LIGHT, WATER, AND NITROGEN USE IN LOW INPUT MAIZE –PIGEONPEA INTERCROP IN SUBHUMID KENYA

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DECLARATION

I, Isabella Gaiti Nkonge hereby declare that this thesis is my original work and has not been presented for a degree in any other University

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DEDICATION

To: Geoffrey Mbijiwe, my husband for continuous encouragement and inspiration, my mother, Charity Kinanu Kirera, who unselfishly sacrificed to educate me, my children, Ndubi, Mugambi and Gacheri who missed me as I worked on my research

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ABSTRACT

A field experiment was conducted to investigate light, water and nitrogen use in a low input maize-pigeonpea intercrop system in sub-humid conditions at the University of Nairobi, Kabete Field Station. Treatments were three pigeonpea (*Cajanus cajan*) varieties; a medium duration (ICEAP 00557) and two long duration types, semi-erect (ICEAP 00040) or erect (ICEAP 00053), planted alone or intercropped with maize (*Zea mays*)(H511). Two cotton (*Gossypium hirsutum*) varieties (Hart 89 M and UKA 59/146) were used as reference crops to determine amount of N fixed by pigeonpea using the N difference method. The experiment was laid out in a randomized complete block design (RCBD) replicated six times. Data on canopy light interception, changes in soil water, crop dry matter accumulation, grain yield, plant total nitrogen and soil mineral N at key phenological stages was determined. There were two maize cropping seasons; April-September 2001 and October- April 2002 as seasons 1 and 2 respectively, but one season of pigeonpea crop.

Peak photosynthetically active radiation (PAR) interception in intercropped pigeonpea occurred after maize was harvested in both seasons. The long duration varieties intercepted more PAR than medium duration variety. The long duration pigeonpea intercrop extracted more soil water than either of the component sole crops. Long duration pigeonpea had a larger canopy and extracted more soil water than the medium duration pigeonpea. Sole maize had highest water use efficiency while sole pigeonpea had the least. Maize average grain yield was 4339 kg ha^{-1} and that of pigeonpea was 1400 kg ha^{-1}. Long duration pigeonpea had significantly higher yield (1600 kg ha^{-1}) than medium duration pigeonpea (935 kg ha^{-1}). The land equivalent ratio (LER) was 1.0, 0.96, and 0.84 for maize intercropped with the ICEAP 00040, ICEAP 00053 or ICEAP 00557, respectively, indicating lack of pigeonpea - maize-intercropping advantage.

There was better N use in the intercrop than in the sole cropped pigeonpea system. The long duration pigeonpea fixed more nitrogen than the medium duration one early in the season. It was difficult to estimate the amount of N fixed by pigeonpea later in the season because cotton, the reference crop, accumulated more biomass than pigeonpea. Pigeonpea litter fall N contribution ranged from 58 kg ha^{-1} to 92 kg ha^{-1} in intercropped medium and long duration pigeonpea, respectively.

The average grain yield of maize obtained from plots previously planted with the sole of the long duration pigeonpea erect was higher (3940 kg ha^{-1}) than from the plots that were previously intercropped with pigeonpea (3521 kg ha^{-1}) or those that were continuously planted with maize (1833 kg ha^{-1}). This may be an indication of increased nutrient supply from decomposed litter. Intercropping of maize with long duration pigeonpea improved light, water and nitrogen use in the system more than the medium duration pigeonpea.

CHAPTER ONE

1.0 INTRODUCTION

Modern crop production technology is based on inputs, such as quality seeds, fertilizers, pesticides, machinery and irrigation However, farmers rarely use these inputs due to high costs and low incomes This has lead to continuous crop cultivation, nutrient mining through crop harvests and severe soil loss with little or no soil replenishment (Anonymous, 1997; Sanchez *et al.*, 1997). Opportunities for maintaining and replenishing soil fertility through traditional cropping systems such as fallowing are no longer feasible, while inorganic fertilizer utilization per unit area is low due to its high costs Moreover, organic sources are inadequate to meet the crop nutrients requirements (Kapkayai *et al.*, 1998).

The use of low cost and appropriate technical inputs is central to improvement of the resource constrained Kenyan small-scale subsistence farming systems and is a national priority (Anonymous, 1997; FAO, 1997). Legume-grain intercrops a common subsistence production system, has been found to reduce soil erosion, increase levels of soil organic matter and available nitrogen through nitrogen fixation (Scott *et al.*, 1987). The legumes contribute N to the system through biologically N fixation, decomposition of residue and N transfer to the cereals (Fujita *et al.*, 1992). This reduces over dependence on chemical fertilizers

Pigeonpea (*Cajanus cajan*) is one such crop which improves soil fertility through N fixation and leaf fall at maturity, and also adds organic matter to the soil (Sheldrake and Narayanan, 1979, Rao and Willey, 1981). In addition, pigeonpea is a source of cheap protein, firewood and prevents soil erosion (Nene and Sheila, 1990; Mutheka, 1994). Extensive ground cover by pigeonpea prevents soil erosion by wind and water, by encouraging infiltration. It also smothers weeds (Nene and Sheila, 1990). This implies that the use of cereal-pigeonpea intercrop system is likely to result to improvement in ultimate yield of the intercrop.

1.1 Justification

Maize (*Zea mays*) is the staple food of most Kenyan population. It is normally consumed together with grain legumes. Conventionally, maize is grown in rotation or as an intercrop with a legume, mostly the common bean (*Phaseolus vulgaris L.*) in high rainfall areas (Pilbeam *et al.*, 1995) and with pigeonpea or cowpea in the semi-arid areas (S.N. Silim, personal communication). Nitrogen is one of the nutrients most limiting in maize production because it is applied in inadequate amounts, resulting in low yields (less than 2 t ha^{-1}). This is attributed to high cost of commercial fertilizers and low selling prices of the produce. This, therefore, calls for a production system that can potentially enhance maize productivity and at the same time being economically and environmentally sustainable. Maize-pigeonpea inter-cropped offers this possibility. The pigeonpea supplies nitrogen through atmospheric fixation as well as through litter decomposition (Giller *et al.*, 1997) to the system. The initial slow growth rate of the traditional long duration pigeonpea (10 to 11 months) varieties allows the relay cropping, while introduction of medium duration (5-6 months) types provide farmers with greater flexibility in the system. Low temperatures hasten the phenological development of long duration pigeonpea (Silim *et al.*, 1995) and this offers the possibility of their production in more humid cooler areas.

There is difference in the rooting habit of maize and pigeonpea Maize has extensive, but shallow root system, while pigeonpea has deep root system This result in better use of water and nutrients from different soil horizons (Nene and Sheila, 1990). Information on light, moisture and nitrogen utilization of maize intercropped with, medium or long maturity pigeonpea intercrop is useful in the development of management strategies that would improve the productivity and sustainability of the system.

1.2 Research objectives

1.2.1 Broad objective

The objective of the research was to quantify light, nitrogen, and water use in low input maize-pigeonpea intercrop so as to determine the best pigeonpea variety suited for intercropping with maize in sub humid conditions. Low temperatures hasten the phenological development of long duration pigeonpea and this offers the possibility of pigeonpea production in more humid cooler areas

1.2.2 Specific objectives

- Assess effect of intercropping maize with various pigeonpea varieties on the productivity of intercrop
- Evaluate light interception and water uptake in maize - pigeonpea intercrop under rain fed condition
- Assess N use efficiency of the maize -pigeonpea intercrop system without N application
- Asses BNF contribution and litter fall of pigeonpea

CHAPTER TWO

LITERATURE REVIEW

2.1 Origin and distribution of pigeonpea

The pigeonpea (*Cajanus cajan* (L.) is generally popular throughout the tropics and is widely grown in Africa, Asia and America. India contributes 92% of the world's recorded total production (1.57 million tons) followed by Africa (4%) (Uganda, Tanzania, Malawi and Kenya) and 1.7% in Burma (Dart and Krantz, 1976). Pigeonpea originated in India and spread quite early. A secondary centre of diversity of the species is in eastern Africa (Van der Maesen, 1990).

Pigeonpea grows well in subtropical and tropical environments, extending between Latitude 30° S to 30° N, at elevations from sea level to 2000 m. Although little of the crop enters world trade, pigeonpea is the fifth most important pulse crop in the world after broad bean (Laxman, 1991).

2.2 Pigeonpea and maize production in Kenya

2.2.1 Pigeonpea production in Kenya

Pigeonpea is the second most important food legume in Kenya after field beans (*Phaseolus vulgaris*). It is the leading pulse in semi-arid areas (Onim, 1984). The other important legumes include cowpeas (*Vigna unguiculata)*, green grams (*Vigna radiata)* and groundnuts (*Arachis hypogea)*. Pigeonpea production is concentrated in eastern province (Machakos, Makueni, Kitui, Mwingi, Mbeere, Tharaka, Meru South, Meru North and Meru Central), and the drier areas of central province (Kirinyaga, Kiambu, Makuyu, Muranga and Thika districts) (Kimani *et al.*, 1994). It is also grown in some parts of Lamu, Kilifi, Kwale, Tana River and Taita Taveta districts of coast province. These semi-arid areas are characterized by high temperatures, low and erratic rainfall and poor soils. The crop is drought-tolerant and produces yields in seasons when other crops fail. The protein-rich grain is an important component in the diet of subsistence farmer, who eat low protein cereals and root crops. The crop is an important component in the sustainability of dry land farming systems because of its ability to incorporate nitrogen into the soil through atmospheric nitrogen fixation, leaf fall, and nutrient cycling (Ndentu, 1994). In Kenya, pigeonpea is grown for both dry and green grain. Dry grain is consumed at home and sold to traders, while most of the green grain is consumed at household level

Pigeonpea is normally inter-cropped with cereals (maize and sorghum) and short duration legumes (beans and cowpeas) (Muthoka, 1994). The traditional pigeonpea are long duration types that take 10 to 11 months to maturity (Silim *et al.*, 1995). These are planted in late October-early November with onset of short rains, and are intercropped with cereals (maize and sorghum), and beans. The cereals and beans are harvested in February or early March. At the start of the long rains (late March-early April), pigeonpea is either sole cropped or under sown with cereals or cowpeas. The relay planted crops are harvested in June-July and pigeonpea is allowed to grow on residual soil water to maturity and is harvested in September (Silim *et al.*, 1995). Pigeonpea yields on farmer's fields are low, averaging 300–500 kg ha^{-1}. A number of factors are responsible: Drought, lack of improved cultivars, poor crop husbandry, pests and diseases (Omanga *et al.*, 1994)

2.2.2 Maize production and use in Kenya

Maize (*Zea mays)* is the most important cereal crop in Kenya (Chui, 1987). It is grown under diverse condition of climate, soils and altitude. Maize production in Kenya takes place on both large and small scale farms, however, 70% of the maize production comes from small-scale farms ranging in size from 0.2 to 0.8 ha (Ackello and Odhiambo, 1986). The yield from small-scale farms is usually low, averaging 1.6 tonnes ha^{-1} (MOA, 2002) due to largely soil fertility problems and poor crop husbandry. The soils have been exhausted due to continuous cultivation without replenishment due to high costs of chemical fertilizers which are beyond reach by most small scale farmers in Kenya (MOA, 2002)

Maize is very important for human consumption, eaten as green or dried and cooked whole with beans or potatoes or ground into flour for making commeal ("ugali"). It is also used as livestock food both as silage and as grain. In industrial processing, maize is used in the manufacture of corn starch, syrup, oil and alcohol (MOA, 2002). Maize is mainly grown in an intercropped system with legume such as beans, soyabeans, cowpeas, and pigeonpea (MOA, 2002)

2.3 Intercropping Systems

Intercropping cropping is an age old practice in warmer climate of the world (Agboola and Fayemi, 1971; Searle *et al.*, 1981). Intercropping consists of growing two or more crops together (Van Dermeer, 1992). Crop mixtures may be legume /legume (Rao and Mittra, 1989) or legume/non legume (Maldal *et al.*, 1990). In traditional rain fed agricultural systems of Asia and Africa, intercropping is often practiced because it provides substantial yield advantage over sole cropping, in addition it may give greater stability of yield across seasons (Willey, 1981). Intercropping results in higher yield per given season due to more efficient use of the environmental factors, especially where the component crops differ in their resource use and where they complement each other (Willey, 1979; Singh, 1979)

The different species grown in intercrop need to efficiently utilize environment resources, without competing with each other so that each may approach its yield potential in the given environment (Natarajan and Willey, 1980, Willey *et al* 1981).

Intercropping provide an insurance against total crop failure especially in areas subject to frost, floods or drought (Willey, 1979; Singh, 1979)

The efficiency of production in intercrop system could be improved by minimizing interspecific competition for growth limiting factors. Growing crops with different growth rates and habits may result in complementary rather than competitive use of growth resources (Ofori and Stern, 1987). Competition between component crops in an intercrop is regulated by crop characteristics and agronomic factors (Trenbath, 1976). The crop with relatively higher growth rate, height advantage, and a more extensive rooting system is favored in the component (Willey, 1979). It is generally agreed that when interspecific competition for limiting growth factors is less than intra-specific competition, there is a potential for higher total production on the intercrop system (Willey, 1979).

2.3.1 Legume- cereal intercrop

Intercropping of cereals and legume is wide spread among peasant farmers in the tropics, and also in the warmer regions in the subtropics (Ofori and Stern, 1987; Fujita *et al.* 1992)

Cereal/legume crop associations are known to improve soil fertility through biological nitrogen fixation, leaf fall, mineral nutrient cycling and reduced run off and evapotranspiration. For instance total grain and plant N yields can often be increased by intercropping legumes with non-legumes (Barker and Blamey, 1985, Singh *et al.*, 1986).

In legume/cereal mixtures fixed nitrogen from the legume is available to the cereal, thereby improving the nutritional quality of the mixture (Izaurralde *et al.*, 1990). Nitrogen needs of a cereal intercropped with legume were reported to be less than for sole cropping, due to transfer of some of the fixed nitrogen by legume to the associated cereal during the growing season (Cheminig'wa and Nyakundi, 1994)

2.3.2 Cereal- pigeonpea intercrop

Pigeonpea intercropping systems involves intercropping of pigeonpea with a cereal or legume component. However, the most common is the cereal/pigeonpea intercropping system. The cereal component maybe sorghum, millet or maize (Willey *et al.*, 1981) whereas the most common pigeonpea/ legume intercrop is groundnuts, cowpeas and green grams (Willey *et al.*, 1981).

The suitability of pigeonpea for intercropping lies in its initial slow growth (Reed, 1987) When grown as an intercrop, a companion crop with a fast initial growth phase completes most of it initial growth and development during the lag phase of the pigeonpea thereby minimizing competition for resources (Natarajan and Willey, 1980; Willey *et al.*, 1981)

Pigeonpea appears to response to phosphorous fertilizer because of an extensive rooting system, mycorryzhizal associations and rhizospheric alteration that enhance phosphorus uptake (Johansen, 1990). According to Johansen (1990), growing pigeonpea as an intercrop with cereal crops increased the available phosphorous pool of the entire cropping system by converting the unavailable soil phosphorus reserves into a form available to the other crop more efficiently than most legumes. Consequently, succeeding crops in the rotation have access to available phosphorous and nitrogen from pigeonpea residue

Pigeonpea can be used to restore fertility of soils that are low in nitrogen and also increase yield of cereals like maize, sorghum or millet when intercropped or grown in rotation. Reports indicate that medium duration pigeonpea benefited subsequent maize crop by increasing biomass and grain yield as a result of a contribution of an equivalent 40 kg N ha^{-1}(Kumar *et al.*, 1981)

2.4 Resource use in intercrop systems

2.4.1 Water use

Farmers in semi-tropical and tropical regions under rain fed conditions usually practice mixed cropping Availability of water is one of the most important factor determining production in legume/cereal mixed cropping systems especially under arid and semi-arid conditions. Shackel and Hall (1984) found no differences in either total water absorbed or uptake patterns of sorghum-cowpea intercropped compared to their sole crops. Ofori and Stern (1987) concluded that cereals and legumes use water equally and that competition for water may not be important in determining intercrop efficiency except under unfavorable conditions (water deficient). An intercrop of two crop species such as a legume and a cereal may use water more efficiently than mono-crop of either species if they would explore a larger total soil volume for water, especially if the component crops have different rooting patterns (Willey, 1979). Natarajan and Willey (1980) reported higher water use efficiency (WUE) by sorghum/pigeonpea when they were intercropped than when sole cropped.

2.4.2 Solar radiation and use

Solar radiation is a very important resource for crop production because it is the energy source for photosynthesis and transpiration (Sinoquet and Caldwell, 1995). Certain wave bands of the solar spectrum act on plant photoreceptors involved in plant morphogenesis (Sinoquet and Caldwell, 1995). The rate of dry matter production is largely dependent on incoming solar radiation and is proportional to the amount intercepted and the efficiency with which it is converted to dry matter (Monteith, 1977, Squire, 1992). Intercepted radiation is the difference between solar radiation received at the surface of the canopy, and that transmitted at the soil surface (Squire, 1992). Factors affecting the light regime of plant canopies are the amount and quality of incident radiation, the canopy architecture and the soil

The interception of solar radiation by a canopy depends on both leaf areas index (LAI) and canopy architecture, which in turn is determined by leaf size, shape, orientation and spatial arrangement (Yoshida, 1972, Campbell and Van Evert, 994). For most canopies in moist conditions, fractional photosynthetically active radiation (PAR) interception (f) may be related to LAI (L) by the expression,

$$f = 1 - e^{-kL}$$

Equation 1

Where, k is an extinction coefficient (k is a dimensionless parameter and represents the fraction of Photosynthetic Active Radiation (PAR) interception by unit leaf area) (Squire, 1992) Rearranging equation 1 above, expresses k as follows,

$$k = \ln \left(1 - f\right)/L$$

Equation 2

Therefore, as the fraction of the solar radiation intercepted by a given leaf area increases; k also increases The extinction coefficient (k) ranges from 0.3 to 1.3 for the majority of leaf canopies Where the leaf inclination (angle formed between the long axis of the leaf and the horizontal) is nearly vertical, e.g., in many grasses light penetrates to the leaves readily, hence k is often low, about 0.4 (Nobel *et al.*, 1993)

Canopy architecture refers to the amount and organization of above ground plant material, including the size, shape and orientation of plant organs such as leaves, stems flowers and fruits (Norman and Campbell, 1989) Canopies with most leaves in the horizontal plane are termed planophile, whereas canopies in which the leaves are close to the vertical are termed erectophile (Squire, 1992) The values of extinction coefficient, k, are lower for erectophile canopies and higher for planophile canopies (Monteith, 1969). Therefore, k can be used to determine canopy architecture and hence estimate dry matter production through solar radiation utilization for photosynthesis

The efficiency with which crops can utilize available solar energy for the production of either dry matter or specific economic products can be affected by low or high temperature, water stress and availability of soil nutrients (Eagles, 1984). Optimal incident PAR utilization for photosynthesis generally occurs when incident solar radiation is distributed as uniformly as possible over the exposed leaves (Nobel *et al.*, 1993).

Increasing light capture is presumed to improve primary production through photosynthesis processes. Unequal access to light due to space occupation can have serious, sometimes fatal consequences for the dominated species (Caldwell, 1987). Inversely, partial shading may shelter plants from water stress (Allen *et al.*, 1976) and improve photosynthesis and light use efficiency (Willey, 1979). Given the direct effects of shading on photosynthesis and the addition effects on microclimate features (Stigter and Baldy, 1995), farmers need to consider the entire range of management options that affect light interception and partitioning including the choice of species or cultivars to be mixed, the planting pattern and the planting dates for each component

2.4.3 Nutrient use in intercrop

The efficiency of soil nutrient uptake in intercropping compared to sole cropping is still poorly understood and, therefore, a matter of debate. Nutrient use may be compared between intercropping and monocropping or between intercropping and rotation of sole crops over several seasons (Hardter *et al.*, 1991). Intercropping increase biomass production, yield and nutrient uptake, this may be interpreted as increased uptake efficiency. The increase in nutrient uptake (P and N) in intercropping compared to mono-cropping is the consequence rather than the reason for higher biomass production, provided soil nutrients were not in the deficiency range (Morris and Garrity, 1993).

Efficiency of soil N utilization varies substantially among legumes (Yoneyama *et al.*, 1990). Leucaena and pigeonpea (Tobita *et al.*, 1994), and cowpea (Ofori *et al.*, 1987; Hardter and Horst, 1991) appeared to be very competitive for soil N, while groundnut (Willey and Reddy, 1981) and field beans (Martin and Snaydon, 1982) were less competitive compared to the non-leguminous component crops. Competition for soil N may lead to higher overall N use efficiency of the intercropping system, because the non-legume can derive its N from a larger soil volume and the gain in N to the system through N_2 fixation of the legume may be increased (Martin and Snaydon, 1982, Tobita *et al.*, 1994).

Facilitation occurs when one component crop improves the nutrient uptake of the other crop, thus, leading to an overall increase in biological efficiency of the system (Van Dermeer, 1989). Facilitation may occur through direct transfer to the associated non-legumes *via* root/nodule exudation (Wacquant *et al.*, 1989) and/or vesicular arbuscular (VAM) fungi either through interhyphal connections (Van Kessel *et al.*, 1991) or through more efficient uptake of N released by the legume (Hamel *et al.*, 1991). However, it is generally agreed that this is only a minor contribution to the N economy of the non-legume (Van Kessel and Roskoskoi, 1988) and is often not detectable (Danso *et al.*, 1987, Reeves, 1992). The quantitatively more important pathway for fixed N_2 transfer from the legume to the non-legume in association is *via* decomposition of legume plant residues during the growth cycle, which is especially important when short cycle legumes are intercropped with long cycle non-legume, or after the growing cycle (Henzell and Vallis, 1977).

2.5 Below ground interactions

Snaydon and Harris (1981) argued that below ground interactions between plants are more important than those above ground in producing yield advantages in intercropping though they cause lower yield in some cases. However, Willey and Reddy (1981) found that root segregation had negligible affects on growth of pearl millet and groundnut grown as sole or intercrop thus, suggesting that below ground competition was relatively unimportant. This was confirmed by Gregory and Reddy (1982) who indicated that the rooting density in the same intercropping system was similar to that observed in the sole stand

In another experiment, vertical root barriers installed to a depth of 0.5 m were used to separate above and below ground interactions in a mungbean-upland rice system (Aggrarwal *et al.*, 1992) showed that intercropping resulted in more effective utilization of below ground resources.

2. 6 Information gap

Information on light use, water use, and nitrogen use in maize and pigeonpea intercropping system in eastern and southern Africa is not available. Such information is useful in the development of management strategies that would improve the productivity and sustainability of the system. It is, therefore, important to determine light use, water use and nitrogen use in low input maize- pigeonpea cropping system

CHAPTER THREE

MATERIALS AND METHODS

3.1 Site description

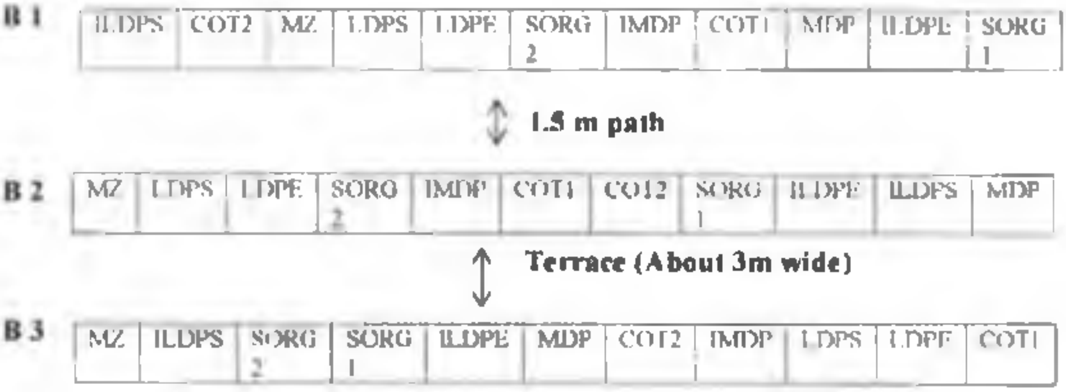
The study was conducted at Kabete Field Station, University of Nairobi farm. Kabete lies on latitude 1°14'S , longitude 36 °44'E and at an altitude of 1820 m above sea level. The site has bimodal rainfall known as long rains (LR) occurring during March to June and short rains (SR) during October to December. The average rainfall is about 1000 mm (Kabete meteorological station), and mean annual temperature of 18°C. The soils are classified as a Humic Nitisols based on the FAO/UNESCO system (FAO, 1990). The soils are underlain by Nairobi trachytes of Tertiary age, well-drained, very deep, and dark red to reddish brown, friable clay (FAO, 1990)

3.2 Experimental design

The first and second season experiments were conducted between April 2001 to September 2001 (long rains 2001) and October 2001 to April 2002 (short rains 2001) respectively. The experiment was laid out as randomized complete block design, replicated six times. The treatments were:

1. Three pigeonpea varieties (one medium, and two long duration) either sole or intercropped with maize (H511). The varieties were ICEAP 00557; ICEAP 00040 and ICEAP 00053 for medium, long duration semi-erect and long duration erect pigeonpea respectively.
2. Two non-fixing crops (2 cotton varieties) were used as reference crops for N fixation by difference method (Giller, 2001). The cotton varieties were Hart 89 M and UKA 59/146.

The experimental plot measured 4 m x 10 m and 3 m x 10 m for intercrop and sole crop respectively.



B 1	ILDPS	COT2	MZ	LDPS	LDPE	SORG 2	IMDP	COT1	MDP	ILDPE	SORG 1

1.5 m path

B 2	MZ	LDPS	LDPE	SORG 2	IMDP	COT1	COT2	SORG 1	ILDPE	ILDPS	MDP

Terrace (About 3m wide)

B 3	MZ	ILDPS	SORG 2	SORG 1	ILDPE	MDP	COT2	IMDP	LDPS	LDPE	COT1

Figure 1. Field layout of the experiment where;

B - Block
MZ - Maize
MDP- Medium duration pigeonpea
LDPE- Long duration erect pigeonpea
LDPS- Long duration semi-erect pigeonpea
IMDP- Medium duration pigeonpea/maize intercrop
ILDPE- Long duration erect pigeonpea/maize intercrop
ILDPS- Long duration semi-erect pigeonpea/maize intercrop
COT1- Cotton (Hart 89 M)
COT2- Cotton (UKA 59/146)
SORG1-Sorghum MB30
SORG2-Sorghum IS255445

Note:
Although initially sorghum was part of the treatment, it was later found to be unsuitable as a reference crop early in the experimental phase hence was discarded

Maize was planted in spacing of 75 cm between the rows and 30 cm between plants giving a plant density of 44,000 maize plants ha^{-1}. The population density of maize in the intercrop maize was 26,667 plants ha^{-1} where three rows of maize were alternated with two rows of pigeonpea. This is the optimal arrangement that does not reduce maize yield (Silim, S.N, ICRISAT, personal communication).

Pigeonpea was sown at a spacing of 75 cm between rows and 20 cm between plants giving a plant density of 66,500 plants ha^{-1} of the sole crop and 26,650 plants ha^{-1} in the intercrop. The total plant population for the intercrop was 53,317 plants ha^{-1}. Sorghum was spaced at 75 cm x 20 cm and cotton at 100 cm x 50 cm. Several seeds were planted per hill, but thinned to one two weeks after emergence. The plots were kept weed free manually and pests and diseases kept to a minimum by spraying Karate 0.75 EC broad spectrum synthetic insecticide at the rate of 10 ml in 20 litres of water and dimethoate (Danadin 40 EC) contact and systemic organo phosphorus insecticides at 30 mls in 18 litres of water to control pests and Acrobat MZ to control fungal infection. Karate and dimethoate were sprayed against pod borers and pod flies every two weeks from flowering to maturity while the Acrobat was sprayed once against the leaf blight.

An experiment to determine residual effect of pigeonpea was conducted between April to September 2002 in the field previously planted with maize and pigeonpea, all the plots were put under maize crop at a spacing of 75 cm between the rows and 30 cm between plants (44,000 maize plants ha^{-1}). Total dry matter, yield and nitrogen uptake were measured.

3.3 Data collection

3.3.1. Crop growth and phenological development

Crop growth was determined by sequentially harvesting pigeonpea, maize, sorghum and cotton plant at different stages of development at 14 days interval from 54 days after planting to maturity. Four plants were taken from each plot were sampled ensuring that subsequent samples were taken far from the gap previously sampled. At each sampling, plants were cut at ground level, placed in brown paper bags and oven dried at 70°C for 72 hours to a constant weight to determine dry mass and total N using micro Kjeldahl method (Okalebo *et al.*, 2002). The final harvest was taken from the center rows. Twenty plants were harvested, fresh weight taken, and then two plants were sub- sampled for oven drying to determine dry mass of grain, cob and stover. The dates to emergence and at 50% flowering and at maturity were noted. Pigeonpea data on 50% flowering and physiological maturity was taken during the first productive period (first flush) and so was the thermal time.

3.3.2. Crop height and canopy PAR interception

Plant heights of 4 randomly selected plants were measured from the ground level to the tip of the main stem every 14 days from 54 days after planting. Attenuation of photosynthetically active radiation (PAR) was measured above and below the canopy at around midday (11.30 am- 1.30 pm local time) using a sunfleck ceptometer (SF 80 Decagon, Pulman, Washington). This was expressed as a fraction of radiation above the canopy (Monteith, 1973).

3.3.3. Changes in soil water content

Changes in soil water content were monitored using a neutron probe (Didcot, Wallingford). Access tubes (120 - 150 cm long with an internal diameter of 50 mm) sealed at one end were installed in auger-bored holes, slightly smaller than the tube diameter. Three access tubes were installed per plot in the intercrop, one between the maize and pigeonpea rows, the second between rows of pigeonpea and the third between the rows of maize. One access tube was placed in the sole crop plots. Sixteen counts per second at 20 cm depth interval were taken every 14 days starting from 20 cm deep. Soil moisture content in the top 30 cm was determined gravimetrically. At the end of each day's measurements, a neutron count in water (Nw) was made. This was used to determine the ratio of count in soil (Nsc) to that in water, which was the basis for calibration with volumetric water content. Data obtained was used to determine soil moisture utilization by different components of the inter-crops.

(a) Neutron Calibration

To convert the neutron probe readings into volumetric soil water content, the neutron probe was calibrated from the dry and wet conditions using separate access tubes installed close to the experimental tubes. Calibration was done at the mid of dry season in late September 2002. At this time the grass was dry and, therefore, a permanent wilting condition was assumed. For the wet calibration, the soil was watered artificially for several times till the area was flooded assuming saturation. The ponded sites were then covered with fresh mulches completely and excess water allowed draining for three days. After this free drainage, it was assumed that the profile had attained field capacity. Calibration involved taking five probes reading for each depth at 20 cm interval and sampling five replicates of 100 cm^3

soil cores at the same depths Twenty standard counts were taken at the beginning and at the end of sampling (water was used for the standard count) The average of the five readings from each depth was divided by the average standard count to obtain a neutron ration for each depth The neutron ratio (count in soil count in water) for each depth was regressed against their corresponding soil core samples volumetric water content The regression relationship obtained for each depth was used to estimate soil water content from the routine field neutron probe readings

(c) Calculation of soil water down the profile.

After neutron probe calibration, the water content was determined for each depth The individual measurement of moisture content down the soil profile was each multiplied by depth of each layer The total water content of the profile to any given depth is the sum of the individual water content (Bell, 1987)

(d) Determination of evapotranspiration

Estimation of evapotranspiration was obtained from the soil water balance equation (Cooper, 1987).

$$P = T + E + R + D + S \qquad \text{Equation 3}$$

Where P= Precipitation

T= Transpiration

E= Evaporation from the soil surface

R= Run off/ run on

D= Drainage

S= Change in storage in the soil profile

At this experimental site R and D were assumed to be negligible hence the equation (3) is better expressed as,

$P = T+E+S$ or $P = EP+S$ Equation 4

Therefore, $EP = P-S$ Equation 5

In each of the days that the data was determined, the total water change down the profile was subtracted from the total rainfall to give evapotranspiration

3.3.4 Available Soil N and crop tissue N

Soil was sampled from the experimental site prior to planting to determine the soil mineral N and total N distribution in the soil profile Samples were taken one week before planting and at the end of each crop-growing season at depths of 0-20, 20-40 40-60 and 60-120 cm Five soil samples were taken at each depth per plot along a transect The five cores were mixed to make a composite from which one sample at each depth was made The analysis for soil available N and crop total tissue N was carried out as described in Okalebo *et al.*, 2002.

3.3.5 Nitrogen fixation determination by difference method

Nitrogen fixation was determined using the nitrogen difference method (Giller, 2001) The N derived from fixation (Ndfa) was calculated as the difference between total N in the pigeonpea crop and the total N in cotton UKA 59/146 that was used as a non-fixing crop The suitable crop was grown along side the inter-crop experiment to provide a check for N fixation especially of pigeonpea The advantage of this method is that N fixation is integrated over time and hence takes care of environmental variables, which influence N uptake by the pigeonpea and the maize crop

3.3.6 Determination of accumulation Thermal Time

Thermal time accumulation (TTDAP) was calculated using maximum and minimum daily temperatures obtained from Kabete Meteorological station using the equation below

$$\mathrm{TTDAP} = \sum_{0} \mathrm{DAP} = \sum_{0}^{\mathrm{DAP}} \frac{[\mathrm{Tmax} - \mathrm{Tmin}]}{2} - T_b$$

Equation 6

Where: DAP is Days after planting

T max = Daily maximum temperatures (°C)

T min = Daily minimum temperatures (°C)

T_b = base temperature (°C) and it was assumed to be 12.8 (Reddy, 1990) for all phenological stages

3.3.7 Land Equivalent Ratio (LER)

The performance of the intercrop was evaluated using land equivalent ratio (LER) (Willey, 1981).

$$LER = \frac{Yield\ of\ maize\ in\ the\ intercrop}{Yield\ of\ maize\ in\ the\ sole\ crop} + \frac{Yield\ of\ pigeonpea\ in\ the\ intercrop}{Yield\ of\ pigeonpea\ in\ the\ sole\ crop}$$

Equation 7

3.3.8 Water Use Efficiency (WUE)

WUE was calculated as shown below

$$WUE = \frac{Grain\ yield\ (kg/ha)}{ET\ (mm)}$$

Equation 8

The grain yield was determined as described in section 3.3.1 whereas ET was the difference between rainfall at given time and the change in soil water content that was determined in section 3.3.3 with an assumption that surface runoff and drainage were negligible

3.3.9 Nitrogen Utilization Efficiency (NUE)

Nitrogen utilization efficiency (NUE), was calculated has defined in terms of units of economic yield (grain yield) per unit of plant total N (Moll *et al.* 1982), that is,

$$NUE = \frac{Grain\ \ yield\ \ (kg\ ha\ \ )}{Plant\ \ total\ \ N\ (kg\ ha\ \ )}$$

Equation 9

Grain yield and total plant N were determined using procedure described in section 3.3.3 and 3.3.4 respectively

3.4 Statistical analysis

Data were analyzed using Genstat software (Lawes Agricultural Trust, Rothamsted Experimental Station, 1995) Fisher's protected Least Significant Difference Tests ($LSD_{0.05}$) was used to separate significant treatment means

CHAPTER FOUR

RESULTS

4.1 Site description

4.1.1 Rainfall and temperature

Figure 2 shows daily rainfall during the study period (Season 1 from April to September 2001 and season 2 from October 2001 to April 2002) and 10 year average. The two seasons were characterized by normal rainfall as indicated by ten years average. However, the distribution was rather erratic. The months of October and November 2001 (176- 222 DAP) received above average as shown in Figure 2. This caused some leaf blight in pigeonpea, leading to pod prematurely and drastic leaf fall. April 2002 (347 DAP) received well above average rainfall leading to delayed pigeonpea harvesting as well as rotting of the pods (Figure 2). Season one received 332 mm, season two 418 mm and season 3 (residual experiment) 149 mm of rainfall. The seasonal rainfall was far below 10 year average during season 3. Mean temperatures during the experimental period were 23.2°C and 13.4°C for the maximum and minimum temperature respectively (Kabete meteorological station).

4.1.2 Soil chemical characteristics

The experimental site was moderately fertile with total soil N ranging from 0.12-0.25. Levels of NH_4^+ - N and NO_3^- -N were highest in the top 20 cm and decreased down the soil profile. The NH_4^-- N: NO_3^- -N ratio in the profile was 3:2 (Table 1)

Table 1 Soil chemical composition at the beginning of the experiment

Depth (cm)	pH in water	Total N (%)	NH_4^+-N	NO_3^--N	P (ppm)	K	Na	Ca	Mg
			(μ g/g)			(cmol/kg)			
0-20	6.4	0.24	7.25	5.21	29.20	2.10	0.80	6.50	2.5
20-40	6.3	0.18	6.35	2.77	14.00	2.00	0.70	6.00	2.50
40-60	6.4	0.16	2.53	2.19	10.00	1.50	0.60	5.00	2.50
60-120	6.2	0.1	4.74	4.07	13.00	1.30	0.70	3.00	1.67
Moderate Levels		0.1-0.25			> 10	0.5-1.8		10-16	0.4-0.8

NB Moderate levels (Telkalign *et al.*, 1991; Okalebo *et al.*, 2002)

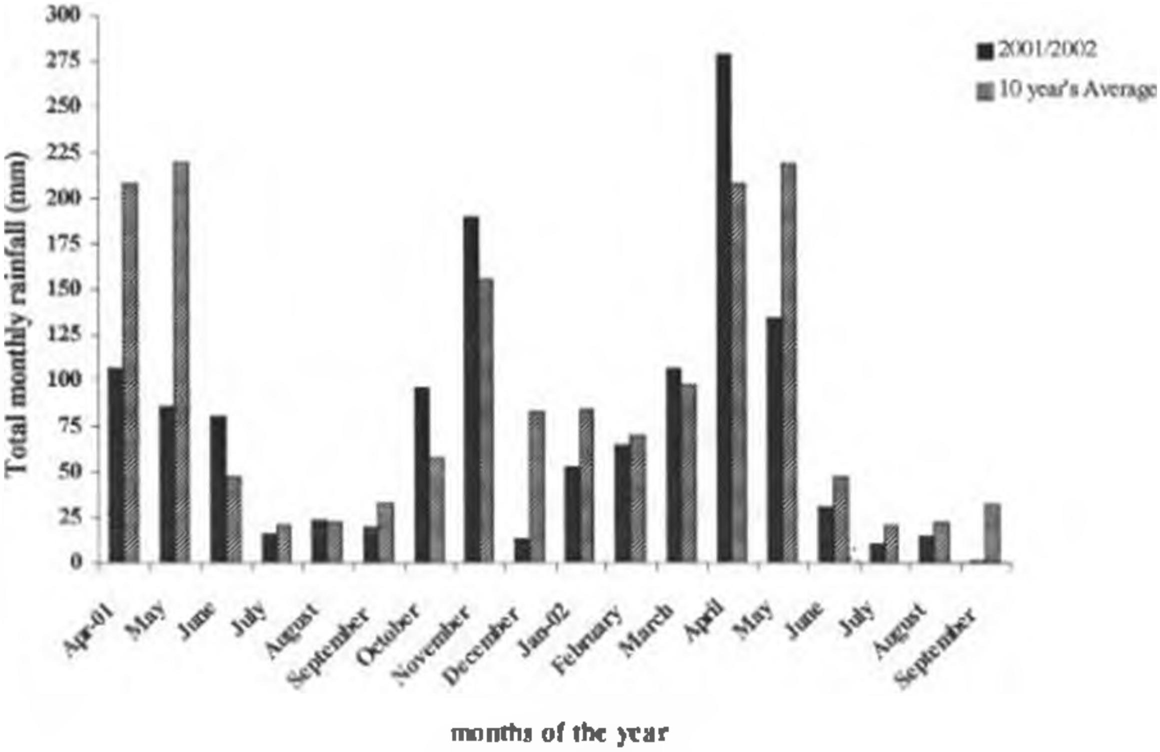


Figure 2 Monthly total rainfall from April 2001 to May 2002 compared to 10 years average (Kabete Meteorological station) at Kabete, Kenya

4.2 Crop phenological development

The experiment was planted on 16th April 2001 and seeds emerged 7 days after sowing. This is shown in Table 2. Maize emergence was 100% and 86% in the first and second season respectively. Pigeonpea had poor germination with, emergence ranging from 71 to 77%. There was variation in the date when different crops achieved 50% flowering and physiological maturity, but intercropping did not alter the phenoduration (Table 2)

Table 2. Summary of phenological duration in days after planting (DAP) of maize and pigeonpea at Kabete, Kenya

Crop	Emergence	Flowering (50%)	Physiological maturity	Final harvest
	…………………	Days after planting	…………………	
MZ	6	58	138	162
MDP	7	120	160	192
LDPS	6	134	168	192
LDPE	7	148	178	192

Where MZ = maize, = medium duration pigeonpea, LDPS = long duration semi-erect pigeonpea and LDPE = the long duration erect pigeonpea

4.3 Thermal time accumulation

Table 3 shows thermal time for the long duration erect pigeonpea was higher at both 50% flowering and physiological maturity than either the long duration semi-erect or medium duration pigeonpea or even maize

Table 3 Crop phenology stages and accumulated thermal time (° C days) at Kabete, Kenya Base temperature used is 12.8 ° C (Reddy, 1990) for all phenological stages

Crop	Emergence	Flowering (50%)	Physiological maturity	Final harvest
	-------------	(° C days)	---------------	
MZ	36	297	593	727
MDP	42	508	716	910
LDPS	36	570	764	910
LDPE	42	649	825	910

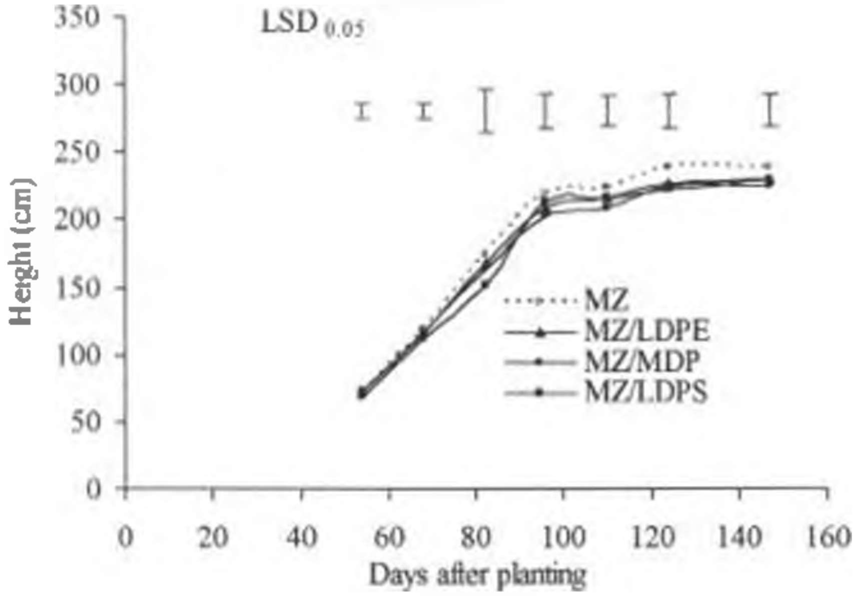
Where MZ = maize, MDP = medium duration pigeonpea, LDPS = long duration semi-erect pigeonpea and LDPE = the long duration erect pigeonpea. MZ S1 and MZ S2 represent maize in seasons 1 and 2, respectively.

4.4. Effects of intercropping on crop growth

4.4.1 Plant height

Mean maize plant height was 233 cm. Intercropping did not affect ($P > 0.05$) the height of maize crop. The average height of sole and intercropped maize at final harvest was similar. This is shown in Figure 3. Pigeonpea height depended on variety. The maximum height attained by different types of pigeonpea were 127, 119 and 108 cm for the long duration erect, long duration semi-erect and medium duration pigeonpea respectively (Figure 3). In the early stages of growth (0-110 DAP) of pigeonpea, intercropping did not ($P>0.05$) influence pigeonpea height either in the sole or as intercrop; the long duration pigeonpea varieties were taller than the medium duration pigeonpea. Later in the season (147 to 318) days after planting, the sole pigeonpea tended to be ($P<0.05$) taller than their respective intercrops (Figure 3). In the range of 160-240 DAP pigeonpea plant height remained constant for all the varieties and up to 320 DAP for medium duration pigeonpea variety. For all varieties, the rate of plant height increase was rather high and constant between 40-160 DAP.

(a) Maize



(b) Pigeonpea

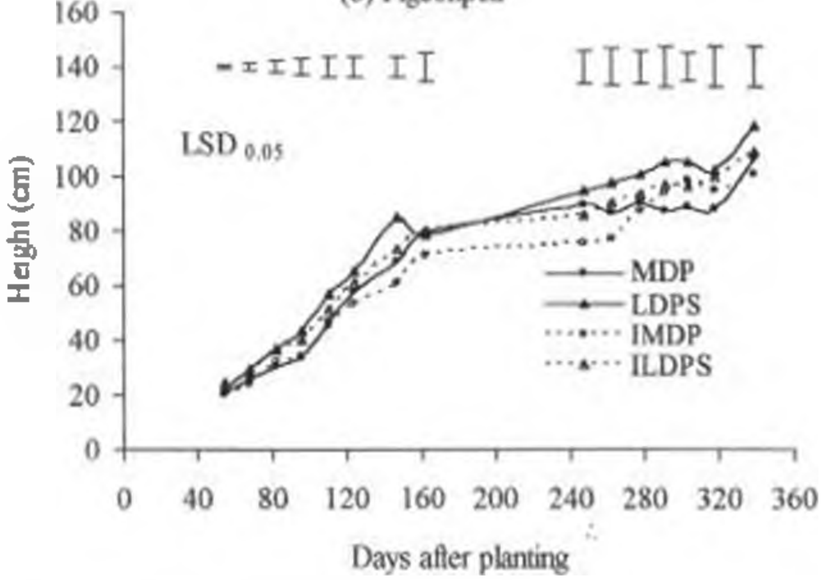


Figure 3 Plant height (cm) of sole and intercrop components crops over time at Kabete, Kenya MZ = sole maize; MDP sole medium duration pigeonpea, LDPS - sole long duration semi-erect pigeonpea; LDPE sole long duration erect pigeonpea and I is intercrop

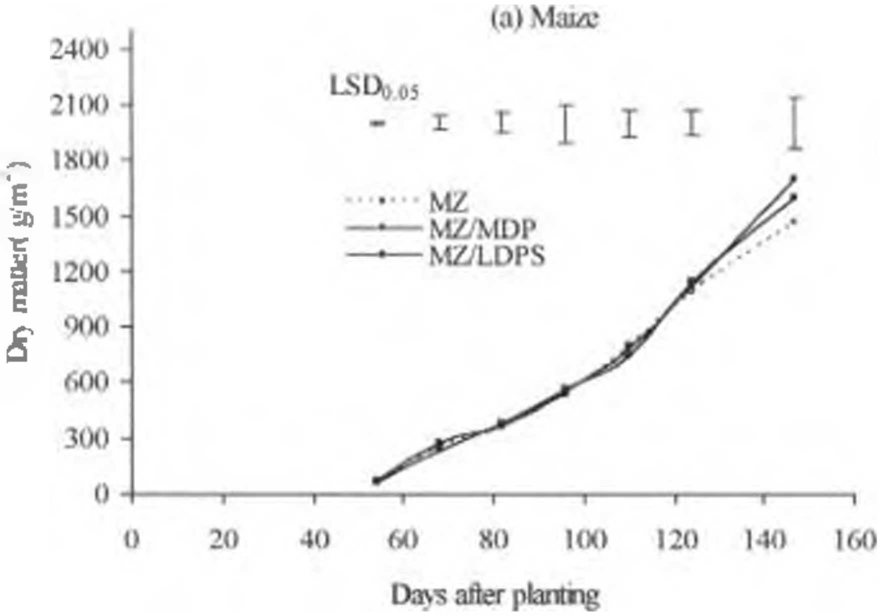
4.4.2 Total dry mass

Figure 4 represents above ground biomass production by maize and pigeonpea. There was increased biomass over time from 54 DAP and was highest at physiological maturity. There was no noticeable difference (P>0.05) in biomass production in sole and intercropped maize (Figure 4a). In the early stages of growth, no significant (P>0.05) difference in dry matter was observed between the sole and intercropped pigeonpea, but at 330 DAP the sole pigeonpea had higher dry matter than the intercrop in all the varieties (Figure 4b).

Intercropped pigeonpea increased biomass after maize was harvested and after one month accumulated biomass was similar in sole and in the intercropped pigeonpea. Maize had accumulated more biomass compared to pigeonpea (Figure 4).

Crop growth rate (CGR) depended on the crop in question and development stage (Table 4). From 54 to 318 days after planting (DAP), the growth rate was very significant (P< 0. 001) among the treatments. Maize initial growth rate was 30 times higher than that of pigeonpea. The differences in growth rate decreased over time and at the later stages of growth (318-339 DAP), the sole pigeonpea and the sole maize growth rate were similar (Table 4).

The growth rate of pigeonpea ranged from 0.2 to 19 gm/m^2/day. At the end of the growing season (318-339 DAP), intercropped pigeonpea crop growth rate was about half that of the sole crop (Table 4). At this time there was no significant (p>0.05) difference between maize and sole pigeonpea growth rate.



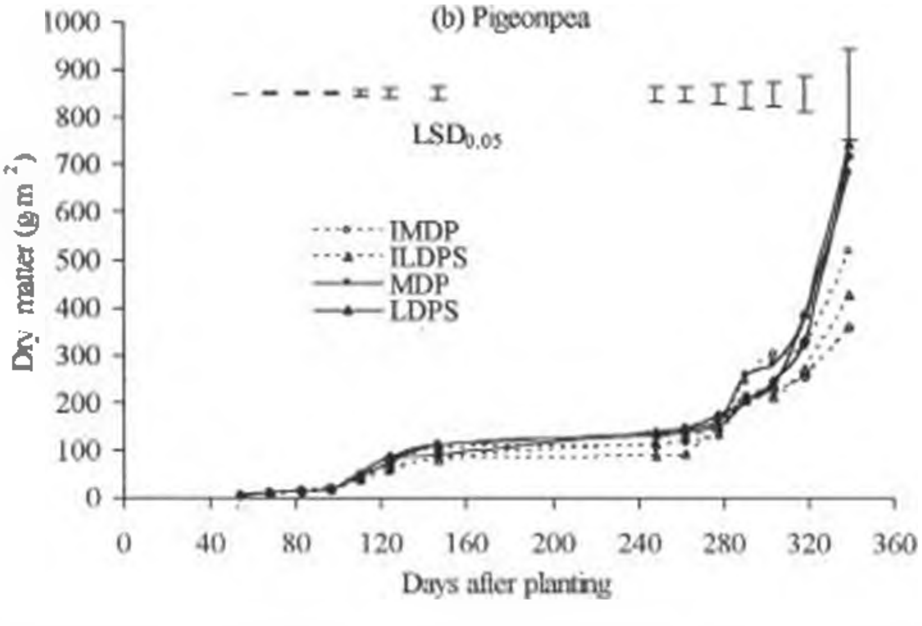


Figure 4 Dry matter production by maize and pigeonpea in sole and their intercrops at Kabete, Kenya. MZ = sole maize, MZ/MDP = maize intercropped with medium duration pigeonpea, MZ/LDPE = maize intercropped with long duration pigeonpea (erect) and MZ/LDPS = maize intercropped with long duration pigeonpea (semi-erect); LDPE = long duration erect pigeonpea, LDPS = long duration semi-erect pigeonpea, MDP = medium duration pigeonpea and I is intercrop

Table 4. Seasonal crop growth rate (g/m^2/day) of sole and intercropped pigeonpea and maize at Kabete, Kenya.

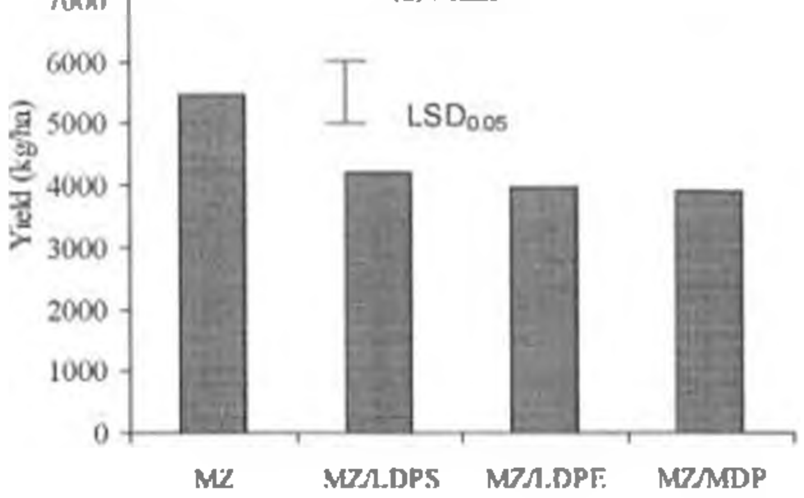
		Crop growth rate (g/m^2/day)			
Cropping		54-68 DAP	82-147 DAP	278-318 DAP	318-339 DAP
Sole	MZ	15	17.5		
Intercrop	MZ/MDP	18	25.5		
	MZ/LDPE	18	22.5		
	MZ/LDPS	17	23.5		
Sole	MDP	0.5	1.8	5.1	15
	LDPE	0.5	2.0	3.7	19
	LDPS	0.4	1.9	6.3	17
Intercrop	IMDP	0.2	1.1	4.0	10
	ILDPE	0.3	1.4	3.1	5
	ILDPS	0.3	1.0	3.5	7
	$LSD_{0.05}$	3.2	2.7	5.2	18

Where: MZ = maize, LDPS = long duration semi-erect pigeonpea, LDPE = long duration erect pigeonpea and MDP = medium duration pigeonpea, MZ/MDP is maize intercropped with MDP, MZ/LDPE = maize intercropped with LDPE, MZ/LDPS = maize intercropped with LDPS and (I) is intercrop. DAP = days after planting.

4.4.3 Grain yield

The mean yield of sole maize was higher (5475 kg ha^{-1}) than of intercropped maize (3961 kg ha^{-1}). Pigeonpea varietal effect on intercropped maize grain yield was not significant (Figure 5a). The long duration pigeonpea varieties had higher yield (1600 kg ha^{-1}) than medium duration variety (935 kg ha^{-1}) both in the intercrop and in the sole crop (Figure 5b).

(a) Maize



(b) Pigeonpea

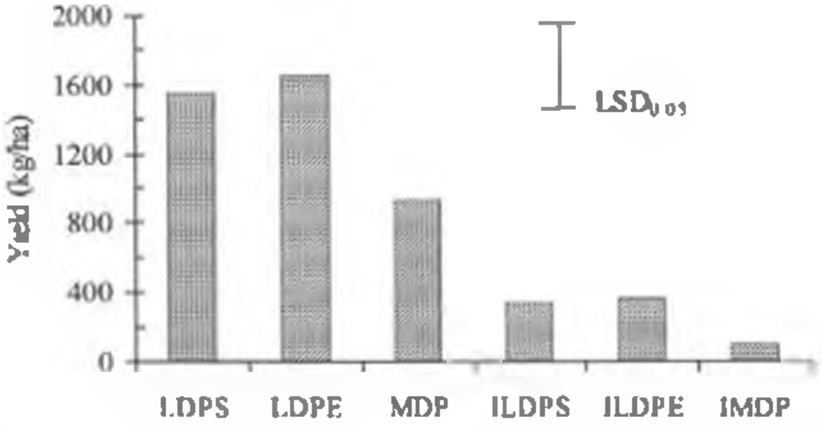


Figure 5. Grain yield of maize (a) and pigeonpea (b) either as sole or intercrop (I) at Kabete, Kenya. Where, MZ = maize, MZ/MDP is maize intercropped with MDP, MZ/LDPE the maize intercropped with LDPE, MZ/LDPS maize intercropped with LDPS, LDPS = long duration pigeonpea semi-erect, LDPE= long duration pigeonpea erect and MDP = medium duration pigeonpea

4.4.4 Dry matter partitioning by pigeonpea

Intercropping did not influence ($P > 0.05$) dry matter partitioning by pigeonpea either. However, there were differences among pigeonpea types. Table 5 shows that all the pigeonpea types allocated most of their TDM to the stem, with medium duration pigeonpea allocating about 80- 90% of TDM, and the long duration about 60%. The proportion of TDM allocated to seed was in the order of 10, 20, and 30 % for medium duration, long duration semi-erect and long duration erect pigeonpea, respectively (Table 5).

Table 5. Dry matter partitioning by three pigeonpea varieties in the sole and intercropped systems at Kabete, Kenya

Cropping system	Variety	Stem	Husk	Grain	TDM	HI
		..................(kg ha^{-1})..................				
Sole crop	MDP	3032	678	602	3784	0.12
	LDPS	4595	1391	1545	7507	0.21
	LDPE	3939	1349	1523	6332	0.26
Intercrop	IMDP	1331	123	100	1388	0.17
	ILDPS	841	297	362	1470	0.24
	ILDPE	746	245	342	1340	0.28
LSD$_{0.05}$		1683.7	451.3	398.9	3591.2	0.08

Where MDP, LDPS and LDPE represent medium duration, long duration semi-erect and long duration erect pigeonpea and their intercrop (I). TDM and HI represent total dry matter and harvest index, respectively

4.4.5 Land equivalent ratio (LER)

Land equivalent ratios from all the intercrops were either equal to or less than a unity. The LER for long duration semi-erect variety was 1.0, long duration erect variety was 0.96 and for the medium duration pigeonpea variety was 0.84.

4.5 Fractional light interception

The percentage of photosynthetically active radiation (PAR) intercepted by both maize and pigeonpea increased over time and thereafter decreased as the crop reached physiological maturity when leaves senesced (Figure 6). In the early stages of growth (54 to 96 DAP) sole maize, intercepted more light than the intercrop system and sole pigeonpea at the same time. At 96 DAP (late vegetative stage) sole maize achieved it peak interception (72%), after which there was decline because of leaf senescence at physiological maturity (138 DAP). The percentage PAR intercepted in the intercropped pigeonpea increased after harvesting maize. PAR interception decline in sole pigeonpea between 200 and 240 DAP. Long duration variety intercepted more PAR (93%) than medium duration pigeonpea (71%). Maximum PAR interception is linearly related to total dry matter and intercrop was 50% of the incident. This is shown in figure 7. The fractional radiation intercepted was positively and linearly related to total dry matter. This is shown in Figure 7.

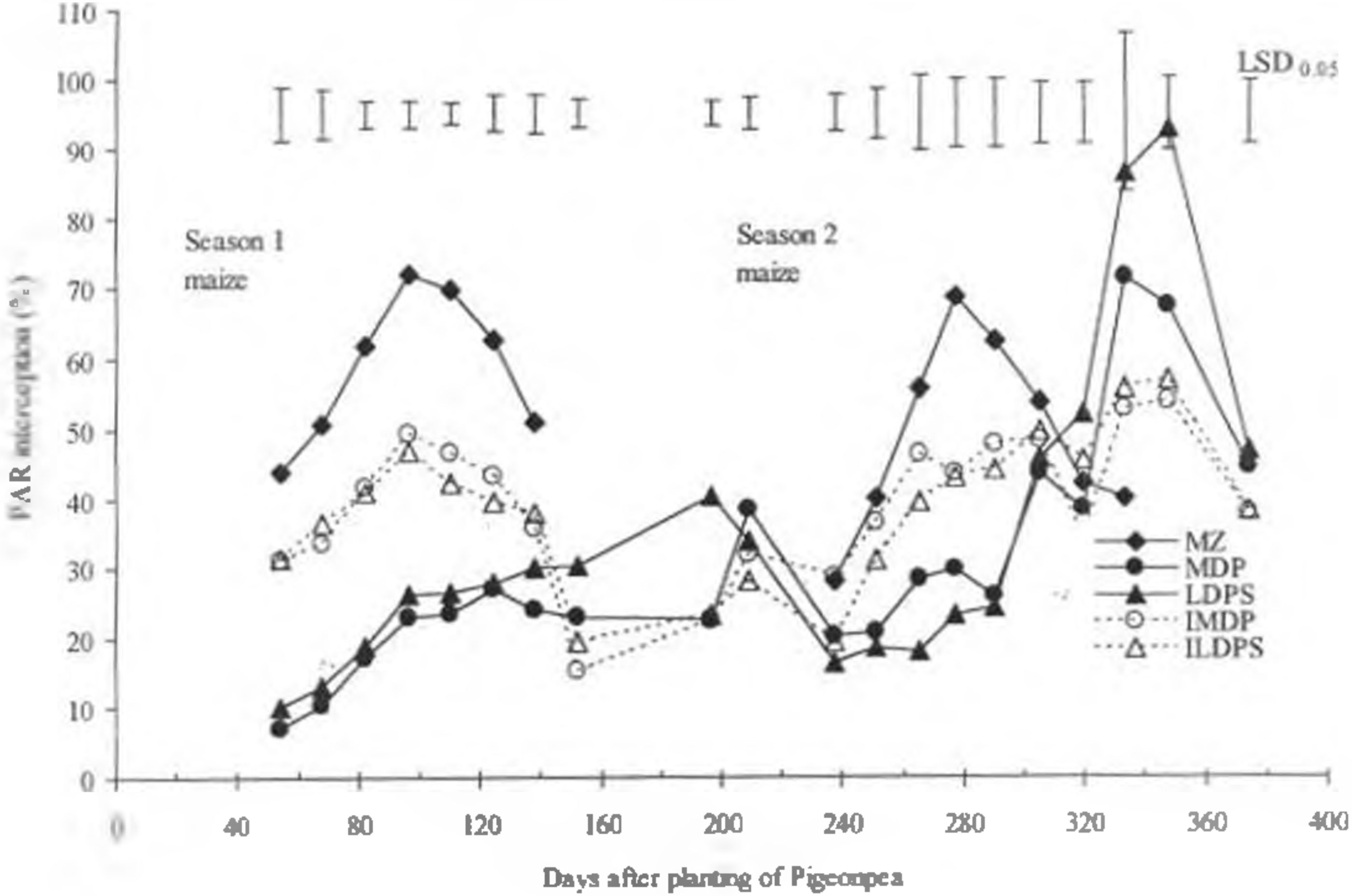


Figure 6. Percentage photosynthetically active radiation (PAR) interception by maize and pigeonpea over time at Kabete, Kenya. MZ= sole maize, MDP= medium duration pigeonpea, LDPS - long duration spreading pigeonpea and I = maize-pigeonpea intercrop

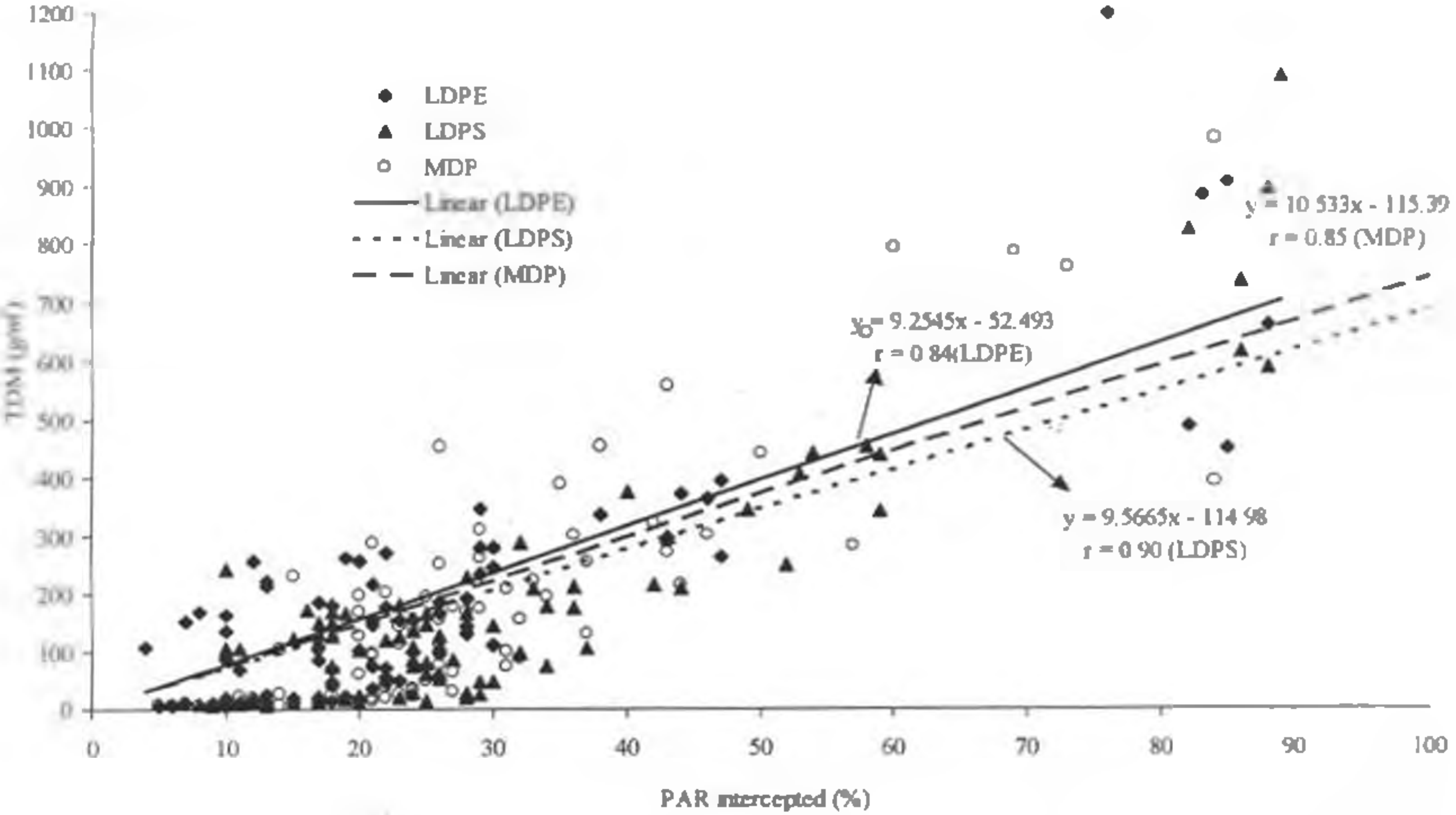


Figure 7. The relationship between the percentage of photosynthetically active radiation (PAR) and total dry matter (TDM) by pigeonpea and maize at Kabete, Kenya. MZ = sole maize, MDP = the medium duration pigeonpea, and LDPS = the long duration pigeonpea semi-erect

4.6.0. Soil water content

4.6. 1 Neutron calibration curves

The soil bulk density at 0-30 cm, 30-60 cm and 60-95 cm was 1 1, 1 1 and 1 2 gm cm^{-3} respectively The bulk density was used to convert the gravimetric soil water content into the volumetric soil water content (mm) Figure 8 shows the calibration curves of neutron ratio in relation to volumetric soil water content The regression relationship obtained for each depth was used to estimate soil water content from routine field neutron probe readings. The variation of neutron count ratio to volumetric water content accounted for 71% in the top 30 cm and 79% at depths between 30 and 100 cm The lower R^2 value in 0- 30 cm was probably due to higher organic matter and neutron loss

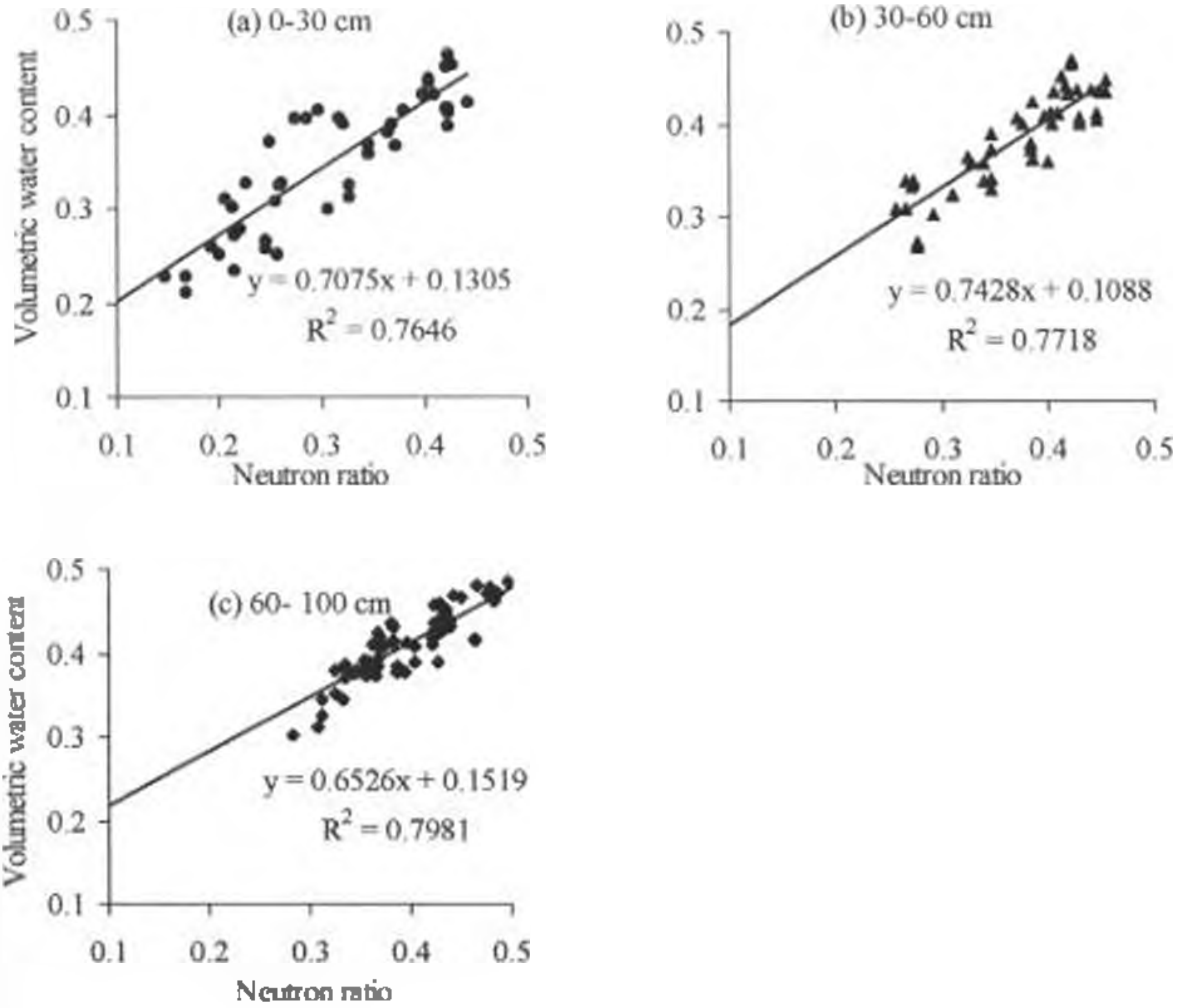


Figure 8. Soil water moisture calibration curves for the experimental site at Kabete, Kenya

4.6.2 Seasonal profile soil water content

Figure 9, shows variation soil water content in the profile for the four cropping systems on four selected dates during the experimental period i.e. 146 DAP (at physiological maturity of first maize in season), 193 DAP after first maize crop was harvested and pigeonpea were growing alone, 263 DAP (tasselling stage of second maize season) and at 319 DAP (physiological maturity of second maize season)

At 146 DAP (maize season physiological maturity), the soil profile under sole maize and medium duration pigeonpea had higher water content than both sole and intercropped long duration semi-erect pigeonpea (Figure 9) Soil water content under the medium duration and intercropped long duration pigeonpea profiles were drier between 30 - 50 cm compared to sole maize and long duration semi-erect pigeonpea Soil water content under both sole and intercropped long duration erect pigeonpea at the lower depths (90 – 130 cm) was lower than under maize and medium duration pigeonpea in the same period The trend was similar at 193 DAP At 263 DAP, maize and intercropped long duration pigeonpea extracted most water between 20-70 cm However, at the greater depths (90-110 cm) the extraction pattern was similar among the treatments.

At 319 DAP (physiological maturity stage of maize and reproductive stage of pigeonpea), water extraction patterns at 10, 50 and at 90 cm deep were similar in all the treatments However, significant differences were observed at 20, 30, 70 and 110 cm, with sole maize extracting the most water at 20-30 cm and sole and intercropped pigeonpea more at 110-130 cm Between 110 – 130 cm, the soil under sole maize had more water than under long duration pigeonpea either in the sole or the intercrop Overall, medium duration pigeonpea extracted the least amount, while the long duration pigeonpea intercrop extracted the most

Total water stored in the 110 cm soil profile varied with cropping system (Figure 10) The soil profile under the intercrop was much drier compared to the sole pigeonpea or maize plots Between 102 and 117 DAP (maize was in its reproductive stage), the soil profile under medium duration pigeonpea was wetter than that under sole maize and the long duration semi-erect pigeonpea At 179 DAP (after first maize crop harvest), soil water content under the long duration semi-erect pigeonpea, in the sole and intercrop, was similar to the medium duration pigeonpea

At 263 DAP, second maize crop was in its mid-vegetative growth with high biomass accumulation At this time the soil profile under both sole maize and intercropped long duration pigeonpea semi-erect were much drier than the sole of medium duration and long duration semi-erect pigeonpea At 345 DAP (after the second maize crop harvest), the pigeonpea were in their late vegetative stage and had developed a large plant canopy and increased in height and branching The soil profile under long duration semi-erect pigeonpea was much drier than the intercropped or medium duration pigeonpea

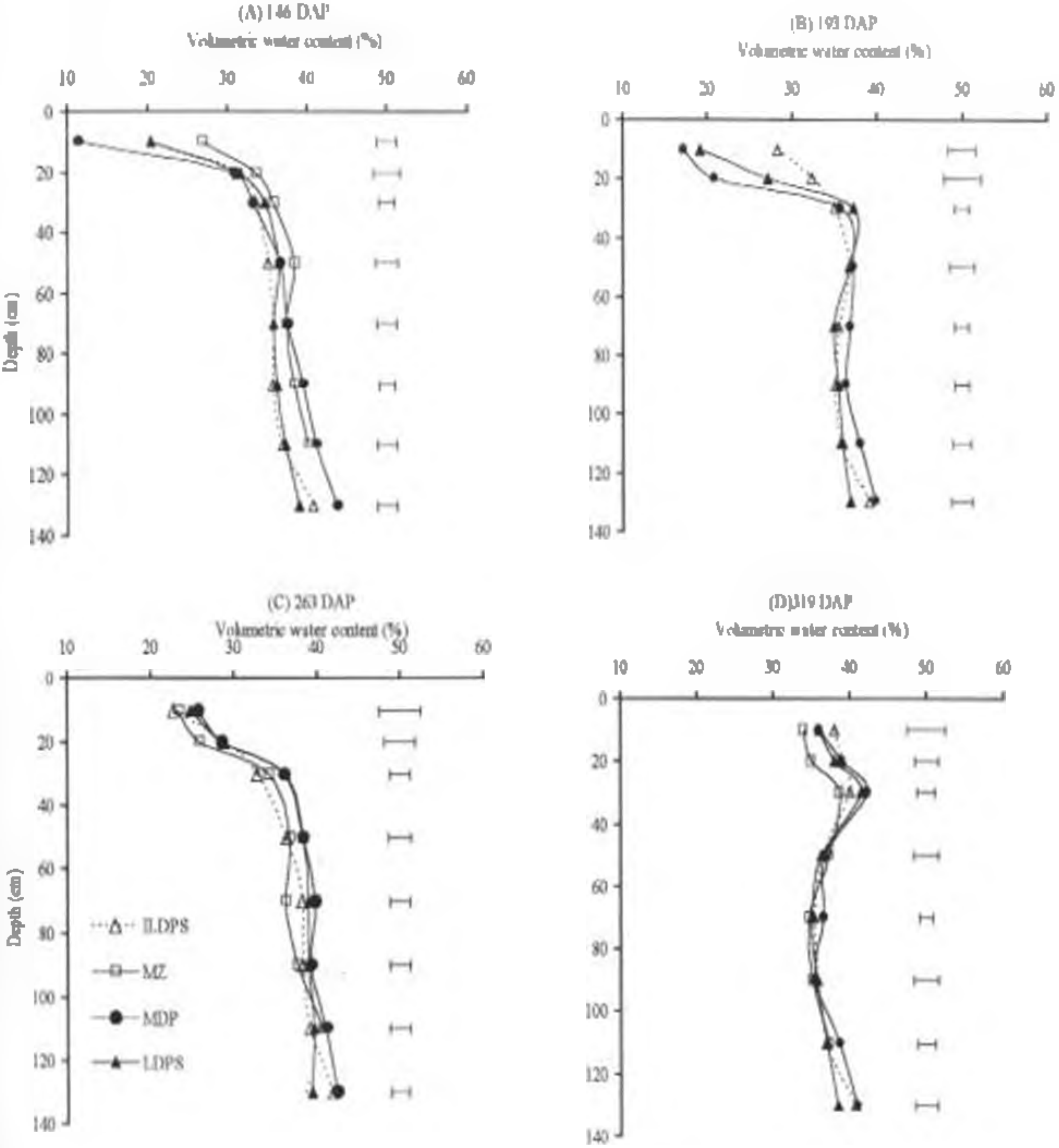


Figure 9 Soil water extraction by sole and intercropped maize and pigeonpea over time. (A) and (D) physiological maturity of maize, (B) pigeonpea at early vegetative stage after 1st season maize harvests, (C) maize at tasselling stage and pigeonpea at late vegetative stage. MZ = Maize, MDP = sole medium duration pigeonpea; LDPS = sole long duration (semi-erect) spreading, and ILDPS =long duration spreading pigeonpea intercrop LSD (p=0 05) bars indicated

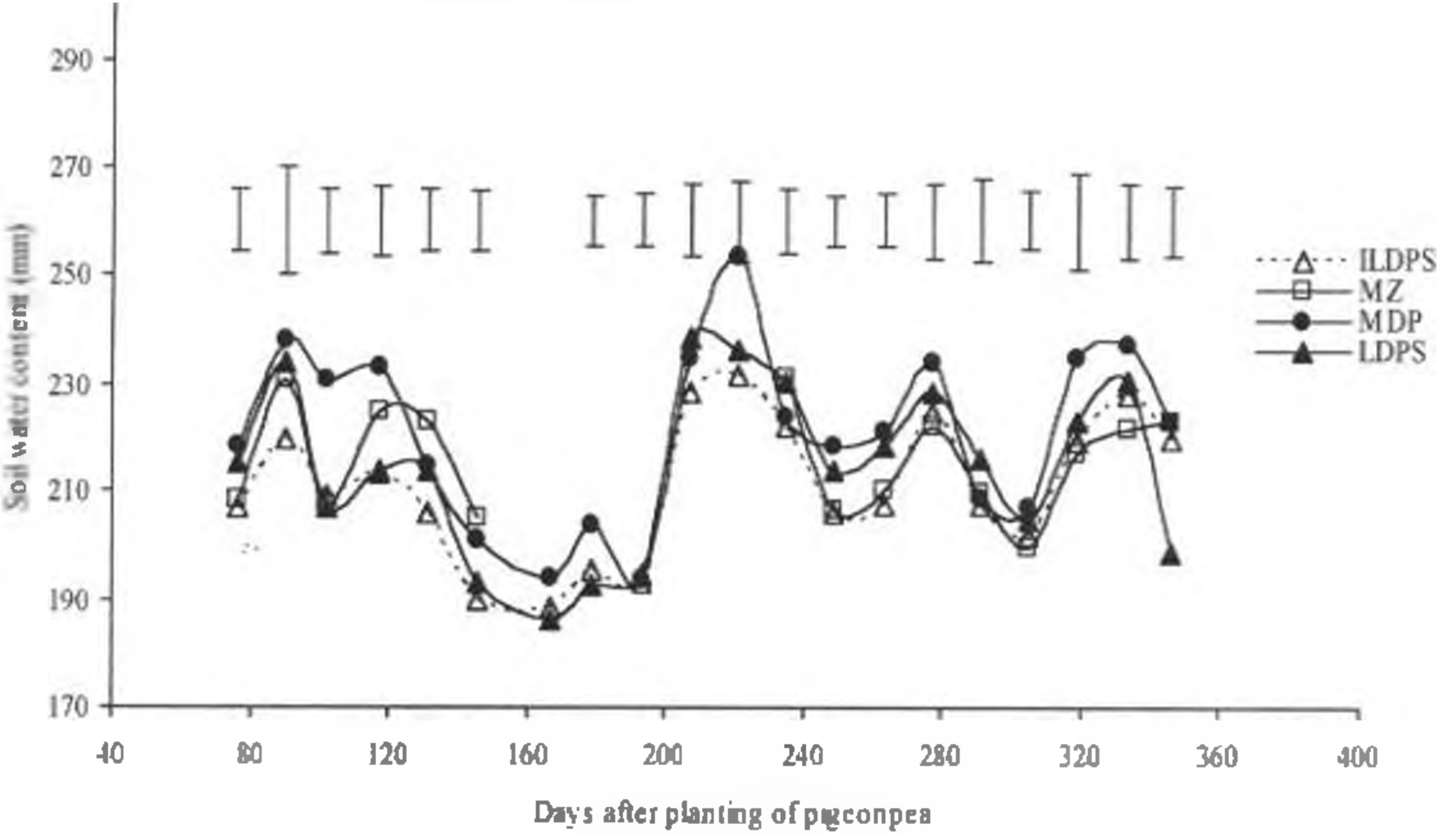


Figure10 Soil profile water content in the (0 to 110 cm) under maize and pigeonpea at Kabete, Kenya MZ = maize; MDP = sole medium duration pigeonpea, LDPS = sole long duration semi-erect and ILDPS =long duration semi-erect pigeonpea intercrop LSD (P= 0.05) bars indicated.

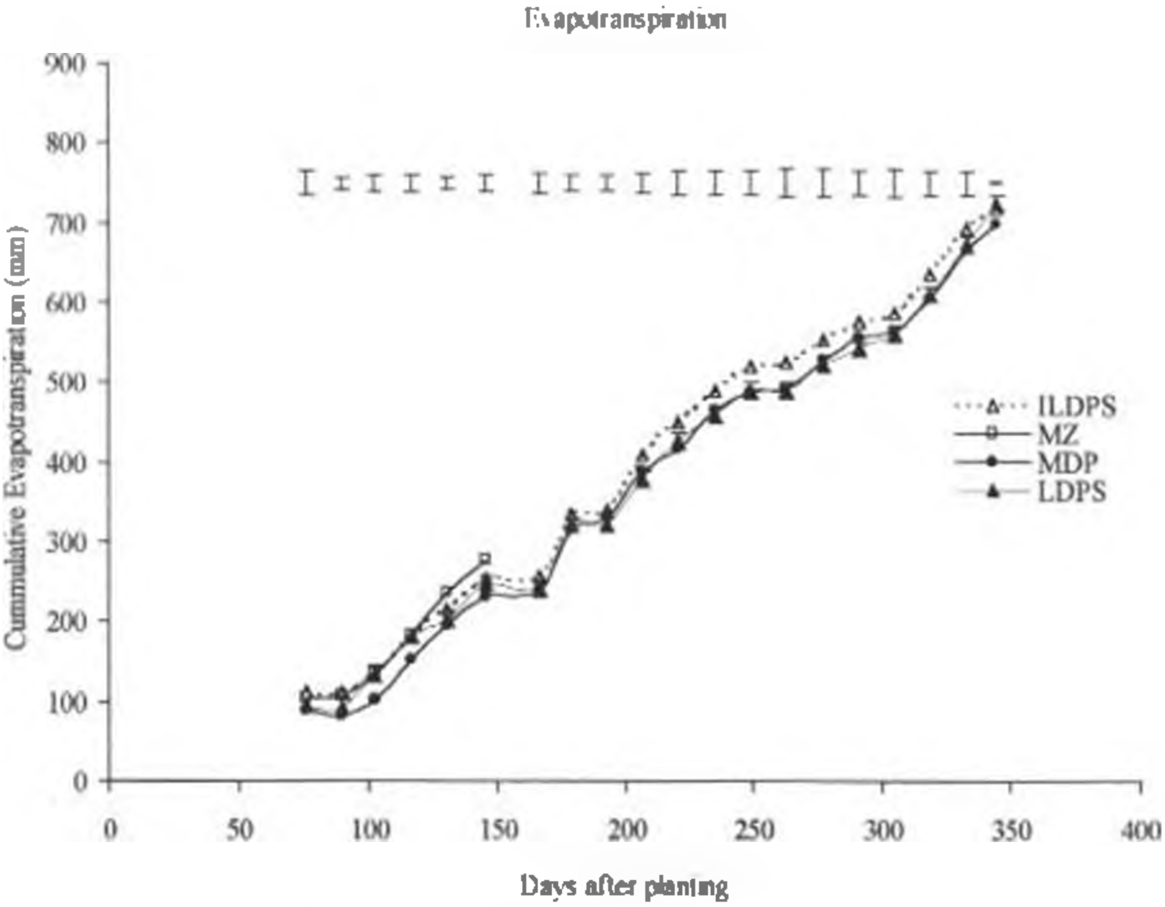


Figure 11. Cumulative evapotranspiration (ET) as influenced by cropping system at Kabete, Kenya. MZ = maize, MDP = sole medium duration pigeonpea, LDPS = sole long duration semi-erect and ILDPS =long duration semi-erect pigeonpea intercrop. LSD (P= 0.05) bars indicated.

4.6.3 Cumulative evapotranspiration (mm)

Figure 11, shows that in the early stages of growth, intercropping had no significant ($p>0.05$) influence on the cumulative evapotranspiration (ET) of sole and intercrop. Sole maize had similar cumulative evapotranspiration to both sole and intercropped pigeonpea however, in later development stage of pigeonpea, the cumulative evapotranspiration in sole maize was lower compared to sole or intercropped pigeonpea. Cumulative evapotranspiration in pigeonpea in both sole and intercrop were similar.

4.6.4 Water use efficiency (WUE)

Table 6 shows that sole maize had the highest water use efficiency while the sole pigeonpea had the lowest. However, the intercrop had higher water use efficiency than the sole pigeonpea, but lower than in the sole maize crop. The water use efficiency (WUE) for pigeonpea varieties was not different.

Table 6. Total evapotranspiration (mm), grain yield (kg ha^{-1}) and water use efficiency (WUE) for maize and pigeonpea either as sole or intercrop at Kabete, Kenya

Cropping system	Crop	Grain yield (kg ha^{-1})	Total ET (mm)	WUE (kg ha^{-1}mm^{-1})
Sole	MZ	5475	278	19.7
	MDP	935	666	1.4
	LDPE	1647	706	2.3
	LDPS	1553	673	2.3
Intercrop	MZ/LDPE	8297	697	11.9
	MZ/LDPS	8793	694	12.7
	LSD $_{0.05}$	1144	32	2.1

NB 1. LDPE represents long duration erect pigeonpea, LDPS = long duration semi-erect pigeonpea, MDP = medium duration pigeonpea and MZ = maize.

2. Intercrop indicates yields from both maize and pigeonpea combined.

3. There were no access tubes installed in maize-medium duration intercrop.

4.7 Nitrogen use

4.7.1 Nitrogen partitioning by maize and pigeonpea

The concentration of N in the maize grain was significantly ($p<0.05$) higher than the concentration in either the cobs or the stover (Table 7). However, N concentration (%) in the cob was similar to that in the stover (Table 7). Intercropping did not influence (p>0.05) both N concentration and N partitioning in maize. Maize allocated 63-69% of its N to the grain, 25-30% to the cobs and 7% to the stover (Table 7). High N allocation to grain would represent high farm export through grain sale. Nitrogen concentration in plant tissue was higher in pigeonpea than in maize (Table 7 and 8).

Pigeonpea tissue N concentration was similar in both sole and in the intercrop (Table 8). However, the concentration was higher in grain than in the husks and stem. The proportion of N allocation to different parts of the plant differed among the pigeonpea varieties (Table 8). The sole medium duration pigeonpea allocated 46% of its N to the stem and 36% to leaves, 7% to husk and 11% to the grain. However, the sole long duration pigeonpea varieties allocated about 38% to the stem, 34% to leaves, 21% to the grain and 7 % to the husks (Table 8 and 9). This implies that burning pigeonpea stems would result in high N loss from the system.

Table 7 N concentration (N %) and partitioning (kg ha^{-1}) in cobs, grains and stems in the intercrop and sole maize crop at Kabete, Kenya

Cropping	N concentration (%)			Amount of N (kg ha^{-1})			
system	Stover	Cob	Grain	Stover	Cob	Grain	Total
MZ	0.7	0.7	1.6	42	11	114	155
MZ/MDP	0.5	0.7	1.6	21	7	53	79
MZ/LDPS	0.5	0.8	1.6	22	8	68	97
MZ/LDPE	0.5	0.8	1.5	23	9	92.5	88.3
LSD$_{0.05}$	0.2	0.3	0.2	13.8	3.5	36.7	40.8

MZ = maize, MZ/LDPS, MZ/LDPE and MZ/MDP are maize intercropped with long duration semi-erect, long duration erect and medium duration pigeonpea, respectively. LSD is the least significant difference.

*Amount of N (kg ha^{-1}) was calculated using the dry matter of respective parts in Table 4.

Table 8 Pigeonpea N partitioning (kg ha $^{-1}$) and nitrogen concentration (N %) of husk, grain and stem in the intercrop and sole crop at 339 DAP at Kabete, Kenya

Cropping system	Variety	N concentration (%)			Amount of N (kg ha $^{-1}$)			
		Stem	Husk	Grain	Stem	Husk	Grain	Total
Sole crop	MDP	2.5	1.7	2.9	75	11	18	104
	LDPS	1.9	1.2	3.1	86	17	47	149
	LDPE	1.8	1.6	2.6	63	20	40	123
Intercrop	IMDP	2.4	1.8	2.9	32	2	3.0	37
	ILDPS	1.8	1.3	3.2	16	4	11	31
	ILDPE	1.7	1.6	2.5	13	4	9	26
	LSD $_{0.05}$	0.9	0.6	0.6	26.5	6.7	11.9	34.0

NB 1 MDP, LDPS, LDPE and (I) represent medium, long duration semi-erect, long duration erect pigeonpea and (I) intercrop, respectively

2. Total plant N excludes litter fall N

4.7.2 Pigeonpea litter fall

Table 9 shows that the estimated amount of leaf fall from sole pigeonpea was higher than from the intercropped pigeonpea The long duration erect pigeonpea had higher leaf fall than either the long duration semi-erect or the medium duration pigeonpea in both sole crop and in the intercrop. Litter fall N concentration indicated that N concentration was similar in both sole and intercropped pigeonpea (Table 9). Values determined by Wanderi et al , 2002 were used to estimate litter fall N because these were not determined at Kabete It is however notable that leaves N both at both Kabete and Thika are fairly close hence assumed to estimate N litter fall reasonably

The estimated amount of litter N was higher in sole crop than in the intercrop in all the three pigeonpea varieties. The sole long duration pigeonpea erect had the greatest quantity of litter N, followed by the long duration pigeonpea semi-erect and medium duration the least (Table 9). However the amount of litter N from the intercrop was similar across the varieties.

Table 9 Litter fall by sole and intercropped pigeonpea as at 339 days after planting (DAP) at Kabete, Kenya

Cropping system	Variety	Leaf fall (kg ha $^{-1}$)	%N	Litter N (kg ha $^{-1}$)
Sole	LDPE	3997	1.7	92
	LDPS	3106	2.5	78
	MDP	3397	2.3	58
Intercrop	ILDPE	562	1.8	10
	ILDPS	359	2.8	10
	IMDP	414	2.8	12
	LSD $_{0.05}$	102	0.6	21.3

MDP, LDPS and LDPE represent medium, long duration semi-erect and long duration erect pigeonpea varieties and (I) intercrop

4.7.3 Total nitrogen uptake and Nitrogen utilization efficiency (NUE)

Maize took 60 % N more than long duration pigeonpea sole crop in the entire cropping season. The intercrop N uptake were 195, 203 and 225 kg N /ha/year for medium duration, long duration erect and long duration semi-erect pigeonpea respectively. The sole cropped pigeonpea had the least N uptake (Table 10). The medium duration pigeonpea N uptake was significantly lower than the long duration pigeonpea semi-erect. Long duration semi-erect pigeonpea intercrop total N uptake was higher than the long duration erect pigeonpea and medium duration pigeonpea intercrops (Table 10). Sole maize and the intercrops had similar NUE, but all the sole pigeonpea had low NUE (Table 10). However, the intercrop tended to have higher NUE than soles of the pigeonpea.

Table 10. Nitrogen Uptake (kg/ha/yr) and utilization efficiency (kg grain /kg N) for maize and pigeonpea at the end of the growing period at Kabete, Kenya.

Cropping system	Crop	Total grain yield (kg ha^{-1}yr^{-1})	Standing Plant N (kg ha^{-1})	Litter fall N(kg ha^{-1})	Total Plant N uptake (kg ha^{-1}yr^{-1})	NUE (kg grain /kg N)
Sole	MZ	10949	308	0	308	36
	MDP	935	104	58	162	6
	LDPE	1647	123	92	215	8
	LDPS	1553	149	78	227	7
Intercrop	MZ/LDPE	8297	203	10	213	39
	MZ/LDPS	8793	224	10	234	38
	MZ/ MDP	7697	195	12	208	37
LSD $_{0.05}$		1144	32	21	32	2.1

MZ = maize, MDP = medium duration pigeonpea, LDPE and LDPS for long duration erect and semi-erect pigeonpea, respectively. The total Yield and total N uptake are derived from summation of yield and N uptake during the whole growing period for each of the cropping system.

4.7.4 Biological N fixation by pigeonpea

Table 11 shows the dry matter accumulation and shoot N for different crops at 162 and at 339 DAP, respectively. In the earlier stage of growth (162 DAP) the rate of biomass accumulation was similar for both pigeonpea and cotton, especially variety UKA 59/146 (Table 11). However, at 339 DAP cotton had a rapid vegetative growth, higher biomass accumulation and a large plant canopy than any of the pigeonpea varieties; therefore it under-estimated the nitrogen fixed by all the pigeonpea varieties (Tables 11 and 12). The long duration pigeonpea fixed more nitrogen than medium duration pigeonpea at 162 DAP (Table 12). At 339 DAP the amount of atmospheric N fixed by pigeonpea decreased tremendously.

Table 11. Crops tissue N and dry matter (above ground biomass) for cotton, maize and pigeonpea at Kabete, Kenya

Crop	162 DAP of pigeonpea			339 DAP of pigeonpea		
	Dry matter (kg ha $^{-1}$)	% N	Shoot N	Dry matter (kg ha $^{-1}$)	% N	Shoot N
Cotton Hart 89 M	3004	3.4	103	16600	1.6	265
Cotton UKA 59/146	1990	2.8	54	16400	1.65	260
MZ	13888	1.2	162	11621	1.3	146
MDP	1833	3.4	63	7181	2.3	162
LDPE	2152	3	66	10329	2.1	215
LDPS	2183	3.6	78	10613	2.1	227
LSD $_{0.05}$	2208	0.6	125	1720	0.4	151

NB 1). * Data not collected for sorghum at 339 DAP

2). MZ represent sole maize, MDP represent medium duration pigeonpea, LDPE is long duration pigeonpea erect and LDPS is the long duration pigeonpea semi-erect

3). % N is the total tissue N (above ground biomass) and shoot N at 339 DAP include litter N

Table 12. Nitrogen derived from atmospheric fixation (Ndfa kg/ha) by different pigeonpea varieties using UKA 59/156 as reference crop at Kabete, Kenya

Crop	162 DAP		339 DAP		
	Total N uptake	Ndfa (kg ha $^{-1}$)	Total N uptake	Ndfa(kg ha $^{-1}$)	Estimated Ndfa (kg ha $^{-1}$)*
Cotton (UKA 59/146)	54	0	260	0	0
Medium duration	63	9	162	-88	35
Long duration (erect)	66	12	215	-45	58
Long duration (semi-erect)	78	24	227	-33	117
LSD $_{0.05}$	37.6	22.6	55.9	44	

- Indicate the assumption of proportionate N fixed based on DM at 162 DAP assuming that N fixation rate was constant in the period (1833*9) =35.
  7181

4.7.5 Soil mineral nitrogen

Total available N in the 0 to 120 cm depth was estimated to be 82 N (kg ha $^{-1}$) before the start of the experiment. After the first season of maize (172 DAP), mineral N increased by more than two times from an average of 82 N kg/ha to 184 N (kg ha $^{-1}$) and after the second season (349 DAP) by one and half times to 258 (kg ha $^{-1}$) of soil (Table 13). Total mineral N under various treatments ranged from 113 to 210 kg N ha^{-1} at 162 days after planting (DAP), and 399 to 591 kg N ha^{-1} at 339 DAP (Table 13).

Table 13. Soil mineral N seasonal changes in the 0-120 cm soil during the experimental period at Kabete, Kenya

Cropping system	Treatment	Mineral N (kg N /ha) at different times				
		Start	172 DAP	349 DAP	Δ (kg ha $^{-1}$) (0-172 DAP)	Δ (kg ha^{-1}) (172-349D AP)
Sole	MZ	82	210	436	208	191
	MDP	82	130	461	48	322
	LDPS	82	162	491	80	291
	LDPE	82	166	401	84	233
Intercrop	ILDPE	82	113	452	31	323
	IMDP	82	204	453	122	257
	ILDPS	82	209	399	127	288
	LSD $_{0.05}$		141	168		

Start = Amount of soil mineral N found in the soil before planting, MZ = sole maize, LDPE = the long duration pigeonpea erect, LDPS = the long duration pigeonpea semi-erect pigeonpea, MDP = the medium duration pigeonpea, and I = the intercrop

NH_4^+- N and NO_3^- -N levels increased over time from 48 to 137 (kg ha $^{-1}$) and 20 to 48 (kg ha $^{-1}$) for NH_4^+ - N and NO_3^- -N, respectively by 172 DAP (Table 14).

Sole maize and intercropped medium duration pigeonpea had higher levels of NH_4^+- N than either long duration pigeonpea erect or sole medium duration pigeonpea. At 349 DAP; the levels had increased 1.8 times and 4.5 times for NH_4^+-N and NO_3^- -N, respectively.

Generally, the NH_4^+: NO_3^- ratio in the soil profile was 3:1 at 172 DAP and decreased to 1:1 at 349 DAP. Intercropped long duration pigeonpea erect and medium duration pigeonpea had the highest NH_4^+: NO_3^- ratio compared to the other treatments, at 172 DAP but the ratio was similar among all the treatments at 349 DAP (Table 14).

Table 14. Amounts of NH_4^+- N and NO_3^- -N in the 0-120 cm soil depth at different sampling periods during the experimental period at Kabete, Kenya

Treatment	172 DAP		349 DAP	
	NH_4^+-N (kg/ha)	NO_3^--N (kg/ha)	NH_4^+-N (kg/ha)	NO_3^--N (kg/ha)
ILDPE	93	17	246	190
IMDP	150	14	262	199
ILDPS	136	73	250	230
MZ	154	55	240	161
LDPE	104	61	206	193
MDP	89	28	198	255
LDPS	136	46	234	219
$LSD_{0.05}$	83.5	64.6	141.3	83.8

MZ = sole maize, LDPE = the long duration pigeonpea erect, LDPS = the long duration pigeonpea semi-erect pigeonpea, MDP = the medium duration pigeonpea and I = the intercrop

NH_4 - N and NO_3^- -N levels were low at the beginning of the experiment (Figure 11). Distribution of both NH_4^+ - N and NO_3^- -N down the soil profile indicates low amounts in the top 60 cm, but high levels at 120 cm during the two dates. At 349 DAP, at 20 cm, sole maize had the highest ($p<0.05$) levels of NH_4^+ - N; while the sole pigeonpea had the least levels. At depth 40 and 120 cm, the long duration pigeonpea erect had the highest amounts of NO_3^- -N and sole maize the least levels (Figure 11).

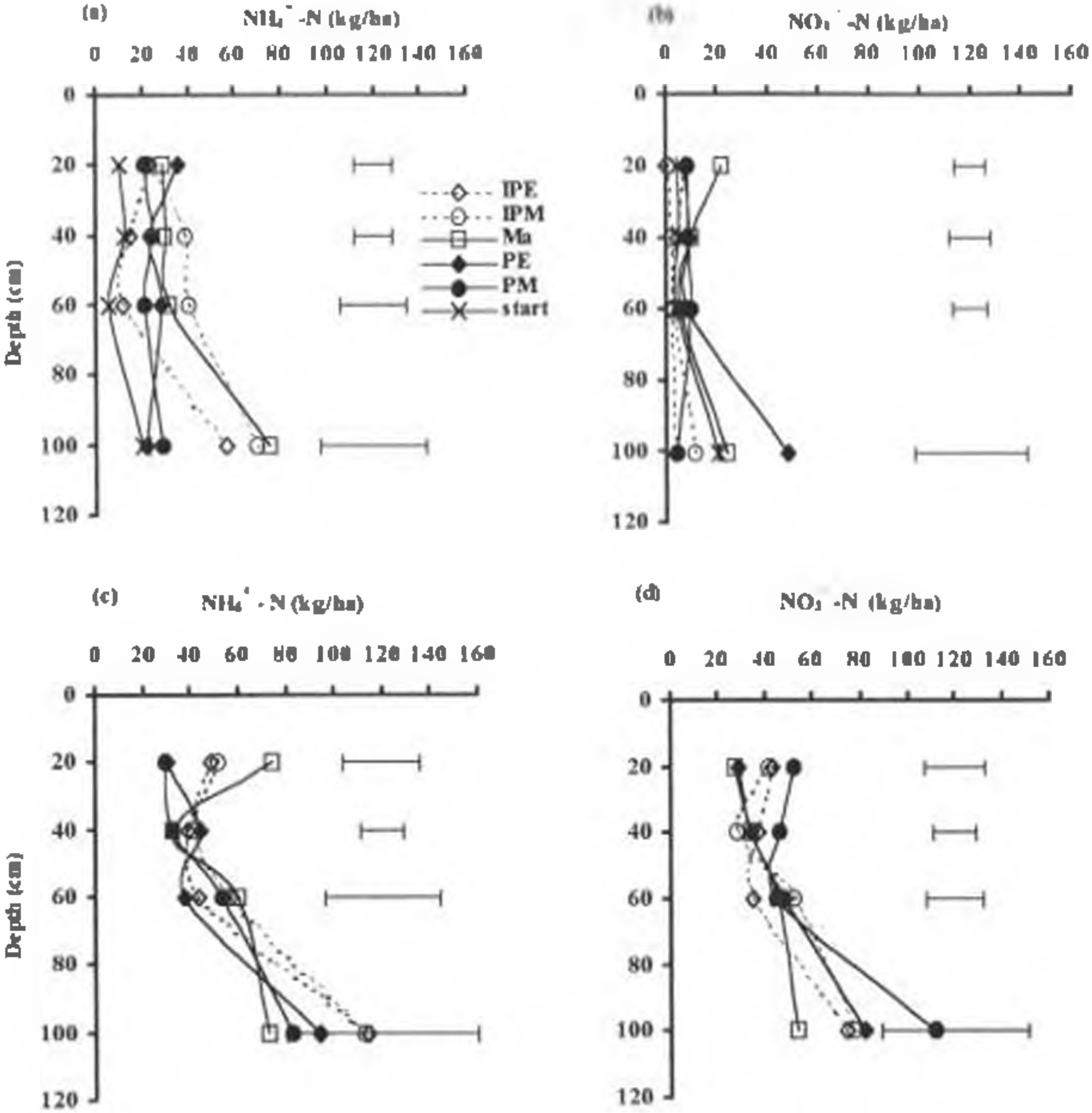


Figure 12 Soil NH$_4^+$-N (a and c) and NO$_3^-$-N (b and d) at 172 DAP and 349 DAP (after maize was harvested) respectively at Kabete, Kenya. ILDPE – intercropped long duration erect pigeonpea, IMDP – intercropped medium duration pigeonpea, MZ – sole maize, LDPE – long duration erect sole pigeonpea and MDP – sole Medium duration pigeonpea.

4.7.6 Summary of the N ($kg\ ha^{-1}$) budget

The source of N in a plant tissue is normally from soil mineral N and fertilizer N (incase the fertilizer is applied) for the non-fixing crop. However, sources of plant N for the nitrogen fixing plant are soil mineral N, nitrogen derived from the atmosphere and fertilizer N

N in a non-fixing crop can be calculated using the equation below (Mburu, 1996):

$$Npl = Nf + Nsoil$$

Equation 10

Where: Npl is total plant N uptake

Nf is N derived from fertilizer application

Ns is N derived from soil mineral N supply

However, fertilizer was not applied in this experiment therefore the only source of N in maize plant was the soil, that is Npl = 0 + Nsoil

Maize took up higher total N from the soil as compared to the pigeonpea (Table 17)

Sources of N in a nitrogen fixing plant can be calculated as;

$$Npl = Ns + Ndfa + Nf$$

Equation 11

Where, Ndfa is the plant N derived from the atmospheric nitrogen fixation. No fertilizer was applied to pigeonpea, therefore N sources include Ns and Ndfa. The long duration semi- erect pigeonpea, long duration erect and medium duration pigeonpea fixed about 52%, 27% and 22% of the total N respectively. N from the soil was 78%, 48%, and 73% of the total N for the medium duration, long duration semi erect and long duration erect pigeonpea varieties respectively (Table 15).

Table 15 Summary of the N (kg $ha^{-1}yr^{-1}$) budget of maize and pigeonpea as sole crops

Crop	N soil (kg ha^{-1})	N dfa (kg ha^{-1})	Total N uptake(kg ha^{-1})
MZ	308	0	308
MDP	127	35*	162
LDPS	110	118*	227
LDPE	157	58*	215

NB * Estimated values from section 4.7.4, Table 13.

MZ, MDP, LDPS and LDPE represent maize, medium duration pigeonpea, long duration semi- erect and long duration erect pigeonpea varieties respectively. Note that Ndfa by pigeonpea in the second season is estimated with the assumption of direct proportionality based on the first season Ndfa

Figure 13, shows that long duration erect pigeonpea allocated 29%, 19%, and 43% and 9% to the stem, grain, litter fall and husk respectively

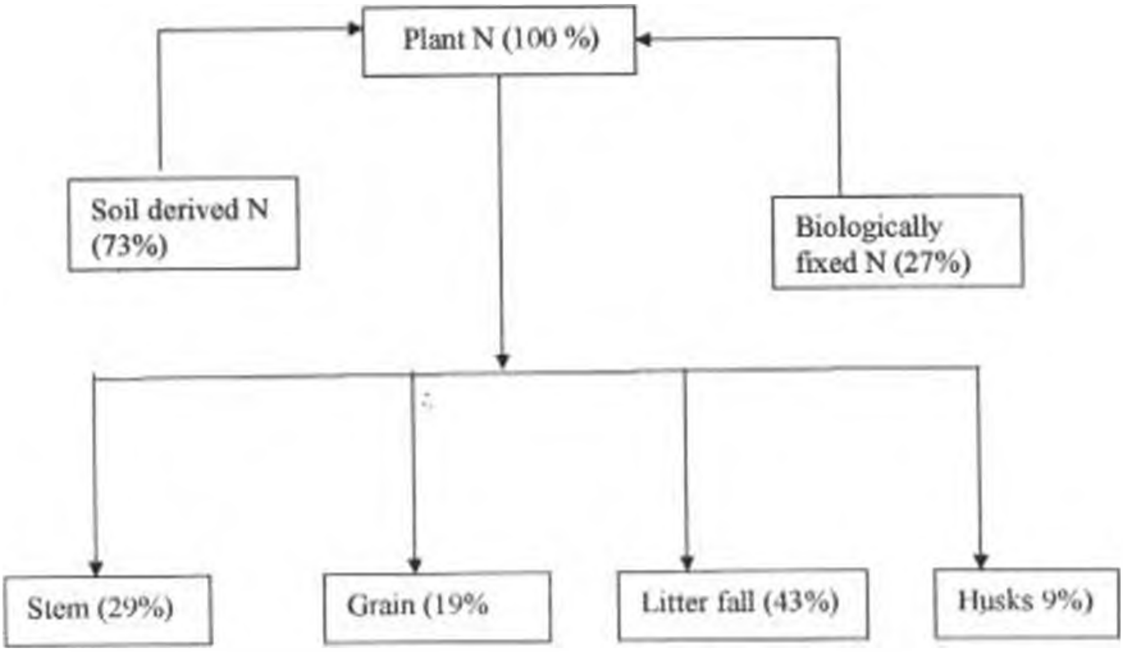


Figure 13 Chart showing long duration erect pigeonpea N sources and partitioning under sub humid conditions at Kabete, Kenya.

4.8 Residual effect of pigeonpea on subsequent maize crop

4.8.1 Maize dry matter accumulation, N uptake and grain yield

Sole cropped pigeonpea was left to grow much longer while the residual maize crop was growing and this suppressed maize growth The average grain yield of maize obtained from plots previously planted with the sole long duration erect pigeonpea was higher (3940 kg ha $^{-1}$) than from the plots that were previously intercropped with pigeonpea (3521 kg ha $^{-1}$) or those that were continuously planted with maize (1833 kg ha $^{-1}$) (Table 18) However, the yield obtained from sole of medium duration pigeonpea was similar to plots that were continuously grown with maize (1833 kg ha $^{-1}$ and 1995 kg ha $^{-1}$) for plots continuously with maize and intercropped with sole medium duration pigeonpea respectively Generally the yield maize of increased by about 100 per cent in plots previously grown with sole long duration pigeonpea erect and by 1% for the sole medium duration pigeonpea compared to those that were continuously grown with maize The total plant biomass increased by about 45% for plots previously planted with long duration pigeonpea and by 35% in plots that were intercropped (Table 16) The stover dry matter did not show any significant differences among the treatments ($p<0.05$)

Total plant N was similar for all the plots irrespective of the previous cropping system However, the N uptake by the stover + cob was highest for the maize following plots intercropped with the long duration pigeonpea semi-erect, and least for the plots following the sole medium duration pigeonpea (Table 16)

Table 16. Residual effect of pigeonpea on maize dry matter partitioning and N uptake at Kabete, Kenya

		Dry matter (kg ha $^{-1}$)				N uptake (kg ha $^{-1}$)		
Cropping system	Crop	Stover	Cob	Grain	TDM	Stover + Cob	Grain	Total N
Continuous plot	MZ	2378	665	1833	4876	21	36	57
Sole cropped plots	MDP	2193	390	1995	4578	14	28	42
	LDPS	257	464	2391	5428	16	34	50
	LDPE	2445	691	3940	7076	17	56	73
Intercropped plots	IMDP	2383	657	3544	6583	20	56	76
	ILDPS	2576	760	3644	6980	22	38	80
	ILDPE	2252	548	3375	6086	19	54	72
	$LSD_{0.05}$	834.6	292.1	1588	2181.3	5.4	25.9	29.5

MZ, MDP, LDPS, LDPE and represent sole maize, medium duration, long duration semi-erect, long duration erect pigeonpea and (I) their intercrop. LSD is the least significance of difference.

4.8.2 Soil N and C after the residual maize crop

Total soil N observed from the plots that were previously planted sole pigeonpea (0.24 %N) was not significantly different from that of continuously planted with maize (0.28 %N). The soil percentage C % was comparable in plots that were previously planted with sole maize (2.4% C) as compared to those previously planted with sole pigeonpea (2.0 % C).

CHAPTER 5

5.0 DISCUSSION

5.1 Rainfall and soil chemical characteristic at the experimental site

The months of April to June 2001 received 50% below average rainfall while in the months of October and November 2001 received more than average rainfall by 22% and 60% respectively. During long rains of 2002, rainfall was 30% higher than average in April. However, during the month of May 2002, the amount of rainfall received was 38% below the average (Figure 2). This was experienced during the most critical stage of maize phenological stage (productive stage) and therefore the grain yield was significantly reduced. Opeke, (1982) stated that rainfall effect on crop yield is dependent on then spread or length of the dry season and water capacity of the soil.

Total soil N % at the experimental site was 0.12-0.25; P 10- 29 ppm, Ca 3-6.5 cmol/kg and K ranged from 1.30-2.1 cmol/kg indicating that the soil was moderately fertile (Tekalign, *et al.*, 1991; Okelaho *et al.*, 2002) and the nutrients levels were within sufficient levels for normal crop growth.

Levels of NH_4^+ -N and NO_3^- -N at the start of the experiment were highest in the top 20 cm and decreased down the soil profile (Table 1). This probably indicates that there was more mineralization at the top layers than down the soil profile. It could be probably because of N inputs from litter decomposition from previous season.

5.2 Crop phenological development

The long duration pigeonpea flowered (148 DAP) and matured (178 DAP) later than the medium duration pigeonpea which flowered at 120 DAP at Kabete (Table 2) compared to warm areas where the long duration pigeonpea flowered at 190 DAP at Kiboko and matured at 251 DAP (Silim *et al.*, 1995) an indication that low temperatures shortened the phenology of the long duration of pigeonpea. In their study, Silim *et al.*, 1995 also concluded that long duration cultivars have low optimum temperature (<18°C) for rapid flowering, and are therefore able to flower and produce grain at intermediate to high elevation or latitudes where temperatures are intermediate to low. This was further confirmed by (Wanderi, 2004) that long duration pigeonpea erect took longer (210 DAP) to mature at Thika (warm dry conditions) compared to Kabete (cool wetter conditions) while the medium duration pigeonpea took shorter (110 DAP) to mature at Thika compared to Kabete (120 DAP). This implies that farmers in the humid areas can take advantage of this and intercrop long duration pigeonpea with maize.

Maize developed faster than any of the pigeonpea varieties i.e. the thermal time to maize physiological maturity (569°C days) than any of the pigeonpea varieties (> 687 °C days). This indicates that maize being C_4 had a rapid initial growth than C_3 pigeonpea it development within the given phenophase were earlier than those of pigeonpea hence good complement in the resource use in the intercrop system. This confirms that pigeonpea has slow initial growth rate (Reddy, 1990) making it suitable for intercropping with more fast growing crops like maize because resources for growth will be required at different phases of their development therefore complementing each other. Natarajan and Willey, (1980) in a study on sorghum-pigeonpea intercrop found that phenological differences was of major importance in intercropping system especially because resources are captured at different times. This is perhaps the most common cause of higher productivity in intercropping and is largely due to the capture of more resources rather than change in efficiency of utilization in dry matter production (Willey *et al.*, 1886)

5.3 Effects of intercropping on plant height, crop growth rate, total dry matter, yield and land equivalent ratio.

Intercropping at Kabete did not influence plant height of both maize and pigeonpea. This could be attributed to differences in growth rate between maize and pigeonpea and the fact that similar phenological phases occurred at different times of the season (Table 2) hence resource utilization differed. Furthermore, the height of pigeonpea (119 cm) was relatively reduced as compared to that of maize (223 cm). This confirms Silim *et al.*, 1995 that low temperatures reduce plant height (116 cm at Kabete compared to 285 cm at Kiboko). At Thika the height of the long duration pigeonpea was over twice as tall (243 cm) compared to Kabete (119 cm) and this resulted in competition for light in the intercropped pigeonpea and the second season maize crop (Wanderi, 2004). This could be attributed to the environmental differences with Thika being a warmer than Kabete

Maize total dry matter accumulation and crop growth rate was higher (Table 4) because of differences in photosynthetic pathways; maize is a C_4 plant while pigeonpea is C_3. The C_4 plants do photorespire hence they grow faster than the C_3 plants. Maize grew very rapidly and developed a higher plant canopy than the pigeonpea, consequently higher biomass production Decrease in dry matter yield in the intercrop system has been reported in soybeans (Dalal, 1974, Wahua and Miller, 1978) and in pigeonpea (Dalal, 1974; Kumar, *et al*, 1981; Chibwana and Wood, 1995).

Grain yield depends on biomass accumulation and the efficiency of partitioning to grain (HI) Maize had a higher harvest index (0 4 to 0 45) than the pigeonpea (0 1 to 0.3) meaning maize was more efficient in partitioning dry matter to grain Also compared to other crops like sorghum (0 34), rice (0.42), groundnut (0.47) (Beadle. *et al.*, 1985) and beans (0 40, Mburu, 1996). HI for pigeonpea was relatively low indicating room for genetic improvement Evans (1993) indicated that genetic yield potential of a crop could be improved through breeding and agronomic management

Long duration pigeonpea had higher yield than the medium duration pigeonpea an indication of higher biomass accumulation and higher harvest index (Table 5). Maize-long duration pigeonpea intercrop had higher LER than maize-medium duration pigeonpea intercrop This could be explained by the fact that crops with longer duration have longer period to utilize resources hence higher values in yields (Evans, 1993).

5.4 Photosynthetically active radiation (PAR) interception

Differences in PAR interception observed between maize and pigeonpea reflected differences in crop growth rates Maize had rapid vegetative growth compared to slow initial growth habit of pigeonpea hence higher PAR interception Sivakumar and Virmani, (1980) in their studies on growth and resource use in maize and pigeonpea concluded that if a slow growing crop such as pigeonpea, which is inefficient in using moisture and intercepting radiation during the early part of the growing season, but efficient in using stored moisture after rains is grown with a fast growing crop like maize, the overall use of water and interception of radiation is greatly increased. Another good example is groundnut-pigeonpea system which combines differing duration to maturity of 105 days (groundnut) and 180 days (pigeonpea). In this study sole groundnut reached its maximum light interception (80%) by about 45-50 days while the pigeonpea took 90- 100 days (Willey *et al.*, 1986)

Long duration pigeonpea captured higher PAR than the medium duration. This was attributed to larger canopy with long duration being larger compared to the medium duration pigeonpea. The fraction PAR interception is a fraction of LAI and plant canopy geometry (Campbell and Evert, 1994) and as a bearing in determining which of the components will intercept more light than the other.

The decline observed after peak photosynthetically active radiation interception towards physiological maturity in all the crops was due to leaf senescence. Leaf fall in pigeonpea with maturity could have been due to remobilization of nutrients from leaves to the seeds (Weil and Ohrogge, 1972). Seeds are stronger sink leading to assimilates remobilization from organs like leaves which leads to their death (Weil and Ohrogge, 1972)

5.5 Seasonal profile soil water content

Variation in soil water content in the profile between the cropping systems crops could be attributed to differences in growth and rooting habits of maize and pigeonpea. In a green house experiment, maize had extensive but shallow root system and pigeonpea deep root system hence extracting water from different soil profile (Wanderi, 2004). The largest depletion in soil water in the top 30 cm in all the crop systems (Figure 8) may indicate that roots were concentrated at this depth. Wanderi (2004) found that at least 50 % root density of most crops is in the top 30 cm. Long duration pigeonpea extracted more water at lower depth (90-130 cm) than the maize (Figure 8) indicating that the pigeonpea roots were able to explore the deeper soil layers than maize. These confirmed findings by Mburu (1996) while conducting an experiment on effect of irrigation, fertilizer nitrogen and planting density on beans yield under different conditions found out that high root density and direct evaporation from the soil occurs in the top soil layers.

Maize extracted the least amount of water at 146 DAP because it had reached physiological maturity hence demand for water was low. Higher depletion of water in the 0-110 cm soil profile by the long duration intercrop (Figure 10) may be probably due to the different crops explored different soil depths.

Higher water use efficiency by sole maize than in the intercrop was an indication of high grain yield from high dry matter production coupled with high harvest index. This was contrary to Willey (1979) and Garba and Renard (1991) who found that an intercrop of legumes with a cereal may use water more efficiently than the sole crop of either species because of exploring a larger total soil volume for water, especially if the component crops have different rooting patterns The results also disagree with Natarajan and Willey (1980) who reported higher WUE by sorghum/ pigeonpea when they were intercropped than when monocropped whereas in this study sole maize (19.7 kg ha^{-1} mm^{-1}) was found to have higher water use efficiency than in the intercrop (11 9- 12 7 kg ha^{-1} mm^{-1}) . This is because probably there was no water deficit at the time this experiment was conducted On the other hand under humid conditions, the pigeonpea was short unlike at Thika which is warmer where the canopy was larger and the intercrop extracted more water compared to sole crops (Wanderi, 2004) It can therefore be concluded that probably the WUE in an intercrop system of cereal and legume depends on type of cereal or legume in question and also the environmental factors

5.6 Nitrogen use, partitioning in maize, litter fall, BNF and soil mineral N

5.6.1 Total N uptake

Higher total N uptake by sole maize can be attributed to higher dry matter accumulation (Table 10) The improved total N uptake in the intercropped system than sole pigeonpea was an indication of better nitrogen use in this system possibly through extra N uptake by maize Low N uptake efficiency by sole pigeonpea was probably attributed to low biomass accumulation rather than N uptake This was deduced from the concentration of N in the plant tissue, which was on average about 3 % and 1 3 % for pigeonpea and maize respectively (Tables 8)

Intercropping did not alter tissue nitrogen concentration (Ofori *et al.*, 1987, Ta and Faris, 1988) Chibwana and Wood (1995), using total nitrogen difference method (TNDM) found no differences in the nitrogen concentration and total nitrogen uptake of the pigeonpea shoot per plant However, it should be noted that differences in total N uptake in the sole and intercrop systems were attributable to biomass, that is plant population per hectare bases (66,500 plants and 26,650 plants for sole and intercrop respectively) rather than tissue N concentration

5.6.2 Litter N

Higher litter fall (kg ha^{-1}) and litter N (kg ha^{-1}) in long duration pigeonpea compared to medium duration pigeonpea can be attributed to high biomass production Higher liter fall (kg ha^{-1}) and litter N by sole pigeonpea compared to the intercropped pigeonpea was attributed to low plant density in the intercrop Wanderi, 2004, reported similar trends at Thika, which is semi-arid condition However, amount of litter N at Thika (60-132 kg N ha^{-1}) was higher compared to Kabete (56- 92 kg N ha^{-1}) because of warmer temperatures in former than later. The differences were due to higher biomass production at Thika compared to Kabete because of warmer temperatures in the later consequently higher litter fall This implies that pigeonpea can be included in sub humid climate maize-based production systems because the litter fall would contribute at least 50% of the recommended fertilizer for maize (60 kg N ha^{-1}) assuming all the pigeonpea biomass is left in the farm

Long duration erect pigeonpea allocated 29%, 19%, 43% and 9% to the stem, grain, litter fall and husk respectively (Figure 13) This indicates that incorporating the stem, litter fall and husk to the soil once decomposed would improve the soil fertility

5.6.3 Biological nitrogen fixation

The small amounts of N fixed by pigeonpea varieties in this study were attributed to their low biomass production and infestation by late leaf blight. The use of cotton as a non- fixing reference crop may have contributed to under estimation of N fixed due to its larger biomass accumulation, which suggests that cotton was not a suitable reference crop in sub humid conditions.

5.6.4 Soil mineral N

There was large variation of soil mineral N during the experimental period as shown in Figure 11. High spartial-temporal variation of soil mineral N is common in soil measurements (Hoosbeek, 1998) and has also been reported for mineral N measurements in both temperate regions (Selles *et al.*, 1986) and the tropics (Wong and Nortcliff, 1995). These soil N fluctuations may be responses to seasonal changes in soil content and may reflect the net effect of inputs of N from mineralization, fertilizer, the atmosphere, and removal by plant uptake, immobilization, leaching and gaseous losses (Wong and Nortcliff, 1995). The greatest concentrations normally occur during the transition between the dry and wet seasons (Wong and Nortcliff, 1995). The increases observed in mineral N is an indication that N mineralization exceeded N losses (Table 13). Low nitrate concentration in the 40-60 cm soil layer compared to ammonium ions could be explained by higher uptake possibly indicating NO_3^- -N preferential uptake. The general increase in both NH_4^+-N and NO_3^- -N down the profile by the end of the season was indicative of leaching High N levels at the end of the season were possibly because of N inputs from litter decomposition (Figure 11)

5.7 Residual effect of pigeonpea on subsequent maize crop

The maize yield increase in plots previously planted with pigeonpea may be an indication of increased nutrient supply from decomposed litter Nair *et al* (1979) found wheat yield to increased by 30% after a maize/soybean intercrop and 34% after maize/cowpea intercrop compared to wheat planted after sole maize In on-station trials on sandy granitic soils in Zimbabwe, the yield of maize almost doubled from 2.5 to 4.6 ton/ha after groundnut crop which yielded only 0.4 ton ha^{-1} (Waddington and Karigwindi, 2001) In India, pigeonpea was found to give a residual benefit to a subsequent maize crop of 38- 49 kg N ha^{-1} which was partially attributed to a contribution of N from pigeonpea leaf fall of 30- 40 kg N ha^{-1} (Kumar Rao *et al.*, 1983) The amount of leaves that fall during growth of long duration pigeonpea may contribute as much as 68- 84 kg N ha^{-1} (Kumar Rao, *et al.*, 1996; Sakala, *et al.*, 2001).

CHAPTER 6

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Low temperatures hastened phenological development of long duration pigeonpea at Kabete This offers the possibility of producing pigeonpea in cooler areas like Kabete as an alternative to the popularly grown beans

Low temperatures reduced plant height and biomass accumulation of long duration pigeonpea at Kabete This resulted in low intercropping advantage (LER) at Kabete (≤ 1) The other fact is that pigeonpea yield was low partly to blight infestation that caused leaf fall

Slow growth rate by pigeonpea makes it suitable to grow with rapidly growing crops because resources are demanded at different period of growth, indicative of temporal separation in light and water use and therefore complementarity.

Long duration pigeonpea may be included in sub-humid climate maize-based production systems because the litter fall would contribute at least 50% of the recommended fertilizer N for maize (60 kg N ha^{-1}) assuming all the pigeonpea biomass is left in the farm However legumes with higher biomass accumulation would be more suitable

Long duration pigeonpea cultivars fix more N and more litter fall compared to the medium duration due to higher biomass accumulation In terms of nitrogen use, the long duration pigeonpea intercrop is more efficient, a further evidence for more suitability in the intercrop

Although pigeonpea has a longer duration than beans, the extra benefit from biological nitrogen fixation and N from litter fall should improve maize in a subsequent season

6.2 RECOMMENDATIONS

Farmers in sub humid areas can intercrop long duration pigeonpea with maize crop to increase crop range and enhance food security especially because low temperatures shorten their phenological development

Cotton and sorghum were not suitable references crops for the variety of pigeonpea under study, therefore it is recommended that for future similar studies using non-fixing pigeonpea of the same maturity period and growth rate or ^{15} N studies be used to asses N fixation by long duration pigeonpea varieties

From the present study it is apparently clear that for a similar study all the crops in question should be of similar period of maturity to minimize disparities when comparing their resource use For instance, it is only fair to compare water use efficiency, or nitrogen uptake of crops that have grown for the same period

Pigeonpea had a low harvest index, therefore breeding for higher index could go along way in improving its comparative advantage with other popular legumes like cowpeas and beans

There is need for more studies on residual effect by pigeonpea on subsequent maize (cereal) to ascertain the real benefits to avoid a conclusion based on one-season findings.

REFERENCES

Adhiambo Mical, 1996 Effects of bean planting density and planting time on growth and yields of maize and beans in an intercropping system. Msc Thesis. University of Nairobi

Agboola, A.A and Fayemi, A.A. 1971. Preliminary trials on intercropping of maize with different legumes in Western Nigeria. *Journal of Agricultural Science. 77: 219-255*

Aggrawal, P.K., Garrity, D.P., Liboon, S.P. and Morris, R.A. 1992. Resource use and plant interactions in a rice-mung bean intercrop. *Agronomy journal. 84:71-78*

Allen, L.H., Sinclair T.R. and Lemon E.R. 1976 Radiation and microclimate relationships in multiple cropping systems. In. *Multiple Cropping*. (Eds. R A Papendick, P A Sanchez and E B Triplet) ASA Special publication 27, Madison, WI, 171-200

Altieri, M.A., Anderson, M.K. and Merrik, L.C.1987. Peasant Agriculture and the Conservation of Crop Resources. *Conservation Biology Journal (Agroecology pp 90-112)*

Anonymous, 1997 National Development Plan 1997-2001. Government Printer Nairobi, Kenya

Baker, C.M. and Blamey, F.P.C. 1985. Nitrogen fertilizer effects on yield and nitrogen uptake of sorghum and soybean growth in sole and intercropping systems. *Fields Crops Research 12: 233-240*

Beadle, C.L.,Long, S.P., Imbamba, S.K., Hall, D.O., and Olembo, R.J. 1985. Photosynthesis in relation to plant production in terrestrial environments. Tycooy/ Cassel, London

Bell, P.J. 1987. Neutron Probe Practice. Institute of Hydrology. pp 34

Caldwell, M.M. 1987 Plant architecture and resource competition. In *Ecological studies* (Eds. E.D. Schulze, H. Zwolfer), 61: 164-179 Springer- Verlag, Berlin 2 pp.211-215.

Campbell, G.S. and Van Evert, F.K. 1994. Light interception by plants canopies efficiency and architecture. In *Resource capture by crops* (Eds. J.L. Monteith, R.K Scott and M.H Unsworth) Nottingham University Press. pp 35-52

Cheminig'wa, G.N. and Nyakundi, J.O.1994. Effects of increased intimacy between maize- beans in an intercropping system on growth and yield of maize and varying nitrogen levels *East African Agricultural journal 59:269-279*

Chibwana, P.A.D. and Wood, M. 1995. Estimation of nitrogen fixation in pigeonpea (*Cajanus cajan*) grown in pure or mixed stand In *African Crop Science Conference Proceedings.*

Cooper, P.J., Gregory, P.J., Tully, D. and Harris, H.C.1987. Improving water use efficiency of annual crops in rain fed farming systems of West Asia and Northern Africa. *Experimental Agriculture 23:113-158*

Dalal, R.C. 1974. Effects of intercropping maize with pigeonpea on grain yield and nutrient uptake. *Experimental Agriculture* 10 219-224

Danso, S.K.A., Zapata, F. and Hardarson, G. 1987 Nitrogen fixation in faba beans as affected by plant population density in sole or intercropped systems with barley *Soil Biological Biochemistry* 19: 411-415.

Dart P.J. and Krantz, 1976. Legumes in semi-arid tropics. In *Exploring the legume-rhizobium symbiosis in Tropical Agriculture* (Eds. J.M. Vincent, A.S. Whitney and A J Bose) pp 119-154 University of Hawaii

Eagles, C.F. 1984. Efficiency of solar energy conversions. In: *Crop Physiology,* Advancing Frontiers (Ed U S Gupta), Oxford and IBH Publishing Co. New Delhi

Ennin, S.A., Clegg, M.D and Francis C.A. 2002. Resource Utilisation in soyabean/maize intercrops. *African Crop Science Journal. Vol. 10 No.3 pp 251-261*

Evans, L.T. 1993. Increased in yield Trends and limit In: Evolution, adaptation and yield

Fujita, K., Ofosu-Budu, K.G. and Ogata, S. 1992. Biological nitrogen fixation in mixed legumes cereal-cropping systems *Plant and Soil 141: 155-175.*

Garba, M. and Renard, C. 1991. Biomass production, yields and water use efficiency in some pearl millet/ legume cropping system at Sador'e, Niger *In Soil water balances in the Sudano-Sahelian **Zone*** (Eds M.V.K.Sivakumar, J.S Wallace, C Renard and C Giroux) Proceeding of the Niamey Workshop, February 1991 pp 431-439

Giller, K.E. 2001. Nitrogen fixation in tropical cropping systems Second Edition CAB International, Wallingford, Oxon Ox 10 8 DE United Kingdom

Giller, K.E., Cadisch, G., Ehaliotis, C., Sakala, W.D. and Mafongoya, P.L. 1997. Building soil nitrogen capital in Africa In ***Production*** *Replenishing soil fertility in Africa* (Eds. Buresh, R.J., Sanchez, P A and Calhoun, F.J.). *Soil Science Society of America Special Publication* No 51 pp 155-192

Gregory, P.J. and Reddy, M. S. 1982. Root growth in an intercrop of pearl millet-groundnut *Field Crops Research 5: 241-252.*

Hamel, C., Barrantes-Cartin, U., Furlan, V. and Smith, D.L. 1991. Endomycorrhizal fungi in nitrogen transfer from soybean to maize *Plant Soil 138:33-40*

Hardter, R. and Horst, W. J. 1991 Nitrogen and phosphorus use in maize sole cropping and maize/cowpea mixed cropping systems on an alfisol in the northern Guinea Savanna of Ghana *Biological Fertility Soils*, 10: 267-275.

Hardter, R., Horst, W.J., Schmidt, G. and Frey, E. 1991. Yields and land use efficiency of maize-cowpea crop rotation in comparison to mixed and monocropping on an alfisol in Northern Ghana *Journal* of *Agronomy and Crop Science 166: 326-337.*

Henzell, E.F. and Vallis L, 1977. Transfer of nitrogen between legumes and other crops In Biological Nitrogen Fixation in farming Systems of the Tropics (Eds. A. Ayanaba and, P.J. Dart) pp 73-88.

Hoosbeek, M.R. 1998 Incorporating scale into spatio-temporal variability applications to soil quality and yield data *Geoderma 85: 113-131.*

International Crops Research Institute for Semi-arid Tropics (ICRISAT), 1990. Annual report Patancheru, Andhra Pradesh 502-325 India.

International Crops Research Institute for Semi-arid Tropics (ICRISAT), 1995. Annual report, Southern and Eastern Africa region pp 13-14.

Johansen, C. 1990. Pigeonpea Mineral nutrition In *The pigeonpea* (Eds Y.L. Nene, S D Hall and V K Sheila) pp 209-231 CAB International, Wallingford, Oxon Ox 10 8 DE United Kingdom

Kapkayai., J.J., Karanja, N., Woomer, P.L. and Qureshi, J.N. 1998 Soil organic carbon fractions in a long-term experiment and the potential for their use as a diagnostic assay in the highland farming systems of central Kenya. *Africa Crop Science Journal, 6: 19-28*

Kimani, P.M., Omanga, P.A. and Silim, S.N. 1994. Status of pigeonpea research in Kenya, and future prospects. In *Improvement of pigeonpea in Eastern and Southern Africa. Annual research planning meeting,* 25-27 July 1993, Bulawayo, Zimbabwe (Eds. S.A.Silim, S. Tuwafe and Laxman Singh) ICRISAT India. pp 37-44

Kumar Rao, J .D. K. 1990. Pigeonpea: Nitrogen fixation. In: *The Pigeonpea* (Eds Y.L. Nene, S.D. Hall and V.K. Sheila). pp 233-256. CAB International Wallingford, Oxon Ox 10 8 DE United Kingdom

Kumar Rao, J.V.D.K., Dart, P.J., and Sastry, P.V.S.S. 1983. Residual effect of pigeonpea on yield and nitrogen response of maize. Experimental Agriculture 19: 131-141

Kumar Rao, J.V.D.K., Dart, P.J., Matsumoto, T. and Day, J.M. 1981. Nitrogen fixation by pigeonpea. In *Proceedings of the International workshop on pigeonpea,* 15-19 Dec 1980. ICRISAT center, India. pp 190-199.

Kumar Rao, J.V.D.K., Johansen, C., Yoneyama, T., Tobita, S. and Ito, O. 1996. Estimation of nitrogen fixation by natural ^{15}N abundance technique and nitrogen uptake by pigeonpea genotypes of different maturity groups grown in an Inceptisol. *Journal of Agronomy and Crop Science 177: 129-138*

Lawn, R.J and Troedson, R. J. 1990. Pigeonpea: Physiology and yield formation. In: *The Pigeonpea* (Eds.Y.L. Nene, S.D. Hall and V.K Sheila). pp 179-208. CAB International. Wallingford, Oxon Ox 10 8 DE United Kingdom

Laxman Singh. 1991. Aspects of pigeonpea and future prospects. In *Uses of Tropical Grain legumes.* Proceedings of Consultant meetings (27-30 March 1989). ICRISAT Center India. pp 121-127

Martin, M P.L.D. and Synadon, R.W. 1982. Root and shoot interactions between barley and field beans when intercropped. *Journal of Applied Ecology 19: 263-272.*

Mburu, M.W.K. 1996. The effect of irrigation, fertilizer nitrogen and planting density on bean (*Phaseolus vulgaris*) yield under different weather conditions. PhD Thesis. University of Reading, United Kingdom

Ministry of Agriculture (MOA), 2002. Field Crops Technical Hand Book.

Monteith, J.L. 1969. Light interception and radioactive exchange in crop stands. In: *Physiological aspects of crop yield (Eds.* J. D. Easton, F.A. Haskins, and C.H.M Van Bavel) *American Society of Agronomy, Crop Science Society of America, pp 89-111*

Monteith, J.L. 1973. *Principles of Environmental physcis.* Edward Arnold, London.

Monteith, J.L. 1977. Climate and the efficiency of crop production in Britain. *Physiological Transaction of the Royal Society* of *London* 281: 277-294

Morris, R.A. and Garrity, D.P. 1993. Resource capture and utilization in intercropping: non-nitrogen nutrients. *Field Crops Research 34: 319-334*

Muthoka, D.K. 1994. Pigeonpea improvement in Kenya. In: *Improvement of pigeonpea in Eastern Africa.* Annual research planning meeting 1994, Nairobi, Kenya 21-23 Sept 1994 (Eds. S.N. Silim, S. Tuwafe and S.B. King) ICRISAT India.

Nair, K.P.P., Patel, U.K., Singh, R.P. and Kaushik, M.K. 1979. Evaluation of legume intercropping in conservation of fertilizer nitrogen in maize culture. *Journal of Agricultural Science (Cambridge) 93: 189-194.*

Natarajan, M. and Willey, R.W. 1980. Sorghum- pigeonpea intercropping and the effects of plant population density II. Resource use. *Journal of Agricultural science, Cambridge 95: 59-65*

Nderitu, C.G. 1994. Welcome address. In: *Improvement of pigeonpea in Eastern and Southern Africa.* Annual research planning meeting 1994. Nairobi, Kenya 21-23 Sept 1994 (Eds. S.N.Silim, S.Tuwafe and S.B. King) ICRISAT, Nairobi, Kenya.

Nene, Y.L., Hall, S.D. and Sheila, V.K. 1990. The Pigeonpea. Wallingford, Oxon, UK.CAB International 1990.

Noble, P.S., Forseth, I.N. and Long, S.P. 1993. Canopy structure and light interaction. *Photosynthesis and production in a changing environment; A field and laboratory manual (Eds.* D.O Hall., J. M.O. Scurlock, H.R. Bolhar-Norden-Kampf, R.C. Leegood and S.P. Long.) pp 79-90. Chapman and Hall, UNEP

Norman, J.M. and Campbell, G.S. 1989. Canopy structure and light interaction. In: *Physiological ecology. Field methods and instrumentation.* (Eds. R.W. Pearcy, J.R. Enhleringer, H.A. Mooney and P.W. Rundell) *pp 301-325.*

Ofori, F. and Stern, W.R. 1987. Cereal-legume intercropping systems *Advances in Agronomy 41:41-90*

Ofori, F., Pate, J.S. and Stern, W.R. 1987 Evaluation of N_2-fixation and nitrogen economy of a maize/cowpea intercrop system using ^{15}N dilution methods *Plant and Soil 102: 149-160.*

Okalebo, J.R., Gathua, K.W. and Woomer.P.L. 2002. Laboratory Methods of Soil and Plant Analysis. A working manual Second Edition pp 29-36 Moi University, Kenya

Omanga, P.A., Silim, S.N., Singh, L. and Kimani, P.M. 1994 Multilocational testing and on-farm trials to growing pigeonpea on farmers' fields In Improvement of pigeonpea in Eastern and Southern Africa. Annual research planning meeting 1994 Nairobi, Kenya 21-23, Sept 1994 (Eds S A Silim, S Tuwafe and S B King) ICRISAT, India pp 23-29

Onim, J.F.M. 1984. On farm testing of improved pigeonpea (*Cajanus cajan*) cultivars in Kenya. In *Crops improvement in Eastern and Southern Africa.* Research objectives and on-farm research A region workshop held in Nairobi, Kenya 20-23 July 1983. (Eds R A Lirkby. Ottawa, Canada) pp 122.

Pilbeam, C.J., Wood, M. and Mugane, P.G. 1995. Nitrogen use in maize –grain legume, cropping systems in semi-and Kenya. *Biological fertility soils* 20:57-62

Rao, M.R. and Willey, R.W. 1981. Stability performance of pigeonpea/sorghum intercrop system. In: *proceedings of the International Workshop of intercropping*, 10-13 January, 1979. ICRISAT, Hyderadad, India pp 306-317

Reddy, L.J. 1990. Pigeonpea morphology In: *The Pigeonpea* (Eds Y L.Nene, S.D Hall and V K.Sheila). CAB International. 3 pp 47-87

Reeves, M. 1992. The role of VAM fungi in nitrogen dynamics in maize-bean intercrops. Plant Soil, 144: 85-92

Sakala, W.D., Cadisch, G. and Giller , K.E. 2001. Productivity, N_2 fixation and N balances in

Sanchez, P.A., Shephered, K.D., Soule, M.J., Place, F. M., Buresh, R.J. and Izac, A.M.N. 1997. Soil fertility replenishment in Africa An investment in natural resource capital In: *Replenishing soil fertility in Africa* (Eds R.J. Buresh, P A Sanchez and F. Calhoun) SSSA special publication 51 1-46 Madison, USA.

Scott, W., Pleasant, J., Burt, R.F and Otis, D.J. 1987. Contribution of ground cover, dry matter and nitrogen from intercrops and cover crops in a corn polyculture system. *Agronomy Journal* 79 792-798.

Searle, P.G.E., Comudom, Y., Sheddon, D.C and Nance, R.A., 1981. Effects of maize + legume intercropping systems and fertilizer nitrogen on crop yields and residual nitrogen. *Fields Crops Research 4 133-145*

Selles, F., Karamanos, R.E., Kachanoski, R.G. 1986 The spartial variability of Nitrogen –15 and its relation to the variability of other soil properties. *Soil Science Society of America Journa*l *50: 105-110.*

Shackel, K.A. and Hall, A.E. 1984. Effects of intercropping on the water relations of sorghum and cowpea. *Field crops research 8:381-387.*

Sheldrake, A.R. and Narayanan, A. 1979 Growth, development, and nutrient uptake in pigeonpea *(Cajanus cajan*) *Journal of Agricultural Science 92: 513-526.*

Silim, S. N., Kimani, P.M. and Omanga, P.A. 1995. Use of Kenya transect for selecting and targeting adapted cultivars to appropriate production systems. In: Improvement of pigeonpea in Eastern and Southern Africa. Annual research planning meeting 1994 Nairobi, Kenya 21-23, Sept 1994. (Eds S A Silim, S Tuwafe and S B King) ICRISAT India pp 44-54

Singh, N.B., Singh, P.P and Nair, K.P.P.1986. Effects of legumes intercropping on enrichment of soil nitrogen, bacterial activity and productivity of associated maize crops *Explemental Agriculture 22:339-344*

Singh, S.P. 1979. Interplanting studies in sorghum In Proceeding of the International Workshop on intercropping, Hyderdad, India, ICRISAT, (10th-13th January, 1979).

Sinoquent, H. and Caldwell, 1995. Estimation of light capture and partitioning in intercropping system In *Ecophysiology of Tropical intercropping* (Eds H Sinoquet and P. Cruz) pp 77-98.

Sivakumar, M.V.K and Virmani, S.M. 1980. Growth and resource use of maize, pigeonpea and maize/pigeonpea intercrop in an operational research watershed. ***Experimental Agriculture 16: 377-386***

Snaydon, R.W. and Harris, P.M. 1981. Interaction below- round the use of nutrients and water. In *Proceedings of International workshop on intercropping pp 188-201* ICRISAT Centre, Hyderabad, 10-13 January, 1979 Hyderbad ICRISAT

Squire, G.R. 1992. The physiology of tropical crop production. C A B International for the Overseas Development Administration

Steel, R.G.D. and Torrie, J.H. 1980. Principles and procedures of Statistics A biometrics approach (McGraw-Hill: London)

Stigter, C.J. and Baldy, C. 1995 Manipulation of microclimate by intercropping making the best services rendered In: *Ecophysiology of Tropical Intercropping* (Eds H. Sinoquet and P. Cruz) pp 29-44

Ta, T.C. and Faris, M.A. 1988. Effects of environmental conditions on the fixation of the transfer of N from alfalfa to associated timothy. *Plant and Soil* 107:25-30.

Tekalign, T., Haque.I. and Aduayi, E.A, 1991 Soil, plant, water fertilizer, animal manure and compost analysis manual *Plant Science division working document* 13, ILCA. Addis Ababa, Ethiopia.

Tobita, S., Ito, O., Matsunaga, R., Rao, T.P., Rego, T.J., Johansen, C. and Yoneyama, T. 1994. Field evaluation of nitrogen fixation and N-fertilizer utilization by sorghum/pigeonpea intercropping on an Alfisol in Indian semi-arid tropics. *Biological Fertility Soils* 17: 171-183

Trenbath, B.P. 1976. Plant interaction in mixed communities. In: *Multiple Cropping.* Proceeding for a Symposium (Eds. R.I Papendick, P A. Sanchez and G B Triplett) pp 76-102. ASA, SSSA and SSSA, Madison WI

Van der Maesen, L. J.G. 1989. *Cajanus cajan* In *Plant resources of South East Asia* No 1 Pulses (Eds L.J G Van der Maesen and S Somaatmadja) Pudoc/Prosea, Wageningen, Netherlands pp 39-42

Van der Maesen, L.J.G 1990 Pigeonpea Origin, History, Evolution and Taxonomy In *The pigeonpea* (Eds Y L. Nene, S D. Hall and V K Sheila) CAB International pp 15-46

Van dermeer, J. 1989. *The ecology of intercropping.* Cambridge Universal press, Great Britain

Van dermeer, J. 1992. Intercropping and Agroforestry a perspective from ecological theory In: *Ecological process in Agro-Ecosystems*. National Institute Agro-Environmental Science of Japan. Yokenda. Tokyo. *pp 205-224.*

Van Kessel, CH and Roskoski, J.P. 1988 Row spacing effects on N_2-fixation, N-yield and soil N uptake of intercropped cowpea and maize *Plant Soil* 111: 17-23

Van Kessel, CH., Singleton, P.W. and Hoben, H.J. 1991 Enhanced N- transfer from a soybean to maize vesicular arbuscular mycorrhizal (VAM) fungi *Plant Physiology* 79: 562-563.

Wacquant, J.P., Ouknider, M. and Jacquard, P. 1989. Evidence for a periodic excretion of nitrogen by roots of grass-legume associations *Plant Soil* 116: 57-68

Waddington, S.R. and Karigwindi, J. 2001 Productivity and profitability of maize and groundnut rotations when compared with continuous maize on smallholder farms in Zimbabwe *Experimental Agriculture. 37: 83-98*

Wahua, T.A.T. and Miller, D.A. 1978 Effects of intercropping on soybean N_2-fixation and plant composition of associated sorghum and soybeans. *Agronomy journal 70: 292-295.*

Wanderi, S.W. 2004 Light, water use in low inputh of maize (*Zea mays*) and Pigeonpea (*Cajans cajan*) intercop in warm conditions of Kenya. Msc Thesis University of Nairobi

Well, R.R. and Ohlrogge, A.J. 1972. The seasonal development of the effect of interplant competition on soybean nodules *Agronomy Abstract pp. 59.*

Willey, R.W. 1979 Intercropping It's importance and research needs, Part 1: Competition and yields advantages *Field Crops Abstract 32: 1-10.*

Willey, R.W. and Reddy, M.S. 1981. A field technique for separating above and below ground interactions in intercropping An experiment with pearl millet-groundnut *Experimental Agriculture 17:257-264*

Willey, R.W. and Reddy, M.S. 1981. A field technique for separating above and below ground interactions in intercropping an experiment with pearl millet/groundnut *Experimental Agriculture 17: 257-264*

Willey, R.W., Natarajan, M., Reddy, M.S and Rao, M.R. 1986 Cropping systems with groundnut Resource and productivity In: *Agrometeorology of groundnut* *pp193-205* Proceeding of an International Symposium, ICRISAT Sahelian Centre, Niamey, Niger. 21st - 26th August, 11985. Patancheru, India ICRISAT

Wong, M.F.T. and Nortcliff, S. 1995. Seasonal fluctuations of native available N and soil management implications *Fertility Research 42: 13-26.*

Yoneyama, T., Nambiar, P.T.C., Lee, K.K., Srinivasa, R.B. and Williams, J.H. 1990. Nitrogen accumulation in three legumes and two cereals with emphasis on estimation of N_2 fixation in the legumes by natural ^{15}N – abundance techniques. *Biological Fertility Soils 9: 25-30.*

Yoshida, S. 1972 Physiology of grain yield *Annual Review of Plant Physiology 23:437-464*

APPENDICES

Appendix 1 Analysis of variance table showing mean sum of squares for maize plant height

Season	Source of Variation	Degree of freedom	Days after planting (DAP) of pigeonpea			
1			54	82	110	149
	Block	5	63.02	970.7	240.5	56.7
	Treatment	3	13.26	1175.8	958.7	131.7
	Error	15	89.21	795.8	368.7	437.4
	Total	23				
2						
	Block	5	76.98	142.3	256.1	160.1
	Treatment	3	65.76	225.6	493.4	19.5
	Error	15	46.10	252.0	420.3	279.6
	Total	23				

NB There was no significant difference observed among the treatments

Appendix 2 Analysis of variance table showing mean sum of squares for pigeonpea plant height

Source of variation	df	Days after planting (DAP) of pigeonpea							
		54	82	110	147	248	262	276	318
Block	5	14.058	1601	232.17	66.28	405.31	171.7	193.8	53.4
Treatment	5	13.828*	2040	130.70*	473.2**	197.7	868.2**	424.1*	700.2*
Error	25	3.572	1647	34.27	35.03	80.86	121.7	113.3	154.6
Total	35								

*- Significant at $p < 0.05$ ** - significant at $p < 0.001$

Appendix 3 Analysis of variance table showing mean sum of squares for maize total dry matter

Season	Source of Variation	Degree of freedom	Days after planting (DAP) of pigeonpea			
1			54	82	110	147
	Block	5	254 6	18909	13631	52180
	Treatment	3	242 61	6639	30091	70636
	Error	15	311.7	9178	15668	56799
	Total	23				
2						
	Block	5	221 6	2680	35435	91915
	Treatment	3	41.3	2676	36983	192754
	Error	15	282 5	1812	15164	171031
	Total	23				

NB There was no significant difference observed among the treatments.

Appendix 4. Analysis of variance table showing mean sum of squares for pigeonpea total dry matter

Source of variation	df	Days after planting (DAP) of pigeonpea							
		54	82	110	147	248	262	318	339
Block	5	3 744	32 66	322 66	1563.7	590 5	3253.8	2803	72467
Treatment	5	1.8349*	34.52	333 26*	4647.7**	729.8	2525 3*	17320*	161364**
Error	25	0.4596	21.35	70.73	735.9	574.1	781.7	4275	27157
Total	35								

*- Significant at $p < 0.05$ **- significant at $p < 0\ 001$

Appendix 5 Analysis of variance table showing mean sum of squares for Crop growth rate (CGR).

Source of Variation	Degree of freedom	Days after planting			
		54-68	82-147	278-318	318-339
Blocks	5	8.253	1.3	12.01	219.3
Treatment	9	459.018**	464.622**	267.51**	515.3
Error	45	7.681	5.299	19.93	2490
Total	59				

** Significant at $p < 0.001$

Appendix 6. Analysis of variance table showing mean sum of squares for maize dry matter partitioning

Source of Variation	df	Cob	Stover	Grain	Harvest Index	TDM
Season 1						
Blocks	5	28775	2719004	310165	0.002899	394063
Treatment	3	196091	7199737*	3802325	0.000826	27874987*
Error	15	59750	1524027	127446	0.002282	5545161
Total	23					
Season 2						
Blocks	5	135323	799344	1128831	0.003078	3766800
Treatment	3	67125	2408494	2402746	0.009500	5205451
Error	15	84908	2660847	1874047	0.004796	7178334
Total	23					

Appendix 7 Analysis of variance table showing mean sum of squares for pigeonpea dry matter partitioning.

Source of Variation	Df	Grain	Husks	Stem	Total dry matter	Harvest Index
Blocks	3	1627	77306	1367725	2001246	0.002945
Treatment	5	1194121**	959934**	8338183*	29942499**	0.027780**
Error	15	48087	61528	856526	1040904	0.002667
Total	23					

** - Significant at $p < 0.001$ and * at $p < 0.05$

Appendix 8 Analysis of variance table showing mean sum of squares for % PAR interception

Source of variation	df	Days after planting (DAP) of pigeonpea									
		76	102	117	146	179	207	235	263	291	345
Block	3	0.65	286.32	167.70	80.14	51.78	1165	126.67	170.47	99.2	37.11
Treatment	5	88.83	323.92	317.80	138.89	135.73	1185	65.12	119.17	42.1	332.60
Error	15	63.91	71.63	84.05	61.92	40.96	1411	72.80	45.22	119.1	85.45
Total	23										

Appendix 9 Analysis of variance table showing mean sum of squares for soil water status in the 0- 110 cm profile

Source of variation	df	Days after planting (DAP) of pigeonpea									
		54	82	110	138	196	237	265	290	305	345
Block	5	38.71	17.78	8.011	60.95	71.64	109.32	91.74	45.62	294.13	780.4
Treatment	6	1257.38	1828.61	1775.996	545.53	429.067	214.89	1277.85	1386.94	307.55	1976.5
Error	30	45.72	11.59	6.508	21.88	9.947	20.85	24.21	73.00	73.40	384.1
Total	41										

Appendix 10. Analysis of variance table showing mean sum of squares for water extraction pattern down the soil profile

DAP	Source of variation	d f	Depth in cm						
			10	20	30	50	70	90	110
146 DAP	Block	3	3.145	0.075	3.776	1.084	1.745	6.226	4.508
	Treatment	5	3.565	0.499	3.400	4.962	2.669	7.780	11.875
	Error	15	3.486	4.896	1.718	3.909	3,283	2.050	3.021
	Total	23							
193 DAP	Block	3	20.908	25.591	3.691	2.564	1.840	5.292	7.189
	Treatment	4	6.295	5.172	3.031	0.347	3.44	2.826	4.392
	Error	12	5.095	9.486	1.428	4.271	1.240	1.214	2.533
	Total	19							
263 DAP	Block	3	2.86	12.521	9.326	3.330		8.828	4.579
	Treatment	5	1.93	7.196	11.727	6.016		1.388	2.135
	Error	15	12.14	6.122	2.987	3.139		2.992	3.083
	Total	23							
319 DAP	Block	3	54.38	18.689	1.936	0.893	0.220	2.314	1.053
	Treatment	5	3,47	10.790	7.067	2.519	1.950	0.198	2.682
	Error	15	11.01	4.519	2.782	5.028	1.605	4.917	2.328
	Total	23							

Appendix 11 Analysis of variance table showing mean sum of squares for cumulative evapotranspiration (mm) during crop growing period

Source of variation	df	Days after planting (DAP) of pigeonpea									
		76	102	117	146	179	207	235	263	291	345
Block	3	22.8	609.1	393.2	227.8	192.3	321.9	256.8	339.2	244.6	189.1
Treatment	5	316.6	752.1	803.3	417.1*	717.6	843.3	141050.6	131096.2	132985.4	145034.5
Error	15	183.9	137.0	186.3	151.5	322.2	243.3	493.4	699.7	648.9	402.2
Total	23										

Appendix 12 Analysis of variance table showing mean sum of squares for total grain yield, land equivalent ratio (LER) and final cumulative evapotranspiration (mm) during crop growing period

Source of variation	df	Total grain Yield	LER	Final Cum ET
Block	3	250697	0.023866	56.3
Treatment	5	79614797**	0.000973	32830.5**
Error	15	575966	0.009688	451.1
Total	23			

** - Significant at $p< 0.001$ and * is significant at $p < 0.05$

Appendix 13 Analysis of variance table showing mean sum of squares for Ammonium nitrogen at 0- 120 cm soil profile

DAP	Source of variation	d f	Depth			
			0-20 cm	20-40 cm	40-60 cm	60-120 cm
172	Blocks	2	1239.5	1529.33	442.7	4203.3
	Treatment	6	100.2	119.39	241.2	1705.8
	Error	12	108.2	91.19	295.6	824.2
	Total	20				
349	Blocks	2	763.9	264.3	204.2	2921
	Treatment	6	832.3*	240.6*	234.1	2339
	Error	12	360.9	133.3	826.1	2369
	Total	20				

* = Significant at $p < 0.05$

Appendix 14. Analysis of variance table showing mean sum of squares for Nitrates nitrogen at 0- 120 cm soil profile

DAP	Source of variation	d f	Depth			
			0-20 cm	20-40 cm	40-60 cm	60-120 cm
172	Blocks	2	139 41	124.0	161 28	1498 6
	Treatment	6	145 82*	54.1	150 10	1019.2
	Error	12	60.10	102.5	68.62	693.1
	Total	20				
349	Blocks	2	40.2	75.5	362 3	1026
	Treatment	6	232.2	246 9*	103 3	2728
	Error	12	252 3	120.9	230 4	1398
	Total	20				

Significant at $p < 0.05$