seems very likely that, in the absence of other limiting resources, the sole crop at optimum population would have intercepted more radiation and have been more productive than the dispersed planting.

For spatial complementarity in resource use to occur, the fractional interception and/or the conversion coefficient of an intercrop must exceed that of the corresponding sole crops (cf. Section 1.3.2). Fractional interception is related to leaf area index (L) and the crop extinction coefficient (K) according to equation 1.7. Thus, in order to increase fractional interception in an intercrop relative to the corresponding sole crops, there must be an increase in L for similar values of K , or alternatively an increase in overall K (cf. Sivakumar and Virmani, 1980b) for a given value of L . Both of these situations are unusual because sole crops planted at their optimum population are usually able to achieve complete interception (Keating and Carberry, 1993) and spatial complementarity usually results from an increase in the radiation conversion coefficient. The first conclusive evidence that an increase in e was responsible for an intercrop advantage came from a study of millet and groundnut (Marshall and Willey, 1983) in which it was shown that the increase in e for the intercrop of approximately 30 % was almost identical to the observed productivity advantage. Later work by Stirling *et al.* (1991) confirmed that e is increased in shaded groundnut because this species is often light saturated when grown as a sole crop (cf. Section 1.3.2). There have been few detailed studies of radiation interception and utilisation in agroforestry systems (cf. Monteith *et al.*, 1991) and, to date, there are no published examples of spatial complementarity. The current study and the work on a *Leuceana*/millet system by Corlett (1989) have both established that the e value of the understorey crop was increased relative to the sole stand, but that this was insufficient to offset the reduction in radiation interception.

4.4.2 Water

Differences in the productivity of each crop component in the four treatments are discussed here in relation to water capture and utilisation. The water balance (Eq. 1.8) is also considered in some detail in order to determine which losses were of greatest significance in each of the systems examined. The discussion is largely confined to the 1990 growing season when detailed water use data were obtained. Although light was the major limiting factor for groundnut growth in the dispersed treatment, the possible contribution of water stress is also examined. The growth and water use of pigeonpea after groundnut harvest are examined in relation to the available supply of stored soil moisture.

4.4.2.1 *Utilisation of water by the crop stands*

Table 4.14 summarises the measured and estimated components of the water balance between groundnut planting in 1990 (19/7/90) and pigeonpea grain harvest in 1991 (25/1/91). The data show that the greater productivity of the line and dispersed systems relative to the sole groundnut was supported by increased water capture, resulting from extension of the growing season and reduced water losses through deep drainage, interception losses, runoff and soil surface evaporation (D, I, R and E, respectively). In the sole groundnut, approximately 30 % of the rainfall received between 19/7/90 and 25/1/91 (545 mm) was utilised for transpiration, as compared with over 80 % in the treatments containing pigeonpea. The utilisation of water by the line and dispersed systems compares very favourably with other cropping systems. For example, previous studies at ICRISAT have shown that, in a typical intercrop of annual pigeonpea and sorghum grown on the Alfisols of the Deccan plateau, only 41 % of the annual rainfall is accounted for by evapotranspiration (El-Swaify *et al.*, 1987).

Because there were no direct measurements D, I or R, the sum of these components was estimated by entering the known values of P, ΔM , E_t and E_s into equation 1.8. However, the values shown for D, I and R for the line, dispersed and sole pigeonpea

Table 4.14: Summary of the measured and estimated components of the water balance between groundnut planting on July 19 1990 and the final pigeonpea grain harvest on January 25 1991. Rainfall over this period (P) was 545 mm and potential evapotranspiration (E_p) was 819 mm. E_t represents transpiration, E_s soil surface evaporation, ΔM the change in stored soil moisture to a depth of 150 cm, D deep drainage, I interception losses and R losses due to runoff. All values are expressed in mm of water

	E_t	E_s	ΔM	D+I+R	(E_t/P)
Sole pigeonpea	483	176	-125	11	0.8
Sole groundnut	189	201	- 90	245	0.3
Line pigeonpea	309				
Line groundnut	191				
Line system	500	140	- 95	0	0.9
Dispersed pigeonpea	561				
Dispersed groundnut	151				
Dispersed system	712	93	-113	-147	1.3

treatments are potentially misleading due to the discrepancy between the measurement depth for stored soil moisture (150 cm) and the rooting depth of the pigeonpea (> 200 cm). In the dispersed planting, the sum of E_s and E_d was 805 mm, approximately 1.5 times greater than the quantity of rainfall received. This suggests that at least 147 mm of water was extracted from the soil profile below 150 cm; the true quantity of water extracted from below 150 cm would be higher because some water would have been lost as D, I and R. The results indicate that the greatest quantity of water was extracted from the soil in the sole pigeonpea plots. Although E_s was higher in the sole pigeonpea than in the line and dispersed treatments, E_t was lower, with the result that estimated evapotranspiration was approximately 80 % of that in the dispersed system. This discrepancy may again be the result of the absence of neutron probe measurements below 150 cm. It is likely that the dispersed pigeonpea, which produced 24 % more above-ground biomass than the sole pigeonpea, developed a more extensive root system and extracted a greater quantity of water from below 150 cm.

By groundnut harvest in 1990, transpiration by the sole groundnut accounted for 23 % of the annual rainfall (834 mm), as compared with totals of 39 and 42 % for both components of the line and dispersed systems. However, more than half of the water transpired by the line and dispersed pigeonpea was extracted from the soil profile after the rains had ceased. Thus, only 3 % (27.6 mm) of the total annual rainfall (May 1 1990 and April 30 1991) was received between November 1 1990 and January 25 1991, but the trees in the line and dispersed treatments respectively transpired 200 and 314 mm of water during this period, corresponding to 65 and 56 % of the total transpiration between the final fodder cut (August 8 1990) and grain harvest.

4.4.2.2 *Water use ratio*

Dry matter production can be expressed in terms of transpiration and water use ratio (ϵ_w) according to equation 1.9. In the present study, the increased productivity of the intercrop systems was entirely attributable to increases in the quantity of water

transpired since there was little difference between treatments in the mean water use ratio of either crop component. This finding is supported by previous reports showing that specific genotypes grown under comparable environmental conditions have similar ϵ_w values (Jones, 1992). The ϵ_w for the line and dispersed pigeonpea of 0.84 g kg⁻¹ was lower than that for groundnut, with the result that the system ϵ_w values for the line (0.86 g kg⁻¹) and dispersed treatments (0.89 g kg⁻¹) were lower than for the sole groundnut (1.3 g kg⁻¹). In many previous studies of water use by intercrops, the transpiration and soil evaporation components of the water balance have not been separated and water use ratios have been calculated on the basis of evapotranspiration. When increases in water use ratios are observed in intercrops, these are usually the result of an increased proportion of evapotranspiration being used for transpiration (Morris and Garrity, 1993).

4.4.2.3 *Availability of water to the groundnut in the line and dispersed treatments*

Because the groundnut was grown during the rainy season, it is assumed that the heavy shading imposed by the pigeonpea canopy was responsible for many of the differences in groundnut growth and development observed between treatments. However, competition with pigeonpea for water may have resulted in water stress, which could have contributed to the observed differences, particularly because little rainfall was received during vegetative growth in 1990.

Cell growth is one of the first processes to be affected by water stress (Hsiao *et al.*, 1985). Stirling (1988) found that, when groundnut was grown in the post-rainy season at ICRISAT, soil moisture deficits early in the season reduced the rate of vegetative development and delayed canopy closure by approximately 650 °Cd. When stands suffered moisture stress later in the season they also exhibited premature leaf senescence. In addition, Stirling (1988) found that moisture stress early in the season delayed the onset of pod development and, if severe, could reduce the rate of pod fill. Moisture stress later in the season reduced final pod yield by reducing assimilate production during the pod filling phase.

The majority of these drought-induced effects were not apparent in groundnut grown in the line and dispersed planted treatments. However, it is also possible that water stress reduced the rate of cell expansion in the dispersed planting and contributed to the consistently lower rate of biomass accumulation throughout the season. It is possible that the observed delay in the onset of pod development in the dispersed treatment (Section 3.7.2.2) may have been attributable to water stress. There was no significant reduction in mean L in the line treatment relative to the sole groundnut, but leaf area development at L_{max} was slower than at L_{med} and L_{min}. Once again, competition with the pigeonpea for water may have been partly responsible. Although the more prolonged duration of pod fill at L_{max} does not appear to be consistent with water stress, it is likely that, if the water supply to the groundnut had been limited, this would have occurred only during periods of low rainfall. On the basis of this evidence, it is not possible to discount entirely the possibility that below-ground competition was a contributory factor in reducing the biomass production of groundnut in the line and dispersed treatments.

4.4.2.4 Root distribution in pigeonpea in relation to water extraction

Although 80 % of the pigeonpea root ends counted were located in the top 60 cm of the soil profile in both the line and dispersed treatments, approximately 50 % of the measured reduction in stored soil moisture between 0-150 cm depth occurred between 60 and 150 cm. It is reasonable to assume that this decrease was due to extraction by the root system as opposed to deep drainage because transpiration exceeded the measured value for ΔM . Thus, the mean rate of water uptake per unit root length must have been much greater below 60 cm in view of the lower rooting density. In the sole groundnut a similar proportion of the measured change in stored soil moisture between 0-150 cm (54 %) was lost below 60 cm. In this case, it is likely that some water was lost due to deep drainage.

4.4.2.5 Soil water content in relation to water stress in pigeonpea during the reproductive growth phase

When stands are growing on stored soil moisture, a root extraction front moves progressively downwards provided the soil is moist and has a reasonably uniform structure (Squire, 1990). Studies of annual crops (e.g. Simmonds and Azam-Ali, 1989) have shown that maximum water extraction occurs in horizons just behind the rooting zone, although the root system remains capable of extracting at all depths behind the extraction front provided the soil remains above the permanent wilting point.

Studies of deep Alfisols at ICRISAT Center (El-Swaify *et al.*, 1987) have indicated that the mean water content at the permanent wilting point for the 5-140 cm horizons is approximately 14 %. The neutron probe data indicate that the soil moisture content on 14/12/95 was between 10 and 15 % (corresponding to 15.0-22.5 mm for the 15 cm depth increments examined) at most depths in the dispersed and sole pigeonpea treatments. Although the regression coefficient for the calibration was poor, this evidence suggests that the dispersed and sole pigeonpea probably experienced some water stress during the reproductive phase. The more extensive root system of the dispersed trees, although able to provide sufficient water to support productivity twice that of the line treatment, may have exploited most of the available water during vegetative and early reproductive growth, resulting in the development of mild water stress during pod maturation. Changes in stored soil moisture to a depth of 150 cm were similar in the sole and dispersed plantings. Therefore, if the supposition that the sole stand had a shallower rooting system is correct, then the actual availability of water to the trees may have been limited to a similar degree as in the dispersed treatment despite the fact that overall water use was lower.

Water stress may reduce the rate and/or duration of reproductive growth in pigeonpea and also harvest index (Lawn and Troedson, 1990). There was no significant difference between treatments in harvest index, but since the number of

pod-bearing branches is influenced by plant population and spacing (Section 3.7.1.2), any drought-induced effects may have been confounded by these factors.

The scarcity of soil moisture reserves may have been responsible for the high pigeonpea mortality following the harvest in January 1991. It is probable that, although the residual stored soil moisture was sufficient to sustain the trees through the 1990 dry season, the greater productivity of pigeonpea in 1991 depleted the available water reserves earlier in the season. Although transpiration was not measured during the dry season in the current study, perennial pigeonpea has previously been shown to utilise substantial quantities of stored soil moisture during the first dry season after planting. For example, Odongo *et al.* (1995) used the heat balance technique to measure transpiration by perennial pigeonpea between December 1988, five months after sowing, and October 1989, and found that 46 % of the total transpiration (897 mm) occurred between February and June, when only 211 mm of rainfall were received. High mortality rates were observed during the second dry season.

4.4.2.6 *Response of pigeonpea to limiting soil moisture*

The drought tolerance strategies adopted to minimise the effects of drought on growth and development often involve optimising the balance between transpiration and assimilation in relation to the quantity of water available, in order to conserve sufficient water for completion of the life cycle (Jones, 1992). Transpiration is controlled by root, shoot and environmental variables, in such a way that it is often difficult to determine which are the primary limiting factors. The interdependence of the root and canopy systems in modifying transpiration can be expressed as follows (Squire, 1990):

$$(gL)(v_i - v_a) = R I \quad \text{equation 4.12}$$

where g is the sum of the leaf and aerodynamic conductances, v_i is the saturated vapour pressure at leaf temperature (g m^{-3}), v_a is the vapour pressure of the

surrounding air (g m^{-3}), R is the total length of root per unit area of ground and I is the mean inflow of water per unit length of root. This relationship provides a basis for further examination of the degree of water stress experienced by the dispersed pigeonpea during reproductive growth and its physiological responses. The present discussion is confined to a comparison of the dispersed and line treatments because of the limited water use data available for the sole pigeonpea.

In December 1990, the estimated root length per unit ground area (R) in the dispersed planting was approximately three times greater than in the line treatment (1.1 and 0.3 km m^{-2} in the dispersed and line plantings respectively), but the mean rate of inflow per unit root length (I) was considerably lower (3.6 vs. $8.0 \text{ g m}^{-1} \text{ d}^{-1}$ in the dispersed and line pigeonpea respectively). Thus, the mean transpiration rate was 3.8 mm d^{-1} for the dispersed and 2.5 mm d^{-1} for the line pigeonpea.

These values of I are extremely high compared with previous estimates of water uptake by roots in drying soil. For instance, Squire (1990) studied data for a number of pearl millet and groundnut stands grown during the monsoon period and concluded that the mean root inflow rates were within the range 1.7 - $2.5 \text{ g m}^{-1} \text{ d}^{-1}$. When plants are dependent on stored soil moisture, the inflow rate is likely to decrease because of the lower gradient of water potential between the soil and root and the declining hydraulic conductivity of the soil. It seems likely that an underestimation of the true root length for pigeonpea resulted in the very high observed values of I . Indeed, short duration crops such as groundnut have typically been found to produce root densities of approximately 3 km m^{-2} , whilst longer duration legumes can attain root densities of up to 7 km m^{-2} (Squire, 1990). There is some evidence that root development in pigeonpea may be more restricted, or proceed more slowly than in other crops (cf. Lawn and Troedson, 1990), although this is based on studies of annual crops, and may simply reflect the slower initial growth rate of pigeonpea. Despite the uncertainty over the absolute values, the lower water uptake per unit root length recorded in the dispersed planting indicates that inflow to the roots probably limited transpiration to a greater extent in this treatment. Thus, if it is assumed that the aerodynamic resistance (g_a) and leaf to air

vapour pressure difference were similar in the line and dispersed plantings, L and/or stomatal conductance (g_s) may have been reduced to a greater extent in the latter treatment in order to conserve water. The quantity of radiation intercepted per unit leaf area may also be reduced during drought by paraheliotropic leaf movements and leaf rolling in pigeonpea (Hughes and Keatinge, 1983).

Senescence and leaf fall began earlier in the dispersed pigeonpea, with the result that transpiration began to decrease on December 1 1990, approximately ten days earlier than in the line planting. This is a recognised response of pigeonpea to drought during late reproductive growth, which enables the plant to reduce its effective leaf area and hence transpiration (Lawn and Troedson, 1990) and has the effect of increasing the R/L ratio. The R/L values for pigeonpea at the time of the root excavations, based on the destructive estimates of L obtained on 21/12/90, were $0.9 \text{ kg (root) m}^{-2} \text{ (leaf)}$ for the dispersed planting and 0.5 kg m^{-2} for the line planting. The values of L based on the f values (calculated from solarimeter measurements) for the line planting were similar to the estimates from destructive samples, the corresponding estimate for the dispersed planting was twice the destructive sampling value. This can be explained by the fact that the solarimeter estimate of f included green and senescent leaves, whilst L was measured as green leaf area in the destructive samples. On the assumption that there was no root growth during December, the estimated R/L values on December 1, prior to the premature leaf senescence in the dispersed pigeonpea, were similar for both treatments (0.4 kg m^{-2}). However, drying of the upper horizons may have caused the dispersed pigeonpea to produce a greater proportion of its roots below 2 m than in the line planting, thereby increasing the true value of R/L . It is common for plants to alter their root:shoot biomass ratio when specific resources are limiting so that a greater proportion of the available assimilate is partitioned to the structures responsible for acquiring the limiting resource (Squire, 1990). On this basis some increase in R/L may have been expected in pigeonpea during the reproductive period.

The quantity of water transpired per unit of intercepted radiation decreased in the dispersed planting after groundnut harvest (Fig. 4.11). Thus, although the dispersed

pigeonpea intercepted considerably more radiation than the line treatment, the associated increase in transpiration was less than proportionate, suggesting that although L and K may have decreased in response to drought, transpiration was still limited by I and/or stomatal conductance (g_s). Stomatal closure is a commonly observed response to reductions in soil water availability (Jones, 1992). Indeed, because partial stomatal closure has a greater influence on water loss than on CO_2 uptake (Raschke, 1975), this response tends to improve ϵ_w . On the basis that soil physical properties were uniform throughout the experimental site, the lower soil moisture content in the dispersed planting would have been associated with a lower soil water potential. It is probable that the soil water potential became sufficiently low to induce some degree of stomatal closure, thereby reducing transpiration. Although reductions in plant water potential and/or turgor may precede stomatal closure, many species exhibit a direct response to decreasing soil water availability which is mediated by a signalling process between the root and the shoot and may involve abscisic acid (Jones, 1992). Since neither stomatal conductance nor leaf water potential were measured in pigeonpea, it is not possible to determine the extent to which stomatal closure was induced by declining soil water availability, or the processes by which this might have occurred. However, pigeonpea is known to be highly tolerant of tissue water deficits (Lawn and Troedson, 1990) and has a low lethal relative water content as compared to other tropical grain legumes (Sinclair and Ludlow, 1986). The extensive premature leaf senescence observed in the dispersed planting was therefore probably preceded by a major reduction in leaf water status.

Although stomatal conductance may have been lower in the dispersed than in the line planted pigeonpea during the latter part of the growing season, the absolute values of canopy conductance and hence transpiration treatment remained much higher than in the line planting because, a much larger leaf area was maintained, despite the premature leaf senescence.

4.4.2.7 Complementarity of water use

It is difficult to establish unequivocally whether true complementarity of resource occurred, due to the sub-optimal pigeonpea population in 1990. It was expected that the productivity of the sole pigeonpea in 1990 would have been at least double that in 1989 (Ranganathan, 1993, Odongo *et al.*, 1995). The mean ϵ_w values for the period shown in Table 4.14 were therefore used to obtain estimates for transpiration in 1989. Transpiration by the sole pigeonpea calculated in this way was approximately 90 % of the annual rainfall. On this basis, the water use of a sole pigeonpea crop at its optimum population in 1990 would have exceeded that of the dispersed treatment, although limited soil water availability might in practice have prevented this from occurring. Although a sole crop grown at its optimum population might have been able to transpire more water than the line or dispersed system during the groundnut growing season, an increase in the proportion of rainfall lost as runoff might have limited the availability of water to the sole pigeonpea later in the season. This evidence suggests that the dispersed system did not demonstrate spatial complementarity of water use in 1990 because, firstly, the sole pigeonpea at its optimum population would probably have utilised more water than either of the intercrop systems and, secondly, the dispersed system did not have a higher ϵ_w . However, temporal complementarity of water use would have occurred in 1989. Due to its slow initial development, water use by the sole pigeonpea would have been lower than in the treatments containing groundnut early in the season, whilst after groundnut harvest, the pigeonpea would have utilised off-season rainfall and stored soil moisture. Estimates of transpiration calculated using ϵ_w values for 1990 show that, whilst the sole groundnut transpired approximately 34 % of the annual rainfall, the line and dispersed treatments transpired 54 and 47 % respectively.

4.4.3 Microclimate

The effect of microclimatic modification on the groundnut in the line and dispersed treatments was negligible, a conclusion similar to that reached in several previous

studies of intercrop systems. For example, Ong *et al.* (1991c) studied a pearl millet/groundnut intercrop over three consecutive rainy seasons at Hyderabad and found that the differences in soil and leaf temperatures between intercrop and sole groundnut were too small to have any significant effect on development or dry matter partitioning. They also found that the increase in VPD in the intercrop would have advanced development by a maximum of 2.5 d. Their work supported the hypothesis of Stirling (1988) that the timing of rainfall is more important than microclimate in determining the partitioning of dry matter in groundnut.

Microclimatic modifications are potentially much larger in agroforestry systems and the rapid development of the dispersed trees might have been expected to produce a high degree of uncoupling between the microclimate experienced by the groundnut and macroclimatic conditions, although there was little evidence that this occurred to any great extent.

Although the quantity of radiation reaching the soil surface was lower at position MLmax and in the dispersed planting than at the other sampling location in 1990 (Section 4.1.2.2), this was offset by a simultaneous increase in aerodynamic resistance which would have reduced the fluxes of sensible and latent heat away from the soil surface. This is consistent with the findings of Corlett (1989), who also reported little difference in soil and leaf temperatures in the *Leucaena*/pearl millet alley cropping system which reduced wind speed by up to 50 %. The reduction in latent heat losses would have resulted in more of the radiant energy that reached the soil surface being stored as heat, whilst the reduction in sensible heat transfer would result in less heat being lost to the atmosphere and canopy at night. Between rainfall events, when the soil surface was dry, the reduction in sensible heat losses would have been the most influential factor on soil temperature. This is in contrast to the leaf temperature, which would have been influenced predominantly by variation in transpiration rate except during periods of drought.

In the *Leucaena*/millet system examined by Corlett (1989) there was no detectable reduction in D within the alleys; but it was suggested (Monteith *et al.*, 1991) that

crops of shorter stature such as groundnut would experience a decrease in D when grown in agroforestry systems and hence ϵ_w would increase. The current findings do not support this hypothesis because, although D was reduced in the dispersed planting, VPD remained below VPD_o for much of the season. However, if the system had been established in an area where the prevailing D was greater, some benefit might have been obtained.

Chapter 5: FINAL DISCUSSION

In the first part of this chapter, results from the present study are discussed, the major physical factors determining productivity in each of the systems are reviewed and applications of the research and possibilities for future developments are considered. Successful planning and implementation of agroforestry research requires an interdisciplinary approach in which biological and social scientists work closely with farmers. In the latter part of this chapter, some of the important socio-economic factors are considered in relation to the acceptability of perennial pigeonpea/groundnut agroforestry systems to farmers in semi-arid India.

5.1 COMPARISON OF PRODUCTIVITY AND RESOURCE USE BETWEEN TREATMENTS

In 1989, the LER values of 1.1 and 1.2 for the line and dispersed treatments (Table 3.39) indicate that there was a slight intercrop advantage, so that a greater area of land would be required to produce sole crop biomass in the same proportions as in the intercrops. In fact, the temporal complementarity in the first year of growth is such that, the overall productivity of the pigeonpea/groundnut systems could have been increased further by increasing the pigeonpea population, with little loss of groundnut yield; for instance, Odongo *et al.* (1995) obtained a TDM of 7.1 t ha⁻¹ when ICP 8094 was sown in a 1:4 row arrangement with groundnut, whereas the productivity of the line and dispersed treatments in the present study was only 4.4 and 4.6 t ha⁻¹ respectively. The differing spatial arrangement of the pigeonpea in the line and dispersed treatments made little difference to the productivity of either pigeonpea or groundnut in 1989 because the slow initial growth rate of the former meant that there was little competition for resources with the groundnut. The similarity of pigeonpea productivity in the line and dispersed treatments indicates that, despite the close intra-row spacing in the line planting, there was no increase in intraspecific competition. However, the possibility that competition from the groundnut reduced pigeonpea growth in both treatments in 1989 cannot be discounted.

The biomass production of the sole pigeonpea in 1989 (8.2 t ha^{-1}) was considerably greater than the totals for either of the pigeonpea/groundnut systems. This resulted entirely from the greater quantity of intercepted radiation by the sole pigeonpea rather than from an increase in the light conversion coefficient, whose value (0.42 g MJ^{-1}) was lower than in either the sole groundnut (0.46 g MJ^{-1}) or the line and dispersed treatments (0.55 and 0.56 g MJ^{-1} respectively). The very low populations of the line and dispersed pigeonpea in 1989 were reflected by their low fractional radiation interception and dry matter production values (Table 4.18). The sole pigeonpea and groundnut stands both developed and maintained a full canopy cover and thus intercepted a similar proportion of the incident radiation between sowing and their respective harvests (0.54 and 0.55 respectively). However, total cumulative radiation interception by the sole pigeonpea (1943 MJ m^{-2}) was almost double that of the sole groundnut (935 MJ m^{-2}) because the growing season was extended from 119 to 212 days. The fractional interception values obtained agreed closely with values reported for sole crops of groundnut and annual pigeonpea (Natarajan and Willey, 1980; Reddy and Willey, 1981).

One potential benefit of growing perennial pigeonpea is the provision of fodder from regular harvests during the dry season. However, dry season production was very low ($0.1\text{-}0.5 \text{ t ha}^{-1}$), contributing $< 7 \%$ of the total annual production in all treatments containing pigeonpea in 1990. However, although there was little apparent benefit from dry season production, perennial pigeonpea is likely to be considerably more productive than sequential annual crops because growth during the second rainy season is rapid, whereas the initial growth after sowing annual crops is slow.

In 1990, pigeonpea was the dominant component of the line and dispersed systems. The LER values were higher than in 1989 despite substantial reductions in groundnut yield because these were more than offset by the considerable increase in pigeonpea productivity. The intercrop advantage apparently resulted from a combination of temporal and spatial complementarity of resource use, but without an appropriate sole crop it is not possible to confirm whether biological complementarity actually

occurred. Because the sole pigeonpea was reduced to a sub-optimal population in June 1990, calculations of relative system productivity between July 1990 and January 1991 tended to overestimate the intercrop advantage. If a sub-optimal population of 0.44 plants m^{-2} had been established in 1989 and maintained throughout the experiment, it might have been possible to predict potential productivity from known relationships between yield and population (Ranganathan, 1993). When calculated on the basis of sole pigeonpea production in 1989, the LER for TDM production in the line treatment in 1990 (1.17) was only slightly higher than in 1989 (1.04) because, although the partial LER for pigeonpea had increased from 0.18 in 1989 to 0.45, this was offset by a reduction in the partial LER for groundnut from 0.83 to 0.72. However, the LER for the dispersed treatment in 1990 (1.52) was greatly increased relative to 1989 (1.08), despite a substantial reduction in groundnut yield (partial LER 0.67), because rapid growth increased the partial LER for pigeonpea from 0.19 in 1989 to 0.85 in 1990.

Spatial arrangement had a considerable influence on the growth rate of pigeonpea from the start of the 1990 rainy season onwards, as indicated by the more rapid increase in light interception and transpiration by the trees in the dispersed treatment relative to those in the line treatment. There was a five-fold increase in biomass in the dispersed planted pigeonpea between 1989 and 1990, and the dispersed pigeonpea produced 7.34 t ha^{-1} between January 31 1990 and final harvest, approximately double the productivity of the line planted trees.

There was little difference in the LER values for pod/grain yield between 1989 and 1990 (Table 3.39) because the increased pigeonpea grain yield in the line and dispersed treatments was offset by reductions in the pod yield of groundnut. Thus, although the grain dry weight obtained from pigeonpea in the dispersed system was considerably greater than in the line planting (0.69 vs. 0.38 t ha^{-1}), groundnut pod dry weight was much lower (0.64 vs. 0.94 t ha^{-1} for the dispersed and line treatments). The harvest index for pigeonpea was much lower in all treatments in 1990-91 than in 1989-90 (Table 3.27), probably largely because of the more extensive damage caused by pod borer (*Helicoverpa armigera*).

No single causal factor for the extensive pigeonpea mortality following the final grain harvest was identified, although it is likely that the low soil moisture content during this period played a major role. This would probably have resulted not only in plant water stress, but also in an associated decrease in the availability and uptake of nutrients and an increased susceptibility to fusarium wilt and sterility mosaic disease.

In general, the differences in dry matter production between treatments originated primarily from changes in fractional radiation interception and water capture (Tables 4.18, 4.19), rather than improvements in the radiation conversion coefficient or water use ratio. However, the overall e value for the dispersed treatment may have been higher than for the other treatments because there was a significant increase in e for the groundnut component, whilst the extent of the decrease in e for pigeonpea remains uncertain (Section 4.4.1.2.2).

5.2 COMPETITION FOR RESOURCES WITHIN THE LINE AND DISPERSED TREATMENTS IN 1990

5.2.1 Effects on groundnut growth, development and productivity

In 1990, the number of pods initiated and the rate of pod development were both lower at L_{max} and at all sampling locations in the dispersed planting than in the sole crop. The reduction in the number of pods was apparently due to the delayed *onset* of pod initiation rather than a reduction in the subsequent *rate* of initiation. The shaded groundnut appeared to respond to the constraints of a decreased assimilate supply and the reduced pod filling period by producing fewer pods so that at least some viable seed was produced. A greater proportion of the pods from shaded plants reached maturity, with the result that the proportion of assimilates partitioned to pods and the mean weight per pod at final harvest were similar in all treatments and sampling positions.

As flowering proceeds, the number of flowers that set pegs becomes progressively

smaller (Duncan *et al.*, 1987) due partly to the increasing competition for assimilates. Pods closest to the ground are better supplied with assimilate than those produced later and flowers produced further from the ground may produce pegs that are incapable of extending sufficiently to reach and penetrate the soil. On the basis that assimilate supply is limited in the shaded plants, suppression of both flowering and peg development would be expected. In addition, it is possible that mainstem height may be increased in shaded plants, further reducing the chances of pegs successfully reaching the ground and forming pods. The timing of the onset of leaf senescence is related to the proportion of pods that have reached maturity (Stirling, 1988). Stirling (1988) observed premature leaf senescence in shaded plants which had a higher proportion of mature pods than the unshaded control. Thus, the early cessation of pod initiation and premature leaf senescence were predictable responses of groundnut to shading in this study. However, these potential effects could not be rigorously examined because of the reduction in L induced by severe foliar disease in all treatments. By 90 DAS, mean L was reduced to approximately 0.4 in all treatments, as compared to 0.9-2.0 in 1989. As a result, there was no increase in pod number and little increase in pod dry weight after 80 DAS in any of the treatments. The increase in pod dry weight between 80-100 DAS was greatest in the sole crop, presumably because the plants were able to produce sufficient assimilate to increase pod dry weight despite their very limited leaf area, whereas the quantity of radiation intercepted by the shaded groundnut plants was insufficient.

The evidence for the involvement of mild water stress resulting from below-ground competition with the pigeonpea in reducing yield in the line and dispersed groundnut in 1990 is inconclusive. It is apparent that any moisture stress was not severe because there was no leaf folding, wilting or detectable increase in leaf temperature relative to the sole crop. In addition, water stress would have been expected to reduce the light conversion coefficient (Chapman, 1993a), whereas the increase in e due to the shading of groundnut in the dispersed planting was of similar magnitude to other studies in which shade was applied in the absence of water stress (Table 4.18). Water stress also tends to reduce the rate of canopy development and increase the thermal time durations for developmental stages (Squire, 1990), but little

difference was noted in the present study for the thermal time required to attain full canopy development or 50 % flowering. However, there was some evidence of delayed pod initiation in the dispersed treatment, which may have resulted from water stress. For example, Chapman, (1993b) found that peg initiation was sensitive even to mild water stress and that the elongation of pegs was halted by water stress, but resumed after rewatering. Water stress may also have reduced turgor within the pegs, impairing their ability to penetrate the soil (Stirling, 1988) and delaying pod initiation. The slight reduction in L in the dispersed planting (Fig. 3.9) may have been due to either water stress or shading or a combination of both.

The effects of shading by pigeonpea on dry matter accumulation by groundnut were partially offset by an increase in e . Other microclimatic modifications in the line and dispersed treatments were insufficient to effect any significant change in groundnut growth or development relative to the sole crop, although the more extended pod filling period observed at position L_{max} as compared to L_{med} and L_{min} remains unexplained.

5.2.2 Limitations to pigeonpea productivity

In 1990, pigeonpea was the dominant component of the line and dispersed systems and so the extent of intraspecific competition for resources was the major factor responsible for the observed differences in pigeonpea productivity between these treatments. The close intra-row spacing of pigeonpea in the line planting resulted in considerable intraspecific competition for resources both above and below-ground because of the extensive mutual shading and overlap of root systems of adjacent trees. The fully developed canopy of the line planted trees covered approximately one third of the land area, while the root system exploited approximately half of available soil profile (Fig. 3.21). In contrast, the canopy of the dispersed trees was much more extensive, there was little mutual shading between trees, and the root system exploited the entire soil profile for water and nutrients.

Water was probably the principal limiting factor for yield in the dispersed pigeonpea

in 1990 since the trees were dependent on the limited residual supplies of stored soil moisture throughout their reproductive growth; at final grain harvest in 1991, the neutron probe data showed that there was little available soil moisture remaining in the soil profile between 0-150 cm in the sole and dispersed treatments. As biomass accumulation and transpiration by the dispersed pigeonpea were approximately double those in the line planting, it is not surprising that late season water stress was visibly more severe in the former treatment. Transpiration per unit of intercepted radiation was lower in the dispersed pigeonpea than in the line treatment (Fig. 4.11) because, although the estimated root length was approximately three times that in the line planted trees, water uptake per unit root length (Section 4.4.2.4) and per unit leaf area was considerably lower. Premature leaf fall and increased stomatal resistance enabled the dispersed trees to conserve water and survive to maturity. The lower light conversion coefficient of the dispersed trees provides some evidence of stomatal closure in response to water stress (Sivakumar and Virmani, 1978a; Jones, 1992), although there may also have been associated mesophyll limitation to photosynthesis (cf. Section 1.4.3). Although water use ratio may have increased in all treatments in response to a limited water supply (Turner, 1986), the water use efficiency of the dispersed trees was not significantly higher than in the line treatment (Table 4.10).

Assuming that the soil profiles in the sole and dispersed treatments were fully charged at groundnut harvest, and that the rooting depth of sole pigeonpea did not exceed that of the dispersed trees (indeed, the rooting depth in the sole pigeonpea may have been significantly less (Section 4.4.2.1), water extraction by the sole pigeonpea stand would probably not have exceeded that of the dispersed trees between groundnut harvest and the final grain harvest. As a result, dry matter accumulation by the sole pigeonpea would not have exceeded that of the dispersed pigeonpea over this period, assuming that there was no change in water use ratio. Biomass accumulation by a sole pigeonpea stand grown at its optimum population during the rainy season of 1990 would probably have exceeded that of the dispersed treatment. Thus, a sole stand planted at its optimum population would have tended to deplete the stored soil moisture more rapidly than the dispersed trees and to suffer

more severe water stress during reproductive growth. Water stress was probably responsible for the reduction in the light conversion coefficient in the dispersed treatment relative to line planted pigeonpea (Section 4.18b). Thus, if the sole pigeonpea experienced greater water stress, it would have tended to exhibit a lower e value than the dispersed pigeonpea in 1990, and a considerably lower value than for the sole pigeonpea in 1989.

Productivity of perennial pigeonpea is generally expected to increase in the second year of growth (Section 3.7.1.2). However, if the above argument is correct, productivity of the sole crop in 1990 might have been lower than in 1989 due to a reduction in the seasonal e value. If this were the case, the 1990 LER values which were based on the productivity of the sole pigeonpea in 1989 (1.17 and 1.52 for the line and dispersed treatments respectively) may have underestimated the true advantage of the line and dispersed treatments. It is not possible to validate this theory without knowledge of water use prior to July 1990 or the extent of root development prior to the cessation of the rains in 1990.

In fact, the e values for pigeonpea were lower in all treatments in 1990 (Table 4.19). The higher values observed in the line and dispersed treatments in 1989 may be explained by the fact that little or no late season water stress would be expected at such low populations. However, it is surprising that the e value for the sole pigeonpea was not lower in 1989. There was little difference in the off-season rainfall in 1989 and 1990; thus, if the soil profile was assumed to be close to field capacity at the end of the rainy season in both years, then the highly productive sole crop in 1989 would have been expected to deplete the available soil moisture more rapidly than the dispersed crop in 1990 and consequently to suffer from more severe water stress and a greater reduction in e . However, the relatively high e value for the sole pigeonpea in 1989 may be explained by considering the development of the root system. The root system of the sole crop would have been relatively shallow in 1989, and would have extended downwards during the post-rainy season as moisture in the upper soil horizons was depleted (Section 4.4.2.5). The plants may have responded to the progressive depletion of water in the upper horizons by restricting

their water use, and may have succeeded in avoiding the degree of water stress required to reduce e . In contrast, the well developed root systems of pigeonpea in 1990 would have extracted water from throughout the profile during the second post-rainy season, rapidly depleting the available soil moisture and resulting in water stress and a consequent reduction in e . Another possible explanation for the lower e values for pigeonpea in all treatments in 1990 is an increase in damage caused by leaf miner and pod borer.

There are several other potential errors in the estimates of relative productivity and resource use in the sole and intercrop systems. For example, despite the relatively large plot sizes and boundary areas used in this experiment, it is possible that the roots of pigeonpea were able to extract water from the sampling areas of neighbouring sole groundnut plots, thereby leading to a potential overestimation of the water use and productivity advantages of the sole pigeonpea and agroforestry systems relative to the sole groundnut (cf. Hauser and Gichuru, 1994). Similarly, the more competitive root systems of the sole pigeonpea in 1989 or the dispersed pigeonpea in 1990 may have been able to extract water that would otherwise have been available to either the groundnut or pigeonpea components of neighbouring plots.

5.3 IMPLICATIONS FOR FUTURE RESEARCH

This section considers the extent to which the experimental aims outlined in Section 1.6.3 were met, and makes specific recommendations for improvements in the experimental design and techniques employed. In addition, priority areas for future investigation are identified.

5.3.1 Comparative Treatment Effects on Productivity.

Total dry matter production

Although the comparison of productivity in the line and dispersed treatments was

successful, there were major difficulties in determining the biological advantage in terms of the LER of these agroforestry systems because of the sub-optimal sole population of pigeonpea in 1990. In future studies, it would be useful to examine productivity over at least a two year period using sole pigeonpea stands established and maintained at a population of 0.5 plants m² throughout. Previous studies have indicated that the productivity of the sole crop may be expected to increase considerably in the second year (Section 3.7.1.2), thereby reducing the actual intercrop advantage as compared with the values presented in Section 3.7.3. However, comparison of line and dispersed systems on Alfisols at ICRISAT Center would be particularly useful in the light of the evidence discussed in Section 5.2.2 which suggests that moisture stress may limit productivity, thereby increasing the biological advantage of the agroforestry system when expressed in terms of its LER.

Some alley cropping systems developed for the humid tropics have proved unsuccessful in semi-arid regions because of intense tree-crop competition for water (cf. Section 1.5). As anticipated, the perennial pigeonpea/groundnut systems appeared promising for semi-arid regions because the majority of tree-crop competition appears to originate from above rather than below-ground effects. The evidence of biological complementarity in this system suggests that it is worthy of further study. However, the substantial losses of groundnut yield in the second year in the dispersed planting may be unacceptable and further experimentation to determine appropriate methods for controlling the extent of groundnut yield losses would be useful. For example, additional fodder cuts of pigeonpea during the rainy season might well be beneficial. Alternatively, the dispersed arrangement could be established with a perennial pigeonpea variety possessing a more erect habit (e.g. ICP-11289) to reduce shading of the groundnut component.

Future studies might also examine ways of increasing the overall productivity of the line planted system. For example, narrower pigeonpea alleys, with frequent pruning during the second year might increase pigeonpea productivity, whilst minimising decreases in groundnut yields. However, the evidence that the dispersed planting was able to exploit the soil profile for moisture more effectively, suggests that a priority

for future experiments would be to examine adaptations of this treatment. This would be particularly beneficial if methods for reducing competition with groundnut in the second year were successful.

Growth and development data

The growth analysis data for groundnut provided a sound basis for examining the major factors contributing to the reductions in yield in the line and dispersed treatments. However, additional observations of peg numbers and mainstem height would be useful in future studies to assist in establishing the factors contributing to the reduced numbers of pods initiated in shaded groundnut plants (Section 3.7.2.1). The reduced number of pods produced may have resulted either from a decrease in the number of pegs initiated because of limited assimilate availability, or an increase in mainstem height which limited the number of pegs capable of reaching the soil, or a combination of both.

It was unfortunate that regular destructive samples could not be taken from pigeonpea for growth analysis, since a comparison of leaf area development in the various treatments would have contributed to the understanding of the processes influencing biomass production in pigeonpea. Examination of the relationships between leaf area, radiation interception and transpiration would also add to the understanding of the responses of pigeonpea to environmental variables such as limited soil moisture availability. If destructive samples proved to be impractical in future studies, alternative indirect techniques for estimating L (see Section 5.3.3) could be adopted.

Further investigation of the cause of the extensive pigeonpea mortality following the second dry season after planting would be an important consideration in future studies (cf. Section 3.5.6).

5.3.3 Quantification and partitioning of light use and light conversion coefficients

The problems encountered in partitioning light interception in the dispersed arrangement have important implications for further studies. It would have been useful to have utilised one or more of the available techniques for taking instantaneous readings of radiation interception to complement the integrated long-term measurements obtained using tube solarimeters in the present study; so that despite the inadequate solarimeter placement in the dispersed planting, some direct measurements of radiation interception by the pigeonpea canopy would have been available. For example, the sunfleck ceptometer (e.g type CEP, Delta T Devices, UK, cf. Howard *et al.*, 1995) would have provided instantaneous measurements of PAR interception by the pigeonpea and groundnut canopies integrated over a 80 cm transect. Measurements repeated throughout the day would have provided diurnal trends for interception. With the instrument in its sunfleck mode, a series of measurements at different solar elevations may have been used to estimate leaf area index. The 'mouse' quantum sensor (cf. Ong *et al.*, 1995) could have been used to investigate PAR interception above and below specific groundnut rows in the line and dispersed treatments. This would have been particularly valuable in the dispersed planting since it would have enabled the extent of shading by the pigeonpea canopy to be determined. In addition, fisheye photography (cf. Norman and Campbell, 1989) could have been used to provide an additional estimate of fractional light interception by the pigeonpea canopy in the dispersed arrangement. Ceptometry and fisheye photography could also be used to obtain regular estimates of L for the pigeonpea component.

Additional physiological measurements to investigate the relationship between dry matter production and resource use might also be of value. For example, infra red gas analysers (IRGA) (e.g ADC LCA4, or CIRAS1, UK) could be used to measure instantaneous CO_2 assimilation rates, construct light response curves for the groundnut and confirm the hypothesis that the increase in e in the shaded crop resulted from the fact that the sole crop was frequently light saturated (Section

1.4.2). The IRGA technique could also be useful for closer examination of the responses of the tree and crop components in each treatment to limited soil moisture availability at various stages during growth and development.

5.3.4 Quantification and partitioning of water use and calculation of water use ratios

The data obtained in this study make a significant contribution to the limited experimental database concerning water use in agroforestry systems. It is clear that the dispersed planting was able to utilise the greatest proportion of available water for transpiration in the second year, but more precise quantification of the other water balance components would be useful for the development of practical recommendations, and would be a high priority in future work. This would require refinements and intensification of the methodologies adopted in the current study and additional experimental techniques. For example, although estimates of water use by the sole pigeonpea were obtained, installation of sap flux equipment in this treatment would be invaluable in future comparative studies of the benefits of the agroforestry systems as compared with sole pigeonpea in utilising the available rainfall.

It is unfortunate that the porometer measurements were not successful, not only because of the consequent difficulty of obtaining reliable estimates of transpiration and water use ratio for groundnut, but also because measurements of stomatal conductance and leaf area would have been useful when assessing the influence of water stress and determining the factors limiting transpiration in pigeonpea (Section 4.4.2.6). Successful miniaturisation and field application of the heat balance technique (cf. Ong *et al.*, 1995) would provide a much more straightforward and potentially more reliable approach for future rainy season measurements. However, if this were not available, more intensive porometry measurements would be a priority.

It became apparent during this study that the depth of access tubes was insufficient and, although this may prove difficult, greater installation depths should be

attempted in future trials. The restriction of the measurements of soil volumetric water to a maximum depth of 1.5 m resulted in an underestimation of the quantity of water extracted from the profile during drying cycles and a consequential underestimation of D, I and R. There may have been important undetected differences between treatments in the pattern of water extraction below 1.5 m.

The root studies proved invaluable in determining the proportion of the soil profile that was exploited by roots and providing a comparative measure of root length and water uptake per unit root length in the line and dispersed treatments. In future work, it would be important to carry out similar studies, including the sole pigeonpea treatment, and also to examine the profiles at an earlier stage in establishment of agroforestry systems, after the first dry season. It would also be interesting to examine the relative rates of movement of the rooting front, possibly through rhizotron studies (cf. Brenner, 1986). These would also facilitate more accurate determination of root length.

The estimates of soil surface evaporation relied on empirical formulae based on micrometeorological data and included a number of approximations and assumptions. Ideally, direct measurements would have been used to verify the validity of the models and assumptions adopted. Future studies should include a direct measurement technique such as microlysimetry (cf. Wallace, 1995).

Individual measurement of the D, I and R components of the soil water balance would also be valuable in further work. For example, Wallace (1995), stated that, although D is rarely quantified, it is the component of the water balance most easily modified by the presence of trees and should be investigated in greater detail. Another potential advantage of agroforestry systems is a significant reduction in R and in associated erosion as compared to the sole crops (Section 1.4.3). The very limited runoff data obtained in the present study indicate that the presence of groundnut reduced runoff greatly relative to the sole pigeonpea. However, the presence of trees might well increase infiltration rate during off-season rainfall events and reduce runoff and soil erosion caused by both water and wind.

Although reliable estimates of water use ratio were obtained for pigeonpea between consecutive harvest dates, more regular estimates of biomass accumulation would be useful for investigating changes in water use ratio between the wet and dry seasons, and the effects of the limited soil moisture availability.

5.3.4 Examination of microclimatic modifications in the agroforestry systems and their influence on the growth and development of groundnut.

As the differences in microclimate experienced by the groundnut in the various treatments had little or no detectable influence on growth and dry matter partitioning, similar measurements would not be recommended for future studies of perennial pigeonpea based agroforestry systems in the semi-arid tropics. Instead, the resources required could usefully be diverted to the more detailed investigations of the water balance and light partitioning, as described above. However, microclimatic modification may have a greater influence on understorey crops in environments where the ambient saturation deficit is higher or the windspeed lower (cf. Section 4.4.3), and larger trees species may also have a greater effect.

5.4 OTHER POTENTIAL BENEFITS OF THE AGROFORESTRY SYSTEMS

It was not possible to investigate all aspects of the tree-crop interactions in the agroforestry systems examined in this study. One of the major potential benefits of agroforestry systems containing leguminous trees is the positive effects on soil fertility and structure resulting from the improved supply of nitrogen and the recycling of nutrients returned to the soil as leaf fall or mulch (Young, 1989) (Section 1.3). Significant beneficial residual effects on soil fertility may occur following pigeonpea crops; for example, Kumar Rao *et al.* (1981) estimated that the residual Nitrogen available to a maize crop following pigeonpea was 40 kg ha⁻¹. Ideally, soil nutrient status would have been determined in all treatments in the current study, and the residual effects on an annual crop after the removal of pigeonpea investigated. As fertilizer was applied at the start of this investigation, and there were no apparent nutrient deficiencies, the influence of nitrogen fixation and

nutrient cycling may have been relatively small, but would probably have been a more significant factor in nutrient-poor soils. Nygren and Jiménez (1993) carried out a simulation study on an agroforestry system containing *Erythrina poeppigiana* (Walpers) and sequential maize and bean crops to determine the influence of the spatial arrangement of the trees on both the shading of crops and the nitrogen supply to them. They found that when both factors were taken into account, a dense within-row spacing (1 m) and a wide between-row spacing (6 m) was preferable because this provided a good N supply with the least shading. However, the study was carried out on relatively fertile soils and the authors pointed out that narrow alleys may be more effective when nutrient supply is poor because the N supply and nutrient recycling would be more effective.

5.5 APPLICATIONS FOR AGROFORESTRY SYSTEMS RESEARCH

Data from this research and other studies of resource use in agroforestry systems (e.g. Corlett, 1989) could make an important contribution to the development of computer simulation models for agroforestry systems. Models based on a sound knowledge of the biological, physical and chemical processes involved would improve our understanding of the interactions between crops and their environment. There has been a rapid increase in recent years in the of number models available for individual crops and marked refinements in their capabilities since they were first introduced in the early 1970s. For example, PNUTGRO (Boote *et al.*, 1986; Hoogenboom *et al.*, 1992) is capable of simulating reproductive development, biomass accumulation and partitioning, and of producing a soil and plant water balance for a wide range of groundnut cultivars. Such models can be used to plan cropping and land use strategies based on the production potential of specific environments and make crop management decisions. They can also provide valuable tools for integrating past and present research results and defining future goals. The task of modelling intercropping or agroforestry systems poses a far greater challenge than monocultures, not only because of the greater number of interacting variables, but also because of the complexity of the microclimatic interactions. Comprehensive models have yet to be developed, although a number of researchers have developed

methods for predicting the radiation regime experienced by understorey crops in intercropping and agroforestry systems (e.g. Queseda *et al.*, 1989; Sinoquet and Bonhomme, 1992.). As the basic data set of information from experimental work grows, so too does the predictive power of the simulation models developed from it. The major constraint to producing growth models for agroforestry systems is the dearth of information from detailed experimental studies of the tree-crop interactions involved. However, it may eventually be possible to simulate an almost infinite number of tree and crop combinations, populations, spatial arrangements and management techniques; the most promising systems developed from predictive studies, probably those that use resources most effectively, could then be tested in the field.

In order to understand the tree/crop interactions involved, this research was necessarily carried out in the absence of many of the restrictions that farmers in the SAT experience. The experimental site was a particularly deep and well fertilised alfisol, and resources for fodder cuts, harvests, weeding and pest control were unlimited. The next logical step in investigating the suitability of perennial pigeonpea/groundnut systems for farmers in Andhra Pradesh and elsewhere in India would be to carry out extensive on-farm trials. The complex nature of agroforestry systems and the necessity for large plot sizes and long-term monitoring accentuate the difficulties in the statistical analysis of on-farm trials, although appropriate methods are being developed (Huxley and Mead, 1988; Shepherd and Roger, 1991; Rao and Coe, 1991).

5.6 OTHER FACTORS DETERMINING THE SUITABILITY OF AGROFORESTRY SYSTEMS FOR LOCAL FARMERS

Total dry matter accumulation by each of the treatments or, more precisely the sum of the products of the appropriate energy contents per unit dry matter and dry matter accumulation, is useful for relating productivity to resource use and investigating biological complementarity. However, the most productive systems are not necessarily the most appropriate to the farmer. An important consideration is the

relative economic return from each system. Ranganathan (1993) studied optimum economic returns from mixed cropping systems in relation to planting density. She found that, during the first year of pigeonpea growth, a population of 5.4 plants m² provided maximum returns in a pigeonpea/groundnut system, mainly because at higher populations there was only a marginal increase in seed yield, which had a much greater market value than fodder.

In terms of absolute biomass accumulation, the sole pigeonpea was the most productive in both years of this study, but groundnut is a valuable cash crop. In terms of economic yield, the dispersed system is potentially preferable to the line treatment. The total combined pod and grain yield from the dispersed treatment was similar to the pod yield obtained from the sole groundnut; although the market value of groundnut pods is 20 % greater than that for pigeonpea grain, a significant additional income could be obtained from the greater fodder and fuelwood production of the dispersed pigeonpea. However, market rates for grain and pods are likely to fluctuate and there is no reliable market for pigeonpea fodder (Ranganathan, 1993). Thus, if the market value of groundnut were to rise further relative to pigeonpea, a line planted arrangement might be preferable. However, pruning the lower branches of the dispersed pigeonpea would probably increase the groundnut yield.

The evidence of significant biological complementarity in perennial pigeonpea/groundnut agroforestry systems indicates that there may be an economic benefit over growing the component crops separately (Walker, 1987). This is in contrast to the much studied agroforestry systems involving leucaena (*Leucaena leucocephala* Lam.), in which there is no evidence of biological complementarity due to the severity of competition by the tree component. In fact, with or without biological complementarity, agroforestry systems are likely to have longer term economic advantages over sole cropping because of their potential for decreasing soil erosion and improving soil structure and fertility.

In terms of dietary requirements, the priorities may be rather different. A detailed

study of diets in six villages in Southern India (Ryan *et al.*, 1984) concluded that there were major deficiencies in energy, vitamins and minerals as compared with recommended daily consumption, but that protein intake was adequate in most age groups. Although groundnut and pigeonpea grain are similar in terms of protein content (23 and 20 % respectively) (Doughty, 1981), the total energy content of groundnut is much greater than that of pigeonpea due to its very high fat content (1.2 and 45 % for pigeonpea and groundnut respectively). Thus nutritionists may wish to promote an increase in home consumption of groundnut in preference to pigeonpea.

Beyond this scientific evaluation of the suitability of farming systems involving perennial pigeonpea, there are numerous other considerations involving the needs and preferences of a given farming community at any particular point in time. For example, land tenure may be a constraint to the adoption of perennial pigeonpea because a 'social fencing' custom is maintained in many traditional farming systems in Andhra Pradesh; livestock is kept away from pigeonpea until grain harvest, after which time it may be allowed to graze freely in neighbouring fields (Faris *et al.*, 1990). Perennial pigeonpea would not survive heavy dry season grazing by animals and it seems likely that a more substantial dry season fodder production would be required before farmers could justify the protection of individual fields. Fencing of the plots would probably be too costly, although live fencing may be a viable alternative for small plots. This has also been reported as a constraint to adopting hedgerow intercropping in other regions (e.g. Minae, 1992).

Some of the new short duration, high yielding pigeonpea cultivars may offer a more attractive, lower risk option to farmers than perennial pigeonpea, particularly because it is more difficult to demonstrate the longer term benefits of agroforestry systems as opposed to the short term benefits of a reliable increase in pod yield. Successful on-farm trials are the only effective method of proving the worth of such systems so that a fully informed choice can be made.

5.7 INFORMATION EXCHANGE AND AGROFORESTRY RESEARCH

As scientific knowledge of agroforestry systems increases, so does the requirement to improve information exchange between researchers from all the disciplines involved, at all levels from institutional to International. The prolific increase and improvement in the number and range of information exchange technologies for agriculture in recent years can assist this process (cf. Powell, 1994). For example, Drews (1993) identified 91 organisations that hold databases and offer information services concerning sustainable agriculture, and Dusink (1989) produced a directory of over 50 on-line information sources for tropical agriculture. However, there is still a long way to go before information exchange technologies can be provided, at the request of the recipient, in an appropriate and affordable format. The majority of organisations representing local farmers' groups in developing countries do not have access to the existing technical information or appropriate training, and are desperately short of funds. However, efficient information exchange between farmers, extension workers, researchers and policy makers is essential to ensure that projects are timely, efficient and appropriate to the needs of the farmer. Fortunately, a great deal of progress has been made in developing effective ways of working closely with farmers to determine research priorities and evaluate their outcome (e.g. Chambers, 1983). Having established an agroforestry technology, the support of local groups to carry out their own community-based projects is often the most successful approach to extension (Scherr, 1992). Thus, the role of scientists and development agencies is not to prescribe solutions, but to act as catalysts and facilitators of change.

Appendix: METHODS FOR ESTIMATING RADIATION INTERCEPTION IN THE DISPERSED PLANTING IN 1990

a1.1 METHOD 1 - ESTIMATING INTERCEPTED RADIATION FROM CROP EXTINCTION COEFFICIENT AND LEAF AREA INDEX

Radiation interception by a crop canopy may be related to leaf area index (L) and the crop extinction coefficient (K) according to equation 1.7. This relationship was used to estimate mean fractional radiation interception by groundnut in the dispersed planting. By deducting the measured fractional interception by the groundnut at position 1 (Fig. 2.5) from the estimated treatment mean, an estimate of interception by groundnut at position 2 was obtained. This value was then subtracted from the total interception at position 2 (calculated from the values provided by solarimeter B2) to give an estimate of interception by pigeonpea.

The relationship described in equation 1.7 is based on the assumption that the canopy is homogeneous, with randomly distributed leaves, and that there is no effect of row structure. If these conditions are satisfied, a plot of L against $\ln(1-f)$ gives a straight line with a gradient of $-K$. The extinction coefficient for the sole groundnut was calculated from values of L and f at 10 day intervals between 30 - 100 DAS, and it was assumed that full ground cover was achieved by 30 DAS on the basis of the growth analysis results (Section 3.2.1). The value of K of 0.44 obtained by this method was then used to estimate fractional interception by groundnut in the dispersed planting (Table a1.1). The estimates of fractional interception by groundnut (G_{int}) shown in Table a1.1 were then used to estimate interception by the pigeonpea (Table a1.2). However, since the growth analysis sites did not correspond exactly to the positions monitored by the solarimeters, it was necessary to estimate mean radiation interception by groundnut for the entire system and then calculate the proportion that would have occurred at site 2, by deducting the measured values at site 1.

Table a1.1: Fractional interception by groundnut (f) in the dispersed planting in 1990 calculated using estimated leaf area index and extinction coefficient values (equation 1.7). Incident radiation was recorded by solarimeters above the canopy. The values are 10 day means; for example, those for 30 DAS were calculated using data for the period 26 - 35 DAS. Calculations were made at 10 day intervals to coincide with the growth analysis measurements of leaf area index (L).

DAS	Estimated f with K = 0.44	Total incident radiation (MJ m ⁻²)
30	0.15	72
40	0.24	152
50	0.34	163
60	0.46	180
70	0.48	150
80	0.32	146
90	0.17	186
100	0.04	158

Table a1.2: Mean radiation interception by pigeonpea (CPPi) in the dispersed planting calculated using mean fractional radiation interception values for groundnut from Table a1.1. Gint represents the mean fractional interception for groundnut in the dispersed planting; Gi2 is the estimated fractional interception by groundnut at position 2; A1 and A2 represent the fractional interception bt pigeonpea at positions 1 and 2 respectively (Figure 2.5); and B1 and B2 represent fractional interception by both the pigeonpea and groundnut components at sites 1 and 2 respectively. PPi was multiplied by the total incident radiation (Table a1.1 to obtain CPPi, and cumPPi represents the cumulative total radiation interception by the pigeonpea.

DAS	Fractional radiation interception (f)							Quantity of radiation intercepted (MJ m ⁻²)	
	2Gint	B1-A1	Gi2	B2	A2	A1	PPi	CPPi	cum CPPi
30	0.30	0.15	0.15	0.31	0.16	0.16	0.16	11.5	11.5
40	0.48	0.30	0.18	0.51	0.33	0.20	0.27	41.0	52.3
50	0.68	0.35	0.33	0.71	0.38	0.34	0.36	58.7	111.2
60	0.92	0.29	0.63	0.82	0.19	0.50	0.35	63.0	174.2
70	0.96	0.20	0.76	0.86	0.10	0.60	0.35	52.5	226.7
80	0.64	0.01	0.63	0.86	0.23	0.70	0.47	68.6	295.3
90	0.32	0.04	0.28	0.90	0.62	0.84	0.73	135.8	431.1
100	0.08	0.00	0.08	0.80	0.72	0.83	0.78	123.2	554.3

Groundnut interception at position 2 (G_{i2}) can be expressed as:

$$G_{i2} = B_2 - A_2 \quad \text{equation a1.1}$$

where A_2 and B_2 respectively represent the intercepted radiation above and below the groundnut canopy at position 2. As no measurements were made at position A_2 , values for G_{i2} were calculated from measured parameters according to the following relation:

$$G_{int} = ((B_1 - A_1) + (B_2 - A_2))/2 \quad \text{equation a1.2}$$

where A_1 and B_1 represent radiation interception above and below the pigeonpea canopy at site 1, and A_2 and B_2 represent the corresponding measurements at site 2 (Fig. 2.5).

By rearranging equation a1.2, G_{i2} can be expressed as:

$$G_{i2} = 2(G_{int}) - (B_1 - A_1) \quad \text{equation a1.3}$$

Having calculated values for G_{i2} , the estimated interception by pigeonpea (A_2) was calculated as:

$$A_2 = B_2 - G_{i2} \quad \text{equation a1.4}$$

and the overall mean interception by pigeonpea (PP_i) was calculated as:

$$PP_i = (A_1 + A_2) / 2 \quad \text{equation a1.5}$$

Mean fractional interception by groundnut, G_{int} (derived from Eq. 1.7) could not be converted directly to a quantity of intercepted radiation because, although the radiation incident on the pigeonpea canopy was measured, the quantity of radiation incident on the groundnut crop was unknown. PP_i values were therefore calculated

in terms of fractional interception, and then converted to quantities of intercepted radiation by multiplying these by the corresponding incident solar radiation values shown in Table a1.1.

Several difficulties are associated with this method of estimating radiation interception by pigeonpea. Firstly, the value of K used in equation 1.7 was derived from the L and fractional interception values obtained for sole groundnut in 1990. A second calculation of K was carried using the data for shaded groundnut at position L_{\max} in the line planting because the analysis was also to be applied to shaded the groundnut in the dispersed planting. Although little difference in K was expected, the value obtained for the groundnut at L_{\max} was considerably lower (0.2 , $r^2 = 0.6$) than in the sole crop. A second analysis of radiation interception by the pigeonpea was made using a K value of 0.22 (Table a1.5) to determine the sensitivity of the final interception value to variation in K . There was no simple relationship between the value of K adopted in the analysis and the final estimate of pigeonpea interception (PPI) obtained, probably because the latter value was the mean of the estimated interception at position A2 and the measured interception at A1 (Eq. a1.5). The final values for interception by pigeonpea were between 18 and 50 % higher than the corresponding values derived using a K value of 0.44 .

As stated above, these estimates of K assume that the canopy was randomly distributed, there was no effect of row structure, and the ground was completely covered. Inhomogeneities in the canopy, such as those induced by row planting, lead to localised variation in light penetration and hence in K . If the heavily shaded groundnut canopies at L_{\max} and in the dispersed planting were unable to attain and maintain full ground cover, whereas the sole crop did, this would explain the disparity between the estimated values of K for groundnut in the sole treatment and at L_{\max} . However, this cannot provide a full explanation because the observed difference in maximum L between groundnut in the dispersed planting and at position L_{\max} and the sole crop (maximum $L = 1.75$) was less than 20 %.

The relationship described by equation 1.7 assumes that the sky is clear, although

diffuse radiation would frequently have been predominant during the monsoon period. If, for example interception by the sole groundnut was reduced when diffuse radiation was predominant, the values of K derived from the f and L values for the sole crop are likely to have been underestimated. Consequently, when these were used to calculate mean radiation interception by groundnut in the dispersed planting (Gint), the true value would have been underestimated, thereby resulting in overestimation of A_2 (Eq. a1.4).

Other factors may have contributed to the overestimation of K values derived from L and f using equation 1.7. For example, measurements of L involved only green leaves and therefore took no account of the fact that senescent leaves also intercept radiation, whereas the f values were based on interception by both green and senescent leaves. The values for L used in equation 1.7 were therefore probably underestimates of the true values required to achieve the corresponding f values, and may have resulted in an overestimation of K (cf. Wallace *et al.*, 1990).

The values of PPI obtained using equation 1.7 were invariably lower than those calculated on the assumption that the solarimeters at positions A1 and A2 (Fig. 2.5) were shaded throughout entire measurement period between groundnut planting and final pigeonpea harvest (Table a1.5), but are greater than those based on the assumption that position A2 remained unshaded by the pigeonpea canopy throughout the measurement period. These results support the supposition that there was a period after the third pigeonpea fodder cut on August 8 1990 when only position A1 was shaded, but that the pigeonpea canopy developed rapidly thereafter to cover position A2.

a1.2 METHOD 2 - ESTIMATING RADIATION INTERCEPTION FROM DRY MATTER PRODUCTION

An alternative method for estimating interception by pigeonpea at position A2 is based on the total dry matter (TDM) data obtained from the periodic groundnut growth analyses. Mean cumulative radiation interception by groundnut at all

sampling positions in the dispersed planting was calculated from the appropriate TDM measurements and an estimate of the radiation conversion coefficient at position Lmax in the line planting. The procedure for estimating radiation interception by the pigeonpea was then similar to that described for method 1. Interception by the groundnut at position 2 (Fig. 2.5) was calculated from the estimate of the mean interception for both positions (Gint) and the measured interception at position 1 (Eq. a1.2-a1.4). The estimate of interception by groundnut at position 2 was then subtracted from the value for interception by both pigeonpea and groundnut at position 2 (determined using the solarimeters located at B2) to determine interception by the pigeonpea (Eq. a1.4). As interception by the pigeonpea component was measured at position 1, the mean interception by pigeonpea within the dispersed treatment could be calculated (Eq. a1.5). The theory underlying this approach and the calculations involved are described below. It is well established that, when water is not limiting, dry matter production is linearly related to intercepted radiation according to equation 1.6.

Similarly, cumulative dry matter production can be related to cumulative intercepted radiation (ΣS_i) as follows:

$$W = \Sigma S_i e \quad \text{equation a1.6}$$

For the purposes of this analysis, the mean value of e (from 30-70 DAS) for the three groundnut rows that were shaded by the pigeonpea canopy in the line planting was used (Lmax in Fig. 2.5). This value (1.0 g MJ^{-1}) was considerably greater than that for unshaded groundnut (0.6 g MJ^{-1}) in the same experiment. The potential errors arising from this assumption are discussed below.

Mean shortwave radiation interception values for groundnut at all positions in the dispersed planting were calculated using the relationship shown in equation a1.4; once a value of G_i was obtained the calculation proceeded in a similar manner to method 1. However, in this case Gint, and hence PPi, was calculated in terms of actual cumulative intercepted radiation, rather than fractional interception. The

results obtained are shown in Table a1.3.

Estimates of radiation interception by groundnut in the dispersed treatment were derived from the TDM values recorded at each harvest between 30-100 DAS. After 80 DAS, however, TDM began to decrease due to leaf senescence and abscission. After groundnut harvest at 110 DAS, the solarimeter at position B2 was left in position to record interception by the pigeonpea at position 2 (A2) which previously had not been measured because of the shortage of solarimeter tubes. Values of radiation interception by pigeonpea at position A2 at 90 and 100 DAS were estimated on the assumption that there was a linear increase between the final estimate of interception derived from TDM at 80 DAS and the reading given by solarimeter B2 at 110 DAS.

The main difficulty with this method was in selecting an appropriate value of e , since a number of uncertainties are associated with the value for groundnut at position Lmax in the line planting. For instance, it is possible that the radiation reaching the groundnut in the dispersed planting would have been depleted of PAR to a greater extent than at position Lmax because the dispersed arrangement of pigeonpea probably resulted in a greater proportion of radiation passing through its canopy before reaching the groundnut as compared with Lmax. If more PAR reached the groundnut at Lmax than in the dispersed planting, the estimated value for e may have been artificially high for the latter position. It is not possible to quantify this effect from the data available. However, because the row orientation of the pigeonpea in the line planting was East-West, most of the radiation reaching the groundnut at Lmax is likely to have passed through the pigeonpea canopy. A larger proportion of the radiation would have reached the groundnut without passing through the pigeonpea canopy at sunrise and sunset when the solar angles are small, partly because direct radiation would pass under the pigeonpea canopy and also because the proportion of diffuse radiation is greatest at these times (Monteith, 1973). However, this would have been relatively unimportant because of the lower irradiances at these times.

Table a1.3: Mean cumulative radiation interception by pigeonpea (cumPPi) in the dispersed planting, 1990. Mean interception values for groundnut (Gint) were obtained using a light conversion coefficient (e) for groundnut of 1.0 g MJ⁻¹ and growth analysis data for TDM (equation 4.9); see text for details (Eq.a1.1-a1.5). Gint represents the cumulative mean quantity of radiation intercepted by groundnut; while Gi2 and A2 represent cumulative radiation interception at position 2 (Fig. 2.5) by the groundnut and pigeonpea components respectively.

DAS	TDM (g m ⁻²)	2Gint (MJ m ⁻²)	Gi2 (MJ m ⁻²)	A2 (MJ m ⁻²)	cum CPPi (MJ m ⁻²)
30	34.7	69.4	69.4	8.0	47.3
40	63.5	127.0	98.7	30.8	70.5
50	92.0	184.0	102.3	118.5	134.6
60	167.3	334.6	182.8	174.4	198.8
70	209.3	418.6	216.2	284.2	304.3
80	248.3	496.6	268.8	314.9	357.9
90	176.5				
100	150.8				

To test the sensitivity of the final estimate of interception by pigeonpea to variation in the value of e used in the analysis, interception was calculated using a range of e values (Table a1.4). When e was reduced to half of the original value (1.0 g MJ^{-1}), the estimates of interception by groundnut alone were higher than the total interception by both crop components at position B2 for all sampling dates. This is clearly impossible, and precluded the calculation of values for interception by the pigeonpea component. A 10 % reduction in the e value used in the analysis reduced the estimates of pigeonpea interception by 8-10 %, whereas a reduction of 20 % reduced the estimates of pigeonpea interception by 20 %.

Table a1.5 compares the values for radiation interception calculated using each of the methods described above. The values obtained all lie between those based on the assumptions that; (i) location 1 (Fig. 2.5) alone was shaded by the pigeonpea canopy throughout the measurement period, and; (ii) that locations 1 and 2 were both shaded throughout this period.

Table a1.4: Influence of variation in the conversion coefficient (e) for groundnut on the estimates of radiation interception by pigeonpea. Abbreviations are as defined in Table a1.3.

DAS	e = 0.5		e = 0.9		e = 0.8		e = 0.7	
	B2	Gi2	Gi2	PPi	Gi2	PPi	Gi2	PPi
30	77.4	138.8	77.1	43.4	86.8		99.1	
40	129.5	225.7	112.8	63.5	130.5		153.1	
50	220.8	286.3	122.7	124.4	148.3	111.6	181.2	95.2
60	357.2	517.4	220.2	180.2	266.5	156.9	326.2	127.1
70	500.4	634.8	262.0	281.4	320.9	251.9	375.8	224.5
80	583.7	765.4	324.0	330.3	393.0	310.8	481.6	251.5

Table a1.5: Comparison of the estimates of radiation interception by pigeonpea in the dispersed treatment obtained using various methods. 'Full shade' indicates that the calculations assumed that positions 1 and 2 (Fig. 2.5) were shaded by the pigeonpea canopy throughout the measurement period; 'half shade' assumes that position 2 remained unshaded throughout the measurement period. Calculations using K and L are explained in Section a1.1, and those using a conversion coefficient of groundnut (e) are explained in Section a1.2.

DAS	Full shade PPi = A1	Half shade PPi = A1/2	From groundnut using K = 0.44 and L	From groundnut using K = 0.22 and L	From groundnut using e = 1.0
30	116.8	58.4	11.5	12.2	47.3
40	162.7	81.4	52.5	66.9	70.5
50	240.0	120.0	111.2	150.0	134.6
60	338.2	169.1	174.2	249.0	198.8
70	452.4	226.2	226.7	333.0	304.3
80	581.4	290.7	295.3	414.8	357.9
90	719.7	360.0	431.1	565.5	497.9
100	867.1	433.6	554.3	691.9	635.9

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