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# THE EFFECTS OF IRRIGATION, FERTILIZER NITROGEN AND PLANTING DENSITY ON BEAN (*Phaseolus vulgaris*) YIELD UNDER DIFFERENT WEATHER CONDITIONS

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# ABSTRACT

## The effects irrigation, fertilizer nitrogen and planting density on bean (*Phaseolus vulgaris*) yield under different weather conditions

The common bean (*Phaseolus vulgaris*) is an important food for many people in Latin America and Africa. However, bean yields are low because of the droughty and limited nitrogen supply conditions prevalent in the minimum input bean production systems in these areas. The objectives of this work were: a) to identify the mechanisms by which water and nitrogen influence bean yield; b) to determine how the application of water and nitrogen interact with weather factors to influence bean yields under various climatic conditions; c) to identify possible management strategies to increase bean yield by improving the efficiency of water use by the crop. Three field experiments were conducted; one at Sonning (Britain) and two at Kabete (Kenya) to determine the effect management and weather on bean yield. The management strategies to improve bean yield included irrigation, fertilizer nitrogen application and altering planting density.

Bean total dry matter and seed yield were highest at Sonning and lowest at Kabete in the dry season. The differences in the amount of total dry matter produced in the three experiments were attributed to differences in LAI, leaf area duration of the canopy and the total amount of solar radiation intercepted. High planting density was the most effective factor in increasing LAI if water and nitrogen were at levels that did not limit leaf growth. Nitrogen fertilizer effect on LAI was primarily through increased leaf emergence and extension rate. High temperature influenced the rate of crop development.

Total plant nitrogen uptake and utilisation depended on plant growth stage, soil water and nitrogen supply. Low crop growth rates due to limited soil water supply resulted in reduced fertilizer nitrogen recovery in the crop.

There appeared to be only a limited extent to which intensifying crop production through the use of fertiliser nitrogen and increasing plant density could influence the partitioning between transpiration and soil evaporation. The microlysimetry measurements showed that, on average, measured rates of evaporation from the soil surface beneath a crop were only 20% slower than from bare soil. High planting density reduced soil evaporation for a maximum of 2 days when evaporation was supply limited.

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**TO HIM WHO IS ABLE TO DO EXCEEDINGLY ABUNDANTLY ABOVE ALL THAT WE ASK OR THINK**

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# Chapter 1

## Overview

### 1.0 Introduction

The common bean (*Phaseolus vulgaris*) is the principal food for more than 500 million people in Latin America and Africa, and for more than 20% of these people, it is the leading source of dietary protein (FAO, 1984). However bean yields are lower than those of the common cereals such as wheat (table 1.1).

Table 1.1 Average seed yields of some important food crops of the world in different continents (t $ha^{-1}$)

| Crop | Africa | South America | North America | Asia | Europe | World |
|---|---|---|---|---|---|---|
| Wheat | 1.7 | 1.7 | 1.9 | 1.7 | 4.4 | 2.3 |
| Maize | 1.5 | 2.1 | 5.3 | 2.8 | 5.7 | 3.2 |
| Soybeans | 1.1 | 1.9 | 1.8 | 1.3 | 2.3 | 1.7 |
| Dry beans | 0.7 | 0.5 | 1.6 | 0.5 | 0.6 | 0.6 |

Source: Fageria (1992).

In general, legumes have lower seed yield than cereals due to physiological and environmental factors. The physiological processes that reduce seed yield in legumes include photorespiration, diversion of carbohydrates to support symbiotic nitrogen fixation and high energy cost for protein and oil production (Fageria, 1992). About 30% of legume photosynthates are consumed in photorespiration while the N fixation accounts for 10% reduction in potential seed yield (Fageria, 1992). In addition to the above physiological processes, the factors that also reduce seed yield in legumes include nitrogen deficiency and water deficits. For example, most of the soils where beans are grown are low in available N (CIAT, 1988) and nitrogen fixation is inadequate to fully compensate for the N deficiency (CIAT, 1987). Approximately 60% of the bean producing areas of the world experience moisture deficits during the growing season (White and Singh, 1991). Irrigation is used in few areas to alleviate water stress effects but water shortages and high irrigation costs prevent irrigation at rates required to eliminate stress.

## 1.2 Bean production in Kenya

Legumes are an important source of protein for the Kenyans. They rank third in the per capita consumption after maize and milk (Kenya Development Plan, 1989-1993). The leading legume in both production and consumption is the common bean (*Phaseolus vulgaris*) with an annual per capita consumption of 21 kg (Martis, 1989). In addition to their importance as a staple food crop, beans are an important export crop (snap beans). In 1990, snap beans comprised 33% by volume and 25% by value of Kenyan horticultural export (Horticultural Crops Development Authority report, 1990).

## 1.3 Kenyan Climate

Kenya is predominantly arid to semi-arid, with about 80% of the country receiving less than 750 mm rain per year. The rainfall is erratic in distribution and unreliable in the total amount received in any given season. A season's rain may fall in a few days at intensities that exceed the rate of infiltration, resulting in run-off. The rest of the rain falls in light intensities, barely penetrating the surface and is predominantly lost through direct evaporation from the soil surface (Fenner, 1982). In a growing season, rainfall events are usually interspersed with dry spells, and this results in crops experiencing water stress to varying degrees; Kenya agricultural production is primarily rainfed. In this context, water stress is defined as plant water deficit that is sufficient to disturb the internal physiological processes (Kramer, 1983).

Bean production in Kenya extends from high potential areas receiving more than 1000 mm rainfall to lower potential areas receiving less than 750 mm rainfall. Production is mainly by small scale farmers. The beans are generally rainfed and intercropped (usually with maize) and with little or no fertilizer application. The low input levels explain the low seed yields. The national bean yields average between 600 and 800 kg/ha (Martis, 1989; Muigai and Ndegwa, 1991).

Nitrogen fertilizer trials on farmers fields in some key bean growing districts in Kenya demonstrated widespread increase in seed yield in response to fertilizer N application (table 1.2). The magnitude of the response was inversely related to the average percent soil N content in each site, indicating bean seed yield are limited by the soil N supply (table 1.2). However, cases of non response of bean yield to N fertilizer application also have been reported (Pilbeam *et al.*, 1995a; Qureshi, 1991).

Table 1.2 Bean yield response to fertilizer N application in Kenya.

| District/Area | Dominant soil type | Response to N (kg beans/kg N) | Average % N in soil |
|---|---|---|---|
| Thika | Nitosol | 9.0 | 0.16 |
| Machakos | Acrisol | 7.5 | 0.10 |
| Hamisi/Vihiga | Acrisol | 7.3 | 0.17 |
| Embu | Ferrasol | 4.8 | 0.20 |
| Ikolomani | Ferasol | 3.0 | 0.22 |
| Kisii | Nitosol | 1.9 | 0.26 |

Source: Muigai and Ndegwa (1991)

Higher bean yields than the national average (i.e. 1500 - 2400 kg/ha) have been attained with a combination of irrigation and 18 kg N fertilizer ha$^{-1}$ (Coulson, 1984; Stewart and Faught, 1984). From those experiments, the crop nitrogen response was 50 kg bean ha$^{-1}$ per kg N fertilizer (i.e. very much greater than response reported in table 1.2 where fertilised crops were unirrigated). The current average bean yield represents a likely nitrogen carry off of approximately 25 kg/ha (assuming 4% nitrogen in the seed and a small allowance for foliage). The yield of the fertilised and irrigated crops imply a carry off of 60 to 96 kg N ha$^{-1}$. The extra nitrogen in the later experiments (17 to 50 kg N ha$^{-1}$) may have come from $N_2$ fixation and/or increased fertilizer N uptake due to irrigation application. Ssali and Keya, (1986) working at Kabete where Coulson (1984) conducted his experiments reported that beans fixed between 0 and 90 kg N ha$^{-1}$. On the contrary, cases of very low or non-fixation have also been reported at Katumani where Stewart and Faught (1984) did their work (Chui and Nadar, 1984; Karanja, 1988).

Nitrogen fertilizer is expensive and biological nitrogen fixation is a cheap way of increasing N available for bean growth. *Phaseolus vulgaris* is known to be a poor fixer of N compared with other legumes (Piha and Munns, 1987). In Kenya, the amount of $N_2$ fixed by beans is quite variable (0 to 130 kg N ha$^{-1}$, Ssali and Keya, 1986; Karanja, 1988; Pilbeam *et al.*, 1995a). The other option of supplying bean N needs is through fertilizer N application. However cases of negligible response of bean yield to fertilizer application are often reported (Pilbeam *et al.*, 1995a; Qureshi, 1991). Ramig and Rhoades (1962) demonstrated that wheat response to applied N was influenced strongly by available soil water. High N supplies through rapid mineralization of soil N at the beginning of the season have also been implied for low fertilizer uptake (Pilbeam *et al.*, 1993). However, soil mineral N concentrations in the growing season were not reported in that work. This indicates that the quantity of soil N may not have been limiting directly, but rather that its use by the crop was limited by aspects of the soil water supply. In the semi arid parts of Kenya, most of the rainfall (at least 70%) in the bean plots was lost through direct evaporation from the soil surface with the unfortunate characteristic that the fraction of water transpired decreased in seasons with low rainfall (Pilbeam *et al.*, 1995b). This indicates that there is potentially a scope for increasing bean production by increasing the proportion of rainfall used for crop production. From the above observations, it is evident that the amount of rainfall *per se* is not the limiting factor to bean yield, but rather it is used inefficiently. Consequently, inefficient use of water influences crop nitrogen use. The key question addressed by this thesis is:

> **How does the nitrogen supply interact with crop water and water use efficiency, thereby influencing bean productivity?**

The next chapter considers some aspects of this question.

i) The mechanisms by which water and nitrogen influence bean yield.
ii) how the application of water and nitrogen interact with weather factors to influence bean yields under various climatic conditions.
iii) the identification of possible management strategies to increase bean yield by improving the efficiency of water use by the crop.

These challenges are addressed in chapter 2.

# Chapter 2

## Literature review

### 2.1 Introduction

Water is a major constituent of plant tissue, a solvent in which plant solutes including mineral nutrients are transported, a reactant in processes like photosynthesis and hydrolysis, is essential for maintenance of tissue turgidity and regulation of leaf temperature (Kramer 1983). On a worldwide scale, water is the most important factor limiting crop yield (Begg and Turner, 1976). Crop productivity has been expressed on the basis of the dry matter produce per unit of water evaporated from a unit of land area. The productivity depends on the partitioning of water inputs between unproductive losses of water (i.e through direct evaporation from the soil, runoff, drainage and uptake by weeds) and water used for dry matter production (i.e transpiration) in a cropping system. When supplies of water are adequate, nitrogen is commonly the most limiting nutrient.

Nitrogen is a constituent of nucleic acids and proteins and comprises 1.5 to 5% of the dry weight of plants. Nitrogen can leave the soil-plant system by more routes than any other nutrient and consequently often limits agricultural production. The amount of N available for plant uptake depends on the balance between gains to and losses from the soil-plant system. The gains include incorporation of soil organic matter the mineral N from the net mineralization of soil organic N, fixation of N by symbiotic and free-living bacteria, N from industrial pollutants, rain or irrigation water and application as fertilizer, while the losses include volatilization, denitrification, run-off and leaching (Vlek *et al.*, 1981). The factors that influence plant N uptake rates include N concentration in soil solution, amount of soil water, size and distribution of the root system, root temperature and photosynthate availability to the roots for active N uptake (Haynes, 1986).

Water and nitrogen supply influence dry matter production. The rate of dry matter production involves reduction of atmospheric carbon dioxide acquired through the stomata. An inevitable consequence of photosynthesis is transpiration; when there is sufficient soil water the photosynthetic rate largely determines transpiration rate and the converse is true. Solar radiation influences both photosynthesis and transpiration, though via very different mechanisms. The rate of transpiration depends on the amount of energy available to evaporate water from the leaves.

### 2.1.1 Crop water use and dry matter production.

There is substantial experimental evidence showing that dry matter production is a predictable function of transpired water (Hanks, 1983). In conditions of ample soil water supply, the potential transpiration and photosynthesis are both attained (de Vries *et al.*, 1989). However most agricultural production systems of the world are characterised by limited water supply through part or all of the season. The relationship between crop yield (total dry matter) and water supply may be expressed as (Bolton, 1981):

$$WUE = \frac{Y}{ET} \qquad 2.1$$

where WUE is water use efficiency (kg $ha^{-1}$ $mm^{-1}$), Y is total dry matter yield in kg

$ha^{-1}$ and ET is evapotranspiration (mm). ET represents the amount of water lost through both evaporation from the soil beneath the crop canopy and transpiration in a season expressed as:

$$ET = T + E_s \qquad 2.2$$

where $E_s$ is evaporation from soil beneath the crop canopy (mm) and T is transpiration (mm).

It is difficult to determine accurately crop transpiration under field conditions and therefore most research has tended to describe water use efficiency on the basis of ET which can, with assumption, be deduced from changes in the water content of the profile. Water use efficiencies for a given crop based on ET can be quite variable depending on location, season and management practices (Ritchie, 1983). Much of the variability may be explained by the ratio of transpiration to direct evaporation from the soil.

Cooper (1983) provided an empirical based on equation 2.1 that helps analyze the impact of the partitioning $E_s$ and T on dry matter production:

$$WUE = \frac{Y/T}{1 + E_s/T} \qquad 2.3$$

Equation 2.3 highlights the components that can be improved to increase WUE. Crop management strategies that either reduce $E_s/T$ or increase Y/T will tend to increase water use efficiency. $E_s$ depends on the soil water supply, radiant energy at the soil surface and factors that influence vapour transfer between the soil and the atmosphere (Hillel, 1980; see section 2.2.3 for details).

There is evidence that Y/T standardised by the saturation vapour pressure deficit (SD) for a given species is constant irrespective of site (Cooper *et al.*, 1983; Cooper *et al.*, 1987; Walker, 1986; Yunusa *et al*, 1993a). Tanner and Sinclair (1983) noted that standardising Y/T with average value of SD for the daylight hours (when transpiration is occurring) removes the variation due to daylength. For example, Singh and Virmani (1990) found WUE values (on the basis of total dry matter) for chickpea based on ET in two years were 13.5 and 19.0 kg $ha^{-1}$ $mm^{-1}$. Plotting dry matter production against ET normalised by the SD between 1200 and 1400 hours fitted the data into a single relationship (normalised WUE was 31.3 kg $ha^{-1}$ kPa $mm^{-1}$), thus removing seasonal yield variability due to variation in SD.

The relationship between crop yield, transpiration and SD may be expressed as:

$$Y = k\left[\frac{T}{(e_s - e_a)}\right] \qquad 2.4$$

where $e_s - e_a$ (SD) is the daily mean saturation vapour pressure deficit of the air weighted for the transpiration period and k is a crop specific constant. The conservative nature of k for a given crop has been explained by consideration of fluxes of water vapour and $CO_2$ at the leaf surface which are influenced by the crop photosynthetic pathway (Bierhuizen and Slayter, 1965); WUE is higher in $C_4$ than in $C_3$ plants presumably due to higher k values in the former (Gregory, 1988).

## 2.2 Crop management strategies for altering the balance between $E_s$ and T.

Crop management practices that increase T relative to $E_s$ are likely to increase WUE provided that any reduction in $E_s$ does not cause an increase in leaf temperature, and hence a decrease in the value of Y/T by raising the internal vapour pressure of the leaf. The largest $E_s$ occurs early in the growing season when a large proportion of the soil surface is exposed to direct radiation and crop water uptake is slow. Therefore rapid establishment of canopy (thereby increase leaf area index to shade the soil) and rapid development of a root system (to exploit the soil water) might increase T relative to $E_s$. The volume of soil water that is exploitable for crop transpiration is determined by the depth and density of the crop root system. Fertilizer N and row spacing are two management methods of manipulating the leaf area index of field grown crops (Cooper *et al.*, 1987). The effects of N fertilizer and planting density are reviewed below.

### 2.2.1 Nitrogen effect on WUE

Cooper *et al.*, (1983) found that N fertilizer increased WUE in both wheat and barley by increasing seasonal T and reducing $E_s$. This was attributed to shading of the soil surface. For barley, N fertilizer almost doubled LAI (3.8 in fertilized stands compared to 1.8 in non-fertilized treatment) and the values of $E_s$ at the time of maximum LAI were 0.3 and 0.5 mm day$^{-1}$ respectively. In the wheat experiment, $E_s$ was reduced to 0.15 mm day$^{-1}$ at LAI of 4.7 and 0.06 mm day$^{-1}$ at LAI 6.7 (fertilized treatments) and solar radiation interception at these LAI was almost complete. Fertilizer N increased T prior to anthesis, but lowered it in the post anthesis period because of greater soil moisture depletion. Cooper *et al.*, (1987) reported a 10% increase in total water use because of fertilizer N application.

Anderson (1992) working with wheat in Australia also found that WUE was improved by N fertilizer. One of the factors shifting the balance between T and $E_s$ is that applying N fertilizer will tend to increase the access of plants to soil water. For example, studies on root growth in barley have shown that fertilizer N increases water use due to increased extraction associated with greater root length densities and deeper penetration within the soil profile (Gregory *et al.*, 1984; Brown, *et al.*, 1987).

### 2.2.2 Planting density effect on WUE

The effect of plant population on WUE is similar in some respects to that of physically covering the ground to reduce evaporation from the soil surface. Ritchie and Burnett (1971) found that LAI was more related to transpiration than percentage ground cover or canopy dry weight. Adams and co-workers (1976) working with sorghum, demonstrated that $E_s$ from wet soil was reduced at narrow row spacings because of increased shading of the soil beneath the canopy. The highest LAI attained in these experiments was 4.3 and shaded 94% of the soil. However Yunusa *et al.*, (1993a) working with wheat in Western Australia found that planting density did not have a significant effect on $E_s$. Maximum LAI was 1.25 and intercepted less than 55% of the total incoming radiation (Yunusa *et al.*, 1993a and b). Yunusa and co-workers (1993a) noted that water supply rather than solar energy was limiting $E_s$ hence shading had little effect. They proposed that most of the soil water was taken up by the plant roots and so was not available for evaporation.

The discrepancy between Yunusa *et al.*, (1993a) and Adams *et al.*, (1976) results may be explained by the fact that the latter did short term evaporation measurements from wet soil surface whilst the former concentrated on seasonal $E_s$ under fairly dry weather conditions. Pilbeam *et al.*, (1995c) working with beans in semi arid Kenya did not find improvement in WUE in *Phaseolus vulgaris* L due to fertilizer N or planting density, probably due to low LAI (less than 2). In these experiments the soil surface was rarely wetted, and so the soil water supply was limiting direct evaporation from the soil surface.

## 2.3 Soil factors that influence WUE.

### 2.3.1 Soil water supply

The source of water is rainfall and irrigation while drainage, evaporation at soil surface and transpiration represent the losses. The balance between gains and losses is expressed as the soil water balance.

$$\Delta S = P - E_s - T - Dr - R_{off} \qquad 2.5$$

$\Delta S$ is change in storage (mm)

P is precipitation (rainfall and irrigation; mm)

$E_s$ is soil evaporation (mm)

T is transpiration (mm)

D is drainage (mm) and $R_{off}$ is run off (mm).

Evapotranspiration (soil evaporation and transpiration) can be measured by monitoring the changes in the water content of the soil profile.

In semi-arid environments with low rainfall, drainage is often assured to be negligible. However, in such environments substantial drainage losses can occur (For example Klaij and Vachaud, 1992 estimated that 37% of rainfall was lost as drainage) leading to overestimation of ET if drainage is ignored.

Separation of evaporation and transpiration is a difficult task. One approach of dealing with the problem is measuring evaporation using microlysimetry from beneath the crop canopy (Boast, 1986; Daamen, 1993). An alternative is to use changes in profile water content measured in bare soil plots next to the cropped plots to correct for drainage and evaporation losses in the course of the season but this makes the unreasonable assumption that the presence of a crop has no influence on $E_s$ or D. The sources of error in the soil water balance estimation of ET include estimating the amount of water applied through irrigation which can be very spatially variable, errors in soil water content measurement, spatial variation in soil water storage content, and unaccounted for drainage loss below the root zone. Simulation modelling has been widely with reasonable accuracy to circumvent some of these errors (Ritchie, 1972; Cooper *et al.*, 1983; Pilbeam *et al.*, 1995b).

### 2.3.2 Soil evaporation

For evaporation process to persist, a number of conditions must be fulfilled. A continuous supply of energy is required to meet the energy requirement for evaporation. A vapour pressure gradient between the soil and the atmosphere must exist (the water vapour is transported by diffusion or convection processes). Finally a continual supply of water through the soil to the surface or site of evaporation is required (Hillel, 1980). The supply of water to the evaporating surface depends on the soil water content, and the water retention and hydraulic conductivity characteristics, which collectively determine the ability of the soil to transmit water to the surface.

Evaporation from a soil can be divided into two stages (Hillel, 1980; Connor and Loomis, 1992).

i) An initial constant-rate stage (stage 1), which occurs while the soil is wet and conductive enough for water movement to meet the evaporative demand. The rate of evaporation rate is determined by the energy exchange at the soil surface and soil evaporation is of similar magnitude to potential evaporation. In a dry climate, this stage is brief and may last a few hours to a few days, depending on the soil texture and the evaporative demand.

ii) A falling-rate stage (stage 2) whereby evaporation rate falls progressively below potential evaporation rate. Soil evaporation is limited by the rate at which the drying soil profile can deliver moisture toward the evaporating surface (soil hydraulic properties).

There is evidence that first stage-drying from sandy soils under semi arid conditions is very short lived (Daamen, 1993); hence most of the evaporation under these conditions is second stage and is limited by water supply rather than energy supply. For bare soils, cumulative evaporation from a soil ($E_s$) in second stage drying is proportional to the square root of time (t) since rain (Black *et al.*, 1969; Ritchie, 1972)

$$\sum E_s = \alpha \sqrt{t} \qquad 2.6$$

where, $\alpha$ analogous to the soil sorptivity factor (that describes the effect of soil characteristics on evaporation and depends mainly soil hydraulic conductivity properties).

t is time (days after rain).

It is difficult to measure cumulative evaporation accurately over a long period to determine $\alpha$ from $\Sigma E_s$.

Although microlysimetry methods provide a simple way of measuring $E_s$, the "lifetime" of a microlysimeter is typically one day (Daamen *et al.*, 1995) and so cannot be used over much longer periods. Pilbeam *et al.*, (1995b) used a modified form of equation 2.6 to determine $\alpha$ to predict seasonal soil evaporation from a few measurements of soil evaporation in a drying cycle (days after rain).

$$E_j = \alpha (\sqrt{t_j} - \sqrt{t_{j-1}}) \qquad 2.7$$

where $E_j$ is the amount of evaporation (mm) between $t_{j-1}$ and $t_j$ where the subscript j refers to the number of days after rain. The slope of the Plot of $E_j$ against $\sqrt{t_j} - \sqrt{t_{j-1}}$ provides an estimate of $\alpha$.

Pilbeam *et al.*, (1995b) found that $E_s$ estimated from equation 2.6 agreed well with measured ET (using neutron probe) when the rate of evaporation was less than 2 mm day$^{-1}$ but was overestimated under higher evaporation rates.

## 2.4 Weather factors that influence dry matter production.

Management and weather factors that influence LAI influence dry matter production. Some management factors that influence LAI include irrigation, planting density, fertilizer N, plant growth regulators and choice of cultivars. Total solar radiation, air temperature and SD are some of the weather factors that have been shown to influence LAI (Squire, 1990). The following section is a review of how weather factors interact with LAI to influence dry matter production.

### 2.4.1 Solar radiation interception and dry matter production

The rate of dry matter production is proportional to the total amount of incoming solar radiation that is intercepted and the efficiency with which it is converted to dry matter by the canopy (Monteith, 1977; Squire, 1990). The relationship between dry matter and the cumulative total intercepted radiation is expressed as follows (Squire, 1990):

$$Y = \varepsilon_s \Sigma S_i \qquad 2.8$$

Y is dry matter (g/m$^2$), $\varepsilon_s$ is the ratio of dry matter to intercepted radiation (conversion efficiency, g MJ$^{-1}$) and $\Sigma S_i$ is the cumulative total of intercepted radiation (MJ/m$^2$), where $S_i$ is the amount of radiation intercepted on day i.

The values of $\varepsilon_s$ and $S_t$ both vary during a crop growth cycle depending on the predominant processes and their respective rates at the times when measurements are made. For example Coulson (1985) working with *Phaseolus vulgaris* L. varieties in Kenya found that approximate values of $\varepsilon$ varied between 0.4 and 1.2 g $MJ^{-1}$ PAR at different stages of development with a seasonal average value of 0.8 g $MJ^{-1}$ PAR. The interception of radiation depends on both LAI and canopy architecture which is influenced by leaf size, shape, orientation and spatial arrangement, (Yoshida, 1972; Campbell and van Evert, 1994). Leaves preferentially absorb visible light (0.4-0.7μm also called Photosynthetically Active Radiation - PAR); many crops absorb 80 to 90% of incident PAR (Monteith, 1969; Campbell and van Evert, 1994). Hence the fraction of incident PAR intercepted may slightly exceed that of total solar radiation, and the proportion of solar radiation that is PAR (approximately 50%) will tend to decrease as radiation is attenuated down the canopy. Radiation that is not intercepted is transmitted through the canopy, and reaches the soil surface and provides some of the energy for soil evaporation. The fraction of radiation transmitted by the canopy ($\tau$) is expressed as (Steve *et al.*, 1986):

$$\tau = \frac{I}{I_o} = e^{-KLAI} \qquad 2.9$$

where LAI is the leaf area index

K is the light extinction coefficient,

I and $I_o$ are solar radiation below and above the canopy respectively.

The fraction of radiation intercepted (hence available for dry matter production) is expressed as follows:

$$f = 1 - \exp^{(-KLAI)} \tag{2.10}$$

Rearranging equation 2.10 above, expresses K as follows.

$$K = \ln \frac{(1 - f)}{LAI} \tag{2.11}$$

Crop light extinction coefficients reported in literature vary between 0.24 to 1.07 (Monteith, 1969); K values are lower for erectophile canopies (grasses) and higher for planophile canopies (cotton). K values for beans range between 0.48 and 0.8 (Gardiner *et al.*, 1979; Coulson, 1985). The variation in K values in the beans may be influenced by choice of cultivar and row spacing used in the experiments (Gardiner *et al.*, 1979).

The above models deal with light attenuation through a random canopy, which is an assumption that holds under closed crop canopies and dense forests (Campbell and Evert, 1994). Non random distribution of leaves occurs in sparse agricultural crops with incomplete canopy cover, where leaves are grouped around an axis or where there are heliotropic leaf movements. There is evidence of heliotropism in beans (Dubetz, 1969; Wien and Wallace, 1973; Berg and Hsiao, 1986; Fu and Ehleringer, 1992).

### 2.4.2 Temperature effect on crop growth (Thermal time)

Temperature has been shown to strongly influence developmental processes (Gallagher, 1979, Squire, 1990) hence the rate at which a crop attains maturity. The concept of thermal time expresses the relationship between temperature and crop development. Thermal time is defined as (Squire, 1990):

$$\Phi = \Sigma_{i=1}^{i=n}(T_i - T_b) \qquad 2.12$$

where $\phi$ is thermal time (°C days), $i$ is the number of days, $Ti$ is mean daily temperature (°C) on day $i$ and $T_b$ is the base temperature at which the development process in consideration ceases.

Thermal time describes the progress of a developmental stage in physiological time rather than chronological time (Loomis and Connor, 1992). Thermal time has been used to bring disparate sets of data of crops grown in different environments (where temperature alone was the cause of differences in time to development) into a single relationship (Cooper and Law, 1978; Cooper, 1979).

Temperature has a strong effect on several bean developmental processes including seed germination, leaf initiation, flower development and dry matter partitioning (Masaya and White, 1991). White and Montes-R (1993) working on the germination of various bean cultivars established a mean $T_b$ for germination of about 8°C with optimum temperatures ranging from 25.5°C to 29.3°C. Hoogenboom and White (1991, cited in White and Montes-R, 1993) used base temperature ($T_b$) for leaf development of 5°C, though there was no experimental evidence for choice of this value.

Loomis and Connor (1992) pointed out the need to take into account the thermal amplitude around the optimum when considering thermal duration of phenological stages of a cultivar in different environments. The simple thermal time relationship given in equation 2.12 is expected to apply in conditions where the maximum and minimum temperatures during the day do not stray outside of base and the optimum temperatures. In Kenya, the concept of thermal time can be used to provide a basis of choice of appropriate crop species and/or cultivars for different ecological zones depending on their predicted maturity dates.

### 2.4.3 Saturation vapour pressure deficit (SD)

SD is the difference between the saturated vapour pressure ($e_s$) and the actual vapour pressure ($e_a$) of air. Campbell (1985) presents an empirical equation to describe the vapour concentration at saturation at temperature T, $\chi_s(T)$

was used to estimate $\chi_s$ (absolute vapour pressure g/m$^3$):

$$\chi_s(T) = \frac{\exp(31.3716 - 6014.79/T - 0.00792495T)}{T} \qquad 2.13$$

T is air temperature (K)

The vapour pressure concentration is converted to vapour pressure (kPa) as follows (Monteith and Unsworth, 1990):

The relation between SD and %RH is:

Air saturation vapour pressure deficit influences dry matter production through

$$e_s(T) = \frac{\chi_s}{2165} * T \tag{2.14}$$

$$D = e_s(T) - e_s(T) * \% RH/100 \tag{2.15}$$

transpiration and leaf area development (Ong *et al.*, 1987). High SD reduce leaf size and leaf number (Ong *et al.*, 1985). The effect of SD on leaf size may be through turgor pressure and or stomatal limitation to dry matter production.

Black and Squire (1979) working with well-watered millet and groundnuts under glass house conditions found that at high SD values, stomatal conductance is lowered. Stomatal responsiveness to SD in non-irrigated treatments in the same experiment was lacking in entire plants, but was induced by reducing the transpiring leaf surface area by covering the plants.

From the foregoing discussion, the importance of canopy size, on dry matter production and water use are apparent.

The following sections review literature on how water and nitrogen influence leaf growth, a central process of canopy construction.

## 2.5 Water and nitrogen effects on leaf growth

### 2.5.1 Water effect

The indirect effect of water on dry matter production is through limitation of leaf growth. Leaf growth is known to be reduced at leaf water potential values at which stomata are open (Hsiao and Bradford, 1983). Acevedo *et al.*, (1971) found that the elongation rate of maize seedlings dropped to zero when the leaf water potential was 0.6 MPa, a value at which stomata are still open. This indicates high sensitivity of leaf expansion to leaf water potential.

The sensitivity of leaf expansive growth to mild plant water stress has been explained by the dependence of cell enlargement on turgor pressure, i.e, the pressure exerted on the cell wall as a result of water uptake (Bradford and Hsiao, 1982; Hsiao *et al.*, 1985; Dale, 1988). However, there is increasing evidence that leaf expansive growth may be influenced by factors other than turgor pressure. It has been observed that plants in drying soil can exhibit high undisturbed turgor, yet show reduced growth rates (Davies and Zhang, 1991). Such modifications of shoot growth even when shoot water relations are not perturbed in a drying soil is indirect evidence for the involvement of some other mechanism regulating leaf growth. A root signal, probably abscisic acid (ABA), which has been found to increase under water and nitrogen limited conditions has been implicated (Davies and Zhang, 1991).

### 2.5.2 Nitrogen effect

Nitrogen effect on leaf area is through reduced rate of leaf expansion, leaf size, number of leaves per plant and leaf longevity (Hunt *et al.*, 1985; Hay and Walker, 1989). Reduced longevity of shaded leaves in the lower parts of the canopy under high fertilizer nitrogen levels has been reported (Pearman *et al.*, 1977). High N supply increases cell division and expansion, increases cell wall extensibility (Taylor *et al.*, 1993) and influences the plant hydraulic properties (Radin and Boyer, 1982).

The mechanism through which N influences plant hydraulic properties has not been fully resolved. Radin and Boyer (1982) working with sunflower under controlled conditions found that nitrogen deficient plants had lower conductance to water flow (into expanding leaf cells) than high N plants. The differences in conductance were alluded to nitrogen effects on the anatomical, ultra-structural and biochemical features of the cells which are not well understood (Radin and Boyer, 1982). Later work with cotton under field conditions indicated that nitrogen deficient plants had higher hydraulic conductance than high nitrogen plants (Radin *et al.*, 1991). Fertilizer application to the cotton plants probably resulted in development of a larger root system (Brown *et al.*, 1987) that improved the rate of water transport to the leaves.

### 2.5.3 Water and nitrogen interaction and effects on leaf growth

Radin and Boyer (1982) working with sunflower under controlled environment showed that a decrease in leaf N resulted in reduced leaf expansion. Daytime leaf expansion was reduced due to inability of the plants to maintain adequate turgor. In the same experiment, it was found that nitrogen deficiency increased the root resistance to water flow (for water transport into expanding leaf cells). From their experiment, Radin and Boyer (1982) concluded that nitrogen influenced growth through its effect on water transport. Conversely, Radin *et al.*, (1991) working with cotton under field conditions, found that nitrogen deficient plants had higher apparent hydraulic conductance (conductance to water flow between the soil and the leaves) than high nitrogen plants. The effect of nitrogen on hydraulic conductance was not clearly resolved from these experiments.

## 2.6 Overall objective

The central objective of the study is to examine how canopy size, manipulated by management strategies (nitrogen fertilizer application and planting density) interact with weather conditions to influence the growth and yield of field-grown common beans under temperate and tropical environments (Sonning, U.K and Kabete, Kenya). Canopy size is very central to crop growth and the treatment effects and their interactions are assessed.

### 2.6.1 Specific objectives

1) To evaluate the effects of E, T, and D on dry matter production of beans under field conditions; in Reading, UK and in Kabete, Kenya. Special attention is given to canopy expansion because of the role of the leaves play in the interception of radiation, and the consequences of solar energy partitioning for the production of dry matter and evaporation from the soil surface.

2) To investigate the role of canopy size on E and T. It is suggested that any improved water use efficiency attributable to input of nitrogen might be because N fertiliser enables vigorous plant growth (particularly in the early stages) which causes an increase in E to ET ratio through a combination of shading and increased root water uptake. Plant density may have a similar effect at first, though eventually high inter-plant competition for water may have adverse effects.

3) To determine crop responses to soil water, nitrogen and planting density in terms of dry matter production and allocation patterns among various plant parts.

4) To use computer models to determine the effect of management practices on the partitioning of precipitation to E, T and D in attempt to accurately determine WUE.

The key assumption is that water availability is the factor that drives biomass productivity. It influences plant productivity through basic plant processes like leaf expansive growth, assimilate partitioning and nitrogen uptake.

## 2.7 Hypotheses

A) At a given site and for a given rainfall plant biomass may increase in response to N application as a result of an increase in the proportion of rainfall used in transpiration (ET/R), an increase in the amount of dry matter produced per unit of water transpired (T/ET) and or an increase in the transpiration efficiency (Y.SD/T). The following mechanisms may be involved:

i) Increased leaf area development leading to reduced soil evaporation especially early in the season. This results in the plant losing more water through transpiration due to increased canopy radiation interception, hence reducing the energy available for evaporation from the soil.

ii) Plants develop larger root systems and consequently exploit a larger soil volume resulting in sustained crop growth because of better water supply to the crop. More vigorous water extraction by plants might influence both drainage and direct evaporation from the soil surface.

B) For a given nitrogen application, plant biomass is able to increase in response to water application for the following reasons:

i) there is increased nitrogen supply resulting from increased N-fixation

ii) Increased root growth results in exploitation of a larger soil volume and increases the N supply to the plant.

To test the above hypotheses, three field experiments were conducted as described in chapter 3.

# Chapter 3

# Materials and methods

## 3.0 Introduction

Dry beans (*Phaseolus vulgaris* L) var Mwezi Moja were grown in three experiments (one at Sonning, U.K. from June to September 1992 and two at Kabete, Kenya from November 1992 to April 1993). The two experiments at Kabete are subsequently referred to as K1 and K2 respectively. Mwezi Moja variety is well adapted to low rainfall areas (500 - 750 mm per annum) where it is commonly grown. The adaptation mechanisms include stomatal responsiveness under limited soil water supply (Masumba, 1984), osmotic adjustment (Runkuntile, 1991), rapid root growth rate (Runkuntile, 1991) and short maturity period (75 to 90 days).

## 3.1 Climatic characteristics

The experiment in the U.K. was conducted at the University of Reading Sonning Research farm (latitude 51° 28'N 0°53'W). The farm is located 8 km east of Reading at altitude of approximately 70 m above sea level. The total annual rainfall is approximately 650 mm which is almost evenly distributed in the year (54 mm month$^{-1}$). December is the wettest month while February is the driest, with 64 mm and 37.5 mm respectively (figure 3.1 a).

The Kabete experimental site is located at the University of Nairobi Field Station farm (1° 15'S and 36° 44' E) at an altitude of 1942 m, 12 km north-west of Nairobi. Average annual rainfall is approximately 1000 mm bimodally distributed with peaks in November and April and separated by a cool dry spell (June to September) (figure

3.1 b). These two rainfall seasons are locally referred to as the "short" (mid-October to December) and "long" rains (mid-March to May) respectively. These terms are used nationwide to describe the duration of the rainy season and do not necessarily reflect the total amount received in the seasons. However on average in Kabete, 57% of total annual rainfall is received in long rains and 43% in the short rains.

At Sonning, the mean annual temperature is 10°C, with monthly means ranging from 4°C) in January to a maximum of 17°C in July (fig.3.1a). The annual temperature regime at Kabete has less fluctuation than Sonning; having a mean of 18°C with a monthly minimum in June (14°C) and a maximum in February (24°C).

Solar radiation at Sonning is lowest in December (2 MJ $m^{-2}$ $day^{-1}$) and highest in July (18 MJ $m^{-2}$ $day^{-1}$). At Kabete, average total insolation is 19 MJ $m^{-2}$ $day^{-1}$, and is lowest in July (13 MJ $m^{-2}$ day) and highest in February (24 MJ $m^{-2}$ $day^{-1}$) (figure 3.2). Potential evaporation at the two sites has a similar pattern to solar radiation. However average annual total potential evaporation in Kabete is higher than average total rainfall and the converse is true at Sonning.

Seasonal weather data was collected from nearby weather stations in all three experiments. The weather data was used to assess the climatic differences among the three experiments that may have contributed to crop growth (see chapter 4). At Sonning half hourly mean values of rainfall, RH, temperature, solar radiation, evaporation, total solar radiation and wind speed were available from an automatic weather station. At Kabete, daily values of the weather parameters were available from a standard meteorological station.

## 3.2 Soil characteristics

### 3.2.1 Sonning

Delete

The soil type is described as the Sonning series, a freely drained sandy loam, overlying reddish brown sandy loam developed on non-calcareous river-terrace gravel (Kay, 1936). The particle size distribution in the top 80 cm is 80% sand, 11% silt and 9% clay (Abbas, 1975). The pH (1:2.5 in water) in the top 80 cm is 5.5 and the average bulk density is 1.1 g $cm^3$ (Harris, 1994). Organic matter content in the top 20 cm is about 2%. The soil is low in available potassium and phosphorus (less than 0.005% potassium and 0.04% phosphorus), therefore requires fertiliser supplement for crop growth (Abbas, 1975).

According to the FAO/UNESCO classification, the soil at the Kabete site is described as Humic Nitosol with kaolinitic clay minerals (Jaetzold and Schmidt, 1983). The soil is deep (water table greater than 15 m), well drained, dark reddish brown to dark brown in colour, friable clay. The soil is not responsive to fertilizer K because of the K supplied from feldspar minerals in the parent material (Lenga, 1979). The physical and chemical characteristics of soil at Kabete are summarised in table 3.1 below.

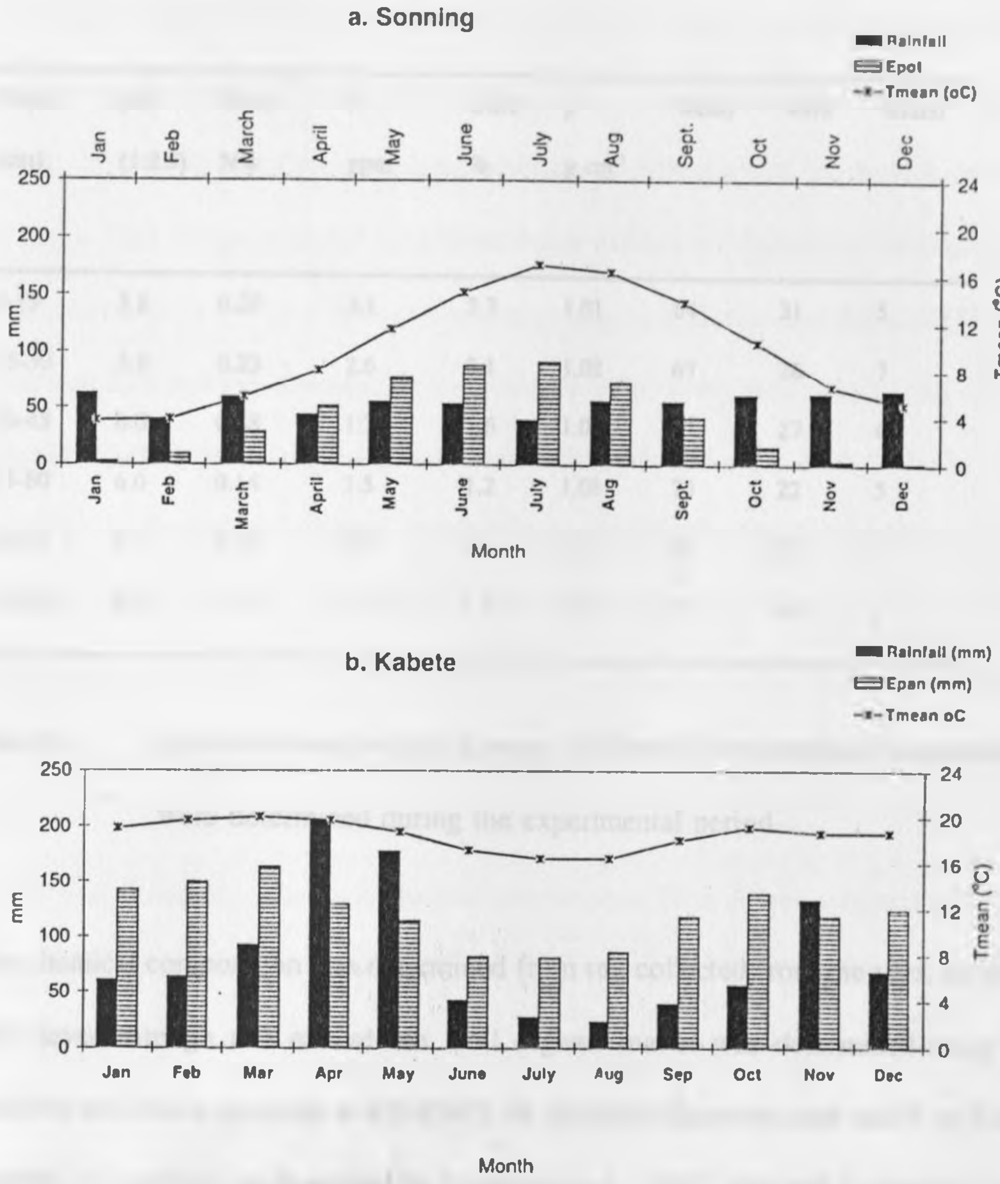


Figure 3.1. Longterm rainfall, Epan and temperature at Sonning and Kabete

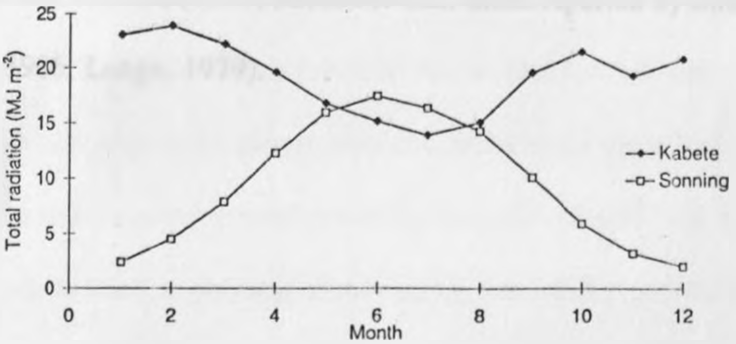


Figure 3.2. Longterm average daily total radiation at Sonning and Kabete

Table 3.1 Some textural and chemical characteristics of Kabete experimental site.

| Depth (cm) | pH (1:2.5) | Total N% | P ppm | O.M % | ρ g cm$^{-3}$ | %clay | %silt | %sand |
|---|---|---|---|---|---|---|---|---|
| 0-15 | 5.8 | 0.26 | 3.1 | 2.3 | 1.01 | 64 | 31 | 5 |
| 15-30 | 5.8 | 0.23 | 2.6 | 2.1 | 1.02 | 67 | 26 | 7 |
| 30-45 | 6.0 | 0.18 | 1.7 | 1.6 | 1.09 | 67 | 27 | 6 |
| 45-60 | 6.0 | 0.14 | 1.5 | 1.2 | 1.08 | 73 | 22 | 5 |
| 60-75 | 6.1 | 0.13 | 1.3 | 1.1 | 1.14 | 75 | 21 | 4 |
| 75-90 | 6.2 | 0.11 | 1.3 | 1.0 | 1.12 | 77 | 19 | 4 |

Source: physical characteristics (Lenga, 1979) while the chemical characteristics were determined during the experimental period.

The chemical composition was determined from soil collected from the sites, air dried and sieved through a 2 mm screen. Soil organic matter was determined using the Walkley and Black method, soil N (%N) by Kjeldhal digestion, and soil P by Olsen method (all methods as described by Okalebo *et al.*, 1993). Soil pH as determined in water at a ratio of 1:2.5 (soil: water). Total %N is comparable to values reported by Barber and Thomas (1981) but lower than those reported by other workers (Ssali and Keya, 1986; Lenga, 1979).

## 3.3 Experimental Design, treatments and field layout

The experimental design in all three experiments was split-split plot factorial design replicated three times (Gomez and Gomez, 1984). The design was chosen to test the effects of three factors (water, nitrogen and planting density) on the growth and yield of beans. This design is useful for a three-factor experiment because it facilitates field operations and keeps treatment combinations together (Little and Hills, 1978). The treatment factors were allocated to experimental units; main plot, subplot and the sub-subplot. There were three plot sizes corresponding to the three factors (main plot > subplot > sub-subplot) and three levels of precision for testing the treatment effects, hence three error terms. The effect of the main factor treatments is tested with the least precision and the sub-subplot receives the highest degree of precision (Gomez and Gomez, 1984).

Water was allocated to the main plots for two reasons. First, it was assumed that water is the factor that drives biomass productivity processes and its effects on plant growth are easy to detect. This assumption finds its justification in the general observation that "in a good year, yields are high" - meaning that in a year when rainfall is abundant, yields are high. Secondly, water was assigned to the main plot to minimize water movement to the not-irrigated treatments and hence reduce the border effects. The use of trickle irrigation system could not allow randomization of irrigation to the main plots. Nitrogen was allocated to the subplot level. Planting density was used as a method of altering the canopy size thus influencing the utilization of both water and nitrogen and required greater precision and was allocated the sub-subplot level. The plot sizes in each experiment depended on availability of land and seed.

The factors were:-

i) Main plots - 2 water levels; not irrigated (W0) and irrigated (W1)

ii) Sub-plots - 2 levels nitrogen; no nitrogen (N0) and 100 kg N $ha^{-1}$ (N100) as a single application early in the growing season.

iii) Sub-sub plots - 2 planting densities; 22 (D1) and 55 (D2) plants $m^{-2}$. These were obtained by setting the row spacing to 40 and 20 cm respectively but maintaining plant spacing within the row at 10 cm. The plots were planted with *Phaseolus vulgaris* var. Mwezi Moja.

The data collected from the three experiments was analysed statistically using Genstat 5 release 3.1 (copyright 1993, Lawes Agricultural Trust), Rothamsted Experimental Station (see table 1, Appendix 1) for typical output. Graphics were created using Microsoft Excel 5.0 and Freelance Graphics (3.1).

Wheat (*Triticum aestivum* L Kenya Paka), obtained from Njoro Plant Breeding Station, was included as a non-fixing reference crop to determine symbiotic biological nitrogen fixation by the beans in the Kabete experiments (section 7.2.3). In K1, wheat was planted as a separate experiment, adjacent to the bean plots whereas in K2 the wheat plots were included in the factorial design. The sub-subplot sizes in the three experiments were 1.2 m x 2 m, 2 x 3.6 m and 1.5 x 3.6 m at Sonning, K1 and K2 respectively. Bare plots adjacent to the main experimental plots were included in all the three experiments to monitor soil water loss by direct evaporation. The field lay out was as indicated in the figures 3.3 to 3.5.

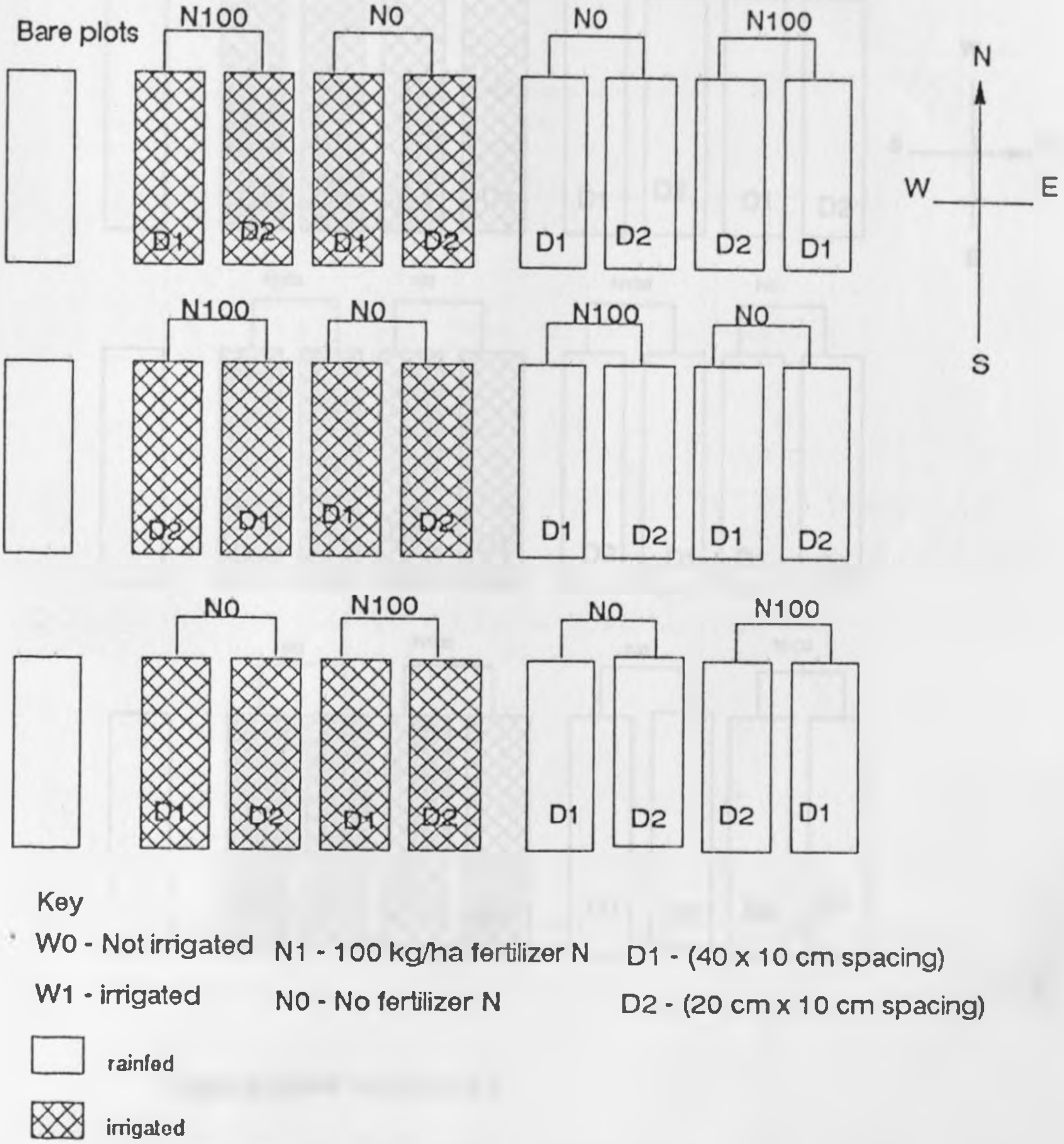
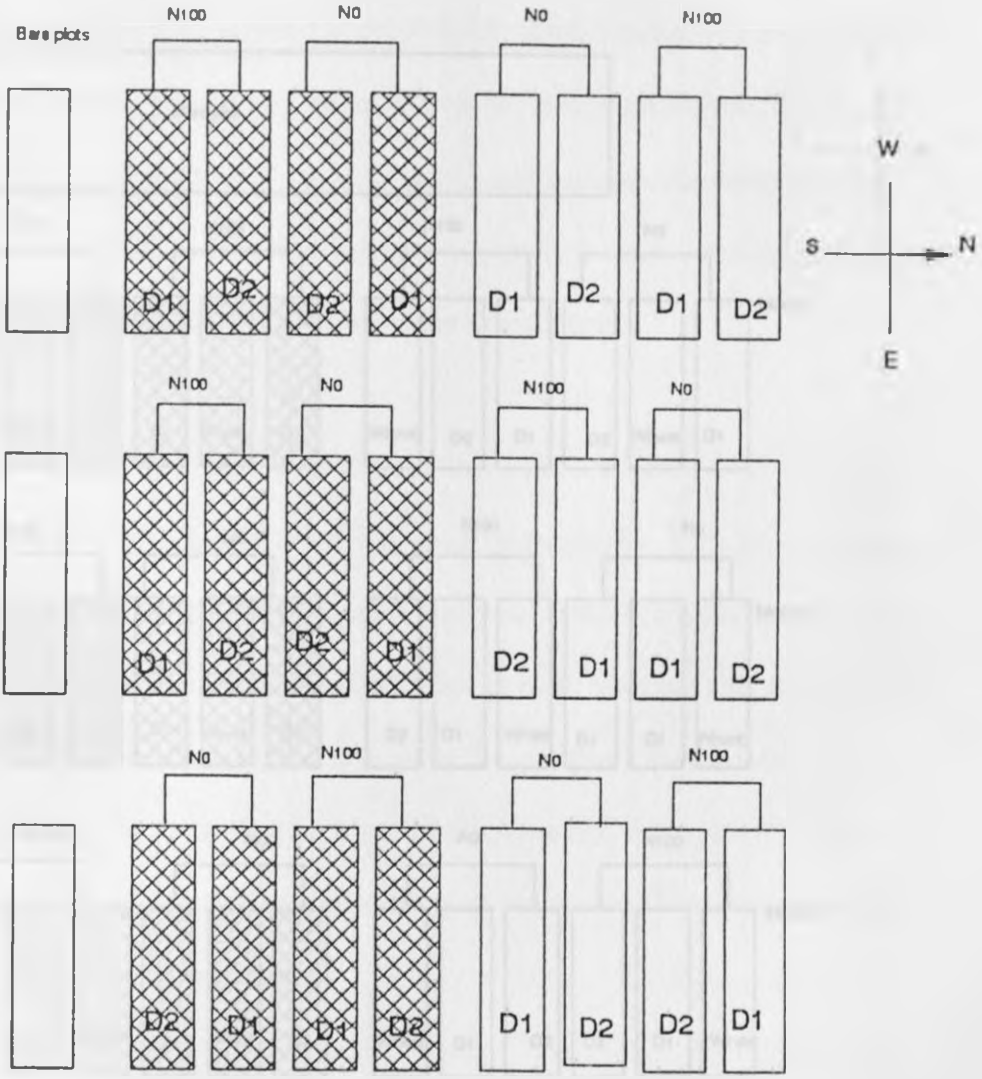
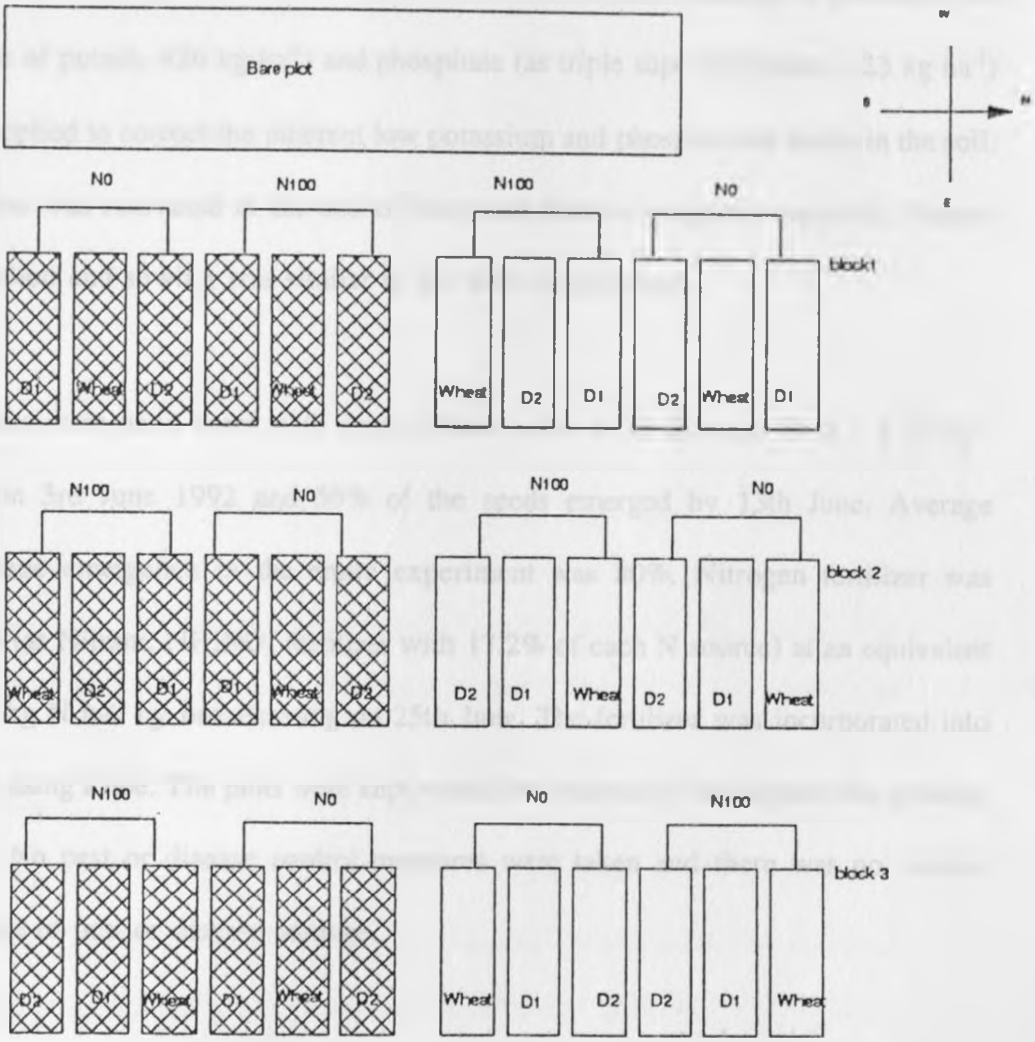


Figure 3.3. Field layout for the Sonning experiment.



Legend similar to figure 3.3

Figure 3.4 Field layout for K1 experiment



Legend similar to figure 3.3

Figure 3.5 Field layout for K2 experiment.

## 3.4 Crop husbandry (land preparation, planting, fertilizer application, crop protection) and irrigation.

### 3.4.1 Sonning.

The land was ploughed and harrowed in mid-March. Basal dressings of potassium (as muriate of potash, 426 kg ha$^{-1}$) and phosphate (as triple superphosphate, 223 kg ha$^{-1}$) were applied to correct the inherent low potassium and phosphorous levels in the soil. The land was rotovated at the end of May and furrows prepared manually. Furrow preparation and sowing was similar in the three experiments.

The plots were hand sown with dressed bean seeds (with Ferasan D at 1 g 20 kg$^{-1}$ seed) on 3rd June 1992 and 50% of the seeds emerged by 13th June. Average percentage emergence in the entire experiment was 80%. Nitrogen fertilizer was applied (as Nitram, $NH_4NO_3$ fertilizer with 17.2% of each N source) at an equivalent of 100 kg N ha$^{-1}$ by broadcasting on 25th June. The fertilizer was incorporated into the soil using a hoe. The plots were kept weed-free (manually) throughout the growing period. No pest or disease control measures were taken and there was no evident incidence of pest or disease damage.

A drip irrigation system was installed with three irrigation lines per plot. The amount of water to be applied each time was estimated based on the cumulative potential evapotranspiration ($E_{pot}$) since the last precipitation event (rainfall or irrigation). $E_{pot}$ and rainfall data was obtained from a weather station approximately 20 meters from the plot. The amount of water applied was measured with a meter attached to the supply line. Below is a summary of dates of the climatological water balance and the irrigation scheduling. The balance sheets give an indication of the theoretical soil moisture deficits in the season.

Table 3.2 Cumulative rainfall, irrigation and theoretical soil moisture deficit (mm) for Sonning for the period between on 3rd June 1992 and 25th September 1992.

| Date | DAP | R | I | $E_{pan}$ | SMD1 | SMD2 |
|---|---|---|---|---|---|---|
| | | (mm) | | | | |
| 3-17 June | 0-14 | 6.4 | 13 | 60.1 | -53.7 | -40.7 |
| 18 July | 15 | 0 | 51.7 | 3.1 | -56.8 | 7.9 |
| 19-24 July | 16-21 | 6.6 | 29 | 23.5 | -73.7 | 20 |
| 25-1 July | 22-28 | 9.2 | 11.7 | 27.3 | -91.8 | 13.6 |
| 2-28 July | 29-55 | 59.2 | 53.3 | 87.1 | -119.7 | 39 |
| 29-3 Aug. | 56-61 | 0 | 8.4* | 26.3 | -146 | 21.1 |
| 4 Aug-25 Sept. | 62-114 | 192.6 | 0 | 122.2 | -75.6 | 91.5 |
| Total | | 274 | 167.1 | 349.6 | | |

*Hose pipe used because of breakdown of irrigation system.

R=rainfall, I=irrigation, $E_{pot}$=Potential evaporation, $E_{pan}$=Pan evaporation, SMD1=theoretical soil moisture deficit in rainfed treatments ($\Sigma(R-E_{pot})$), SMD2=theoretical soil moisture deficit in irrigated treatments ($\Sigma(R+I-E_{pot})$). The legend is similar for table 3.3 and 3.4 with the exception of use of $E_{pan}$ instead of $E_{pot}$

### 3.4.2. K1 experiment.

The experimental field was disc-ploughed in November 1992. Diammonium phosphate ($(NH_4)_2PO_4$, 18% N and 46% P) was applied at an equivalent rate of 100 kg N $ha^{-1}$. The fertilizer was placed in the furrows and incorporated into the soil prior to hand-sowing beans that were seed-dressed with Ferasan D (similar to those in Sonning). The sowing date was 20th November 1992. Emergence (50%) was on 3rd December 1993. Seedling establishment was about 90%. Weed control was manual and no pest or disease control measures taken.

In the irrigated treatments, water was applied manually using 15 litre watering cans (total of 60 mm) early in the season. Irrigation was discontinued because of remarkably heavy unseasonal rainfall (*Daily Nation, 10th February, 1993 pp 24*). The irrigation schedule was as in table 3.3.

### 3.4.3 K2 experiment.

Land adjoining the K1 experimental site was prepared as in K1. Nitrogen fertilizer was applied as calcium ammonium nitrate (26% N) at a rate equivalent to 100 kg N $ha^{-1}$. A basal phosphorous application (single superphosphate, 19% $P_2O_5$) equivalent to 20 kg P $ha^{-1}$ was included at sowing.

This experiment was an "off-season crop", grown at the end of a rainy season, when beans are vulnerable to pests, especially bean fly (*Omphiomyia phaseoli*). Hence a stringent protection program was adopted. The seeds were dressed as in K1. Furadan$^{R}$ (5% carbofuran) was applied in the furrows (at sowing) at a rate of 1.3 g $m^{-2}$ to

Table 3.3 Cumulative rainfall, irrigation and theoretical soil moisture deficit (mm) in the K1 experiment for the period between 20th November 1992 and 23rd February 1993.

| Date | DAP | R | I | Epan | SMD1 | SMD2 |
|---|---|---|---|---|---|---|
| | | mm | | | | |
| 20-25 Nov | 0-5 | 5.9 | 10 | 29.4 | -23.5 | -13.5 |
| 26 Nov-14 Dec | 6-24 | 69.8 | 10 | 67.8 | -21.5 | -1.5 |
| 15-23 Dec | 25-33 | 37.4 | 20 | 38.9 | -23.0 | 17.0 |
| 24-29 Dec | 34-39 | 6.5 | 0 | 25.5 | -42.0 | 8.0 |
| 30 Dec-5 Jan | 40-46 | 40.9 | 0 | 22.4 | -23.5 | 26.5 |
| 6-11 Jan | 47-52 | 35.7 | 10 | 21.2 | -9.0 | 51 |
| 12-23 Feb | 53-95 | 187.9 | 0 | 177.9 | 1.0 | 61 |
| Total | | 384.1 | 60 | 383.1 | | |

control cut worms. The plots were sown on 9th February 1993. The date to 50% emergence was 17th February 1993. Average emergence in all the plots was about 90%. The beans were sprayed with dimethoate (1 ml $l^{-1}$) once weekly (using a knapsack sprayer) from 7 days after emergence (DAE) to flowering to control bean fly (*Ophiomyia phaseoli*) damage.

Water was applied manually twice weekly (using 15 litre watering cans) between 1600 and 1730 h (to reduce loss due to direct evaporation from the soil surface) as is indicated in table 3.4.

## 3.5 Measurements

### 3.5.1 Growth analysis

#### 3.5.1.1 Above ground dry matter.

Treatment effects on the crop growth in the three experiments were determined by sequentially harvesting beans at different stages of development. At each harvest, plants were cut at ground level, placed in plastic bags and stored in the laboratory at 5°C. These were later stripped into various components, namely:- leaves, petioles, stems, flowers, pods and seeds (depending on the crop phenological stage) to determine the dry matter allocation patterns. The number of nodes on the main axis, total number of primary branches on the main stem, total number of the leaves and total number of pods were also counted. The plant components were oven dried at 80° C for at least 72 hours (to constant weight) and weighed to determine dry weight, and ground for total N determination. The sampling intervals selected concided with key phenological stages of bean development growth:- vegetative, flowering, pod growth and physiological maturity. Tables 3.5 a and b summarise the key phenological stages and sampling dates in the Sonning and Kabete experiments respectively.

Table 3.4 Cumulative rainfall, irrigation and theoretical soil moisture deficit (mm) in the K2 experiment for the period between 9th February and 23rd April 1993.

| Date | DAP | R | I | $E_{pan}$ | SMD1 | SMD2 |
|---|---|---|---|---|---|---|
| | | mm | | | | |
| 9-19 Feb | 0-10 | 18.8 | 0 | 44.3 | -25.5 | -25.5 |
| 20-3 Mar | 11-22 | 0.3 | 16.6 | 65.8 | -91 | -74.4 |
| 4-10 Mar | 23-29 | 16.3 | 8.3 | 33.8 | -108.5 | -83.6 |
| 11-17 Mar | 30-36 | 29.5 | 16.6 | 38 | -117 | -75.5 |
| 18-24 Mar | 37-43 | 0.9 | 27.6 | 41.4 | -157.5 | -88.4 |
| 25-31 Mar | 44-50 | 14.7 | 22.0 | 40.7 | -183.5 | -92.4 |
| 1-9 Apr | 51-59 | 5.0 | 22.0 | 40 | -218.5 | -105.4 |
| 10-16 Apr | 60-66 | 17.1 | 22.0 | 30.3 | -231.7 | -96.6 |
| 17-23 Apr | 67-73 | 3.0 | 0.0 | 23.3 | -252.0 | -116.9 |
| Total | | 105.6 | 135.1 | 357.6 | | |

Table 3.5 a Sonning experiment: Summary of crop phenological stages and sampling dates for dry matter analysis.

| Crop phenology and sampling stages | Date (1992) | DAP |
|---|---|---|
| Planting date | 3rd June | 0 |
| Emergence (50%) | 13th June | 10 |
| Harvest 1 (early vegetative stage) | 3rd July | 30 |
| Harvest 2 (late vegetative stage) | 17th July | 44 |
| Anthesis | 18th July | 45 |
| Flowering (50%) | 23rd July | 50 |
| Harvest 3 (flowering stage) | 31st July | 58 |
| Pod formation | 3rd August | 61 |
| Pod growth | 18th August | 76 |
| Seed growth | 26th August | 84 |
| Harvest 4 (pod and seed growth) | 28th August | 86 |
| Physiological maturity | 11th Sept. | 100 |
| Harvest 5 (final harvest). | 25th Sept. | 114 |

Table 3.5b Summary of crop phenological stages and sampling dates for dry matter analysis K1 and K2.

| Crop phenological stage and harvest | K1 | | K2 | |
|---|---|---|---|---|
| | date | DAP | date | DAP |
| Planting | 20th Nov 92 | 0 | 9th Feb 92 | 0 |
| Emergence (50%) | 3rd Dec | 13 | 17th Feb | 8 |
| Harvest 1 (vegetative) | 22nd Dec | 32 | 4th March | 23 |
| Anthesis | 30th Dec | 40 | 16th March | 35 |
| Flowering (50%) | 4th Jan 93 | 45 | 17th March | 36 |
| Harvest 2 (flowering) | 5th Jan | 46 | 21st March | 40 |
| Harvest 3 (pod growth) | 20th Jan | 61 | 1st April | 51 |
| Physiological maturity | 16th Feb | 88 | 16th April | 66 |
| Final harvest | 23rd Feb | 95 | 23rd April | 73 |

At Sonning, four plants were sampled from the inner rows (with the exception of the final harvest) in each plot. Eight plants were sampled in the final harvest. Sampling was sequential along the rows in each plot, leaving at least 2 plants between sampling areas to act as guard plants. In attempt to maintain uniformity in the samples, plants with neighbours 10 cm on either side of the row were selected (figure 3.6a).

In K1 and K2 experiments, plants were sampled systematically in predetermined microplots within each treatment plot. The micro plots were 0.8 m x 0.5 m (0.4 m$^{-2}$)

between and within the rows respectively. The average number of plants per sample in D1 and D2 were 8 and 18 respectively. The sampling pattern was diagonal, with the final harvest located at the middle of the plot (figure 3.6b). This attempted to eliminate within plot variability in plant size. Figure 3.6 a and b show the sampling sites and the positions of neutron probe access tubes (discussed in section 3.5.5.1).

#### 3.5.1.2 Root sampling

Soil samples were taken manually using a Jarret auger (15 cm long cylindrical end and internal diameter of 8 cm) at 86, 48, and 45 DAP at Sonning, K1 and K2 respectively in all the plots. The soil samples were taken at 15 cm intervals (0-15, 15-30, 30-45, 45-60, 60-75 cm). The core volume was 754 $cm^3$. Sampling was done in the middle of the row in D2 plots. In the D1 plots, two samples were taken at 10 cm and 20 cm from the middle of the row. The samples were placed in plastic bags and stored at 4°C while awaiting washing to extract the roots from the soil.

Individual cores were submerged in water in 10 l plastic containers. The water was stirred gently to break the soil clods to release the roots. The heavy soil particles settled to the bottom of the containers while the roots and organic debris were suspended in water. The supernatant was carefully decanted through a 200 μm sieve. The process was repeated several times until all the roots were dislodged from the soil. The contents of the sieve were poured into a tray that was lined up with black polythene. The white roots (living) were picked with forceps and put into bottles

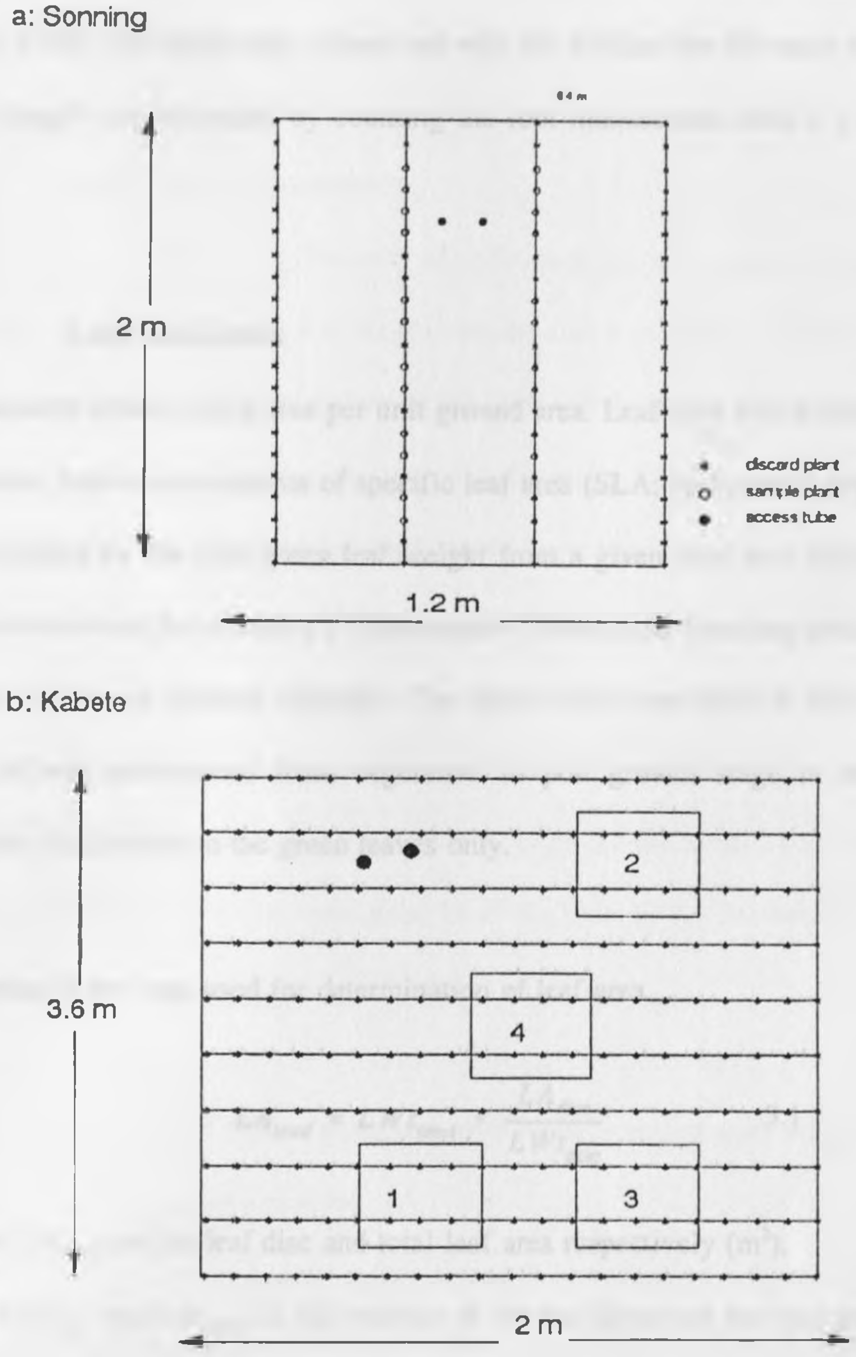


Figure 3.6. Sampling plan in Sonning and Kabete experiments (D1 plot). Numbers 1 to 4 at Kabete refer to harvest dates.

containing clean water and the dead roots (dark brown or black) were discarded. The root samples were stored in a refrigerator at 5°C awaiting root length determination (Tennant, 1975). The roots were stained red with 1% fuschin dye (for easy counting) and root length was estimated by counting the root intersections with a 1 cm grid frame.

### 3.5.2.0 Leaf area index

Leaf area index refers to leaf area per unit ground area. Leaf area was determined at each harvest, from measurements of specific leaf area (SLA; leaf-area-to dry weight ratio) multiplied by the total green leaf weight from a given land area (Hunt, 19..). SLA was determined by selecting a sub-sample of leaves and punching discs with a cork borer of known internal diameter. The discs were oven-dried at 80°C for 48 hours. LAI was determined from vegetative to pod growth stage in the three experiments. LAI refers to the green leaves only.

The equation below was used for determination of leaf area.

$$LA_{total} = LWt_{total} * \frac{LA_{disc}}{LWt_{disc}} \qquad 3.1$$

$LA_{discs}$ and $LA_{total}$ are the leaf disc and total leaf area respectively ($m^2$).

- $Lwt_{discs}$ and $Lwt_{total}$ are the weights of the leaf discs and the total plant leaf weight respectively (g).

At Sonning, leaf area was determined by selecting ten fully expanded green leaflets from each plant and punching 40 discs with a cork borer (internal diameter of 15 mm). In each plot, 120 discs were used to estimate the leaf area. At Kabete, 10 fully expanded leaves from each plant were selected and 10 leaf discs punched using a cork borer of 10 mm internal diameter. All the plants in the sample in each harvest were used.

### 3.5.2.1 Individual leaf expansion

As pointed out in equation 3.1, the area of individual leaves is one of the factors influencing LAI. The change in leaf length was used as a indicator of the change in leaf area. At Kabete, five plants (located in the third row from the edge) in each plot were selected randomly and marked for easy identification. The length and breadth of the middle leaflet in the first four trifoliate leaves were measured twice daily with a plastic ruler to ±1 mm (at approximately 07 and 17 hrs local time). Each leaflet was marked with a tag after it was about 2 cm long for ease of identification. Two small holes were made on the widest part of the leaflet with a fine pen (0.5 mm) where repeated breadth measurements were taken. The length of the leaflet was measured along the midrib. Measurements were done in all the plots in K1 but only in the D1 plots in K2.

### 3.5.2.2 Leaf water potential and relative water content (pressure volume curves)

Pressure/volume curves of leaves provide information that could help interpret any effects of treatments on leaf growth caused by differences in leaf water relations. Leaf water potential at varying relative water content was measured using a pressure chamber, (PMS, Corvalis, Oregon) (Koide *et al.*, 1988). Measurements were made on leaf samples taken from the first four trifoliate leaves in the D1 treatments at K1 and

K2. At Sonning, an entire leaf (three leaflets together) were used. An actively growing mid-trifoliate leaflet was cut and the petiole immediately dipped in a beaker of water. The leaves were taken to the laboratory. The leaf petiole was cut back under water to eliminate air trapped in the vascular system. The leaves were equilibrated initially in a beaker with water on the bench. The beaker was covered with a plastic bag to minimize transpiration for 24 hours to allow the leaves to rehydrate. Each leaf was weighed to obtain the saturated fresh weight, put in the pressure chamber to measure the leaf water potential ($\Psi$) then left to for three to five minutes to lose water through evaporation on the laboratory bench. The leaf was wrapped in cling film while measuring water potential to prevent weight change during the measurement. The procedure was repeated on each leaf for five to six of times (depending on the pressure that could be applied without the stem being crushed). The leaf was then oven dried for 24 hours at 70°C and weighed (Tyree and Jarvis, 1982; Koide *et al.*, 1989) to obtain dry weight. The relative water content (RWC) was computed as:

$$RWC = \frac{fresh\ weight\ -\ dry\ weight}{saturated\ weight\ -\ dry\ weight} \qquad 3.2$$

At least five leaves were measured from each treatment. The sets of values of leaf water potential and corresponding relative water contents enabled pressure volume curves to be constructed.

### 3.5.3 Ground cover.

#### 3.5.3.1 Sighting frame

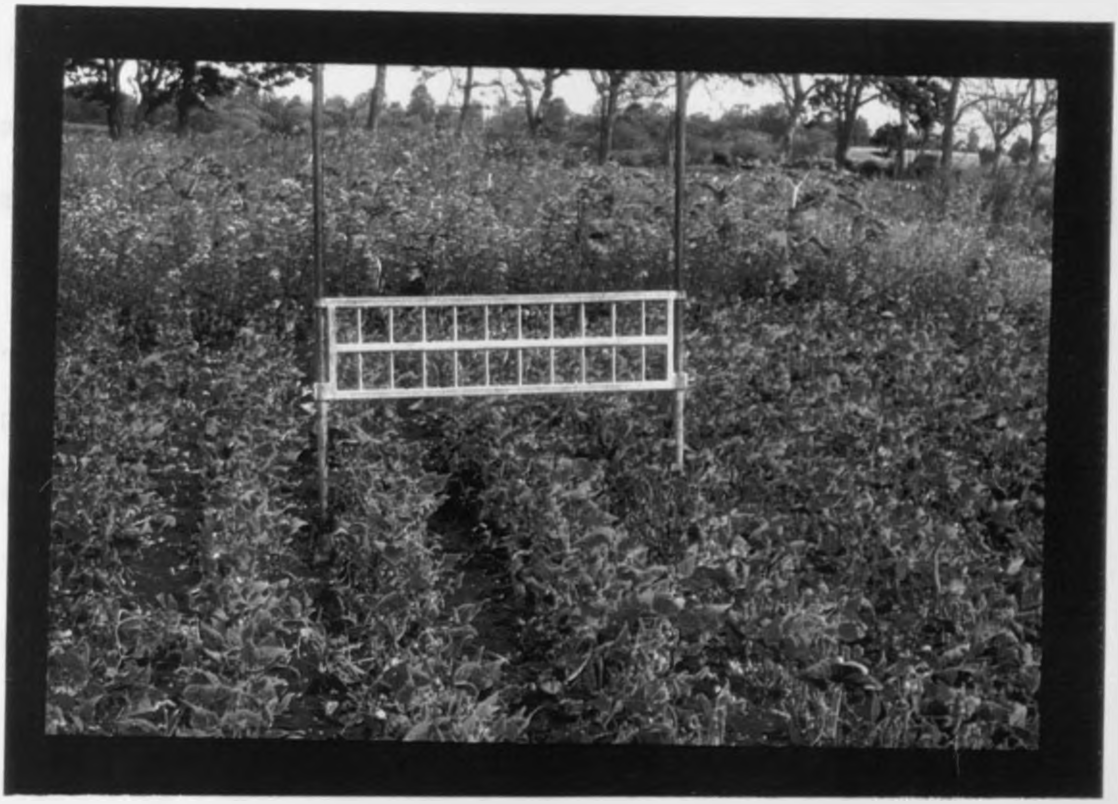
The fraction of the ground that is shaded by the canopy is closely related to LAI. Fractional ground cover can also be used, with caution, as a surrogate for radiation interception in order to determine differences between treatments in the amount of radiation intercepted over the season. A sighting frame the from Agricultural Engineering Department, University of Nairobi (Cackett, 1964) was used to measure ground cover in the Kabete experiments. The frame was made from aluminium and had three parts:

i) - one meter long sighting piece with 10 (10 mm diameter) viewing tubular holes,

ii) - two cylindrical stands to support the viewing piece; the height of the viewing piece was adjustable with screws on the stands.

iii) - Two stand stabilizers to anchor the whole set-up firmly on the ground (see photograph 1)

The frame was placed perpendicular to the rows and firmly anchored to the ground. It was mounted 10 cm above the average canopy height and plants viewed through the holes from above. The number of holes with zero, half or full cover of vegetation were noted. The cover was scored as 0, 50% or 100% for zero, partially and fully covered holes respectively. Three measurements were taken in each plot once a week in all the plots in both K1 and K2. In K1, measurements were taken at three marked spots in the course of the season. In K2, measurements were taken at random in the same rows at approximately the same position. The measurements were taken between



Photograph 1. Sighting frame for measuring canopy ground cover

1200 and 1400 local time in both K1 and K2 experiments to eliminate variation due to diurnal leaf movements.

### 3.5.3.2 Fractional solar radiation interception

Solar radiation attenuation (PAR) through the canopy was measured, between 1200 and 1400 (local time) using a sunfleck ceptometer (SF-80 Decagon, Pulman, Washington). Ten measurements in each plot were taken (at the height where leaves were green) by holding the ceptometer perpendicular to the rows. Two measurements to determine incident PAR were taken at one metre above the canopy. PAR measurements and ground cover measurements were take on the same day and at the same time.

### 3.5.4 Soil water content changes

A neutron probe (HII, Didcot Instruments, Abingdon, UK) was used to monitor changes in soil water content in the Sonning and K1 experiments. The probe had 50-mCi, AM-Be source of fast neutrons. Aluminium access tubes (150 cm long with an internal diameter 50 mm) that were sealed at one end were installed to a depth of 120 cm. At Sonning, the holes were made with an auger and a reamer while at Kabete the holes were made using soil auger slightly smaller than the tube diameter. The tubes was pushed down the hole with a weight placed on top of the tube. Two access tubes were installed in all D1 treatments at 20 and 10 cm from the middle of the row. One access tube was installed in D2 treatments (midway between the rows). The tubes were installed shortly after sowing (before emergence) at Sonning, but prior to sowing at Kabete. The tubes were placed 45 cm and 60 cm from the plot border at Sonning and K1 respectively. In both experiments, three bare plots next to the bean plots had access tubes installed to monitor soil water losses through evaporation and drainage in absence of a crop.

Neutron counts were taken over 16 seconds at 10 cm depth intervals starting from 10 cm depth every 7 to 14 days. No correction was made for measurements made in the top 20cm. At the end of each day's measurement, a neutron count in water ($N_w$) was made. This was used to determine the ratio of count in soil ($N_{sc}$) to that in water, which was the basis for calibration with volumetric water content.

At Sonning, calibration equations obtained in soil bins containing soil collected from the experimental site were used to convert neutron counts to soil water content (Naab, 1994). The linear regression equations used were:

At 10 cm, $\theta = 0.0314 + 1.306*N_{sc}/N_w$

At 20 cm, $\theta = -0.035 + 0.8095*N_{sc}/N_w$

At 30 cm, $\theta = -0.0558 + 0.857*N_{sc}/N_w$

$\geq 40$ cm, $\theta = -0.0595 + 0.8893*N_{sc}/N_w$

At Kabete, the manufacture's calibration equation for clay soils was used.

$\theta = 0.958 - 0.024 *N_{sc}/N_w$

## 3.6 Soil evaporation

Evaporation from the bare soil and beneath the crop canopy was measured with microlysimeters (Boast, 1986; Daamen, 1993) in all three experiments. At Sonning, the microlysimeters were made from PVC pipes 75 mm (internal diameter) x 150 mm length. These were installed in holes lined up with PVC sleeves of 80 mm internal diameter. Soil samples were collected carefully (to minimise disturbance) inside the plots in six replicates on a number of days and weighed (to 0.01 g) between 0900 and 1000 hrs. The cores were reweighed after 24 hours. New cores were taken every two days to ensure that the soil was representative of the surrounding. Cores that were rained on were discarded to avoid erroneous measurements.

In K1, measurements were taken in rainfed treatments, (one plot per treatment). Five microlysimeters were installed per plot. The microlysimeters were 70 mm (internal diameter) x 100 mm long while the PVC sleeve was 80 mm x 100 mm and were weighed twice daily (0900 and 1600 h). Similar measurements were made in K2 throughout the entire season.

The amount of soil water lost through evaporation was calculated from the change in soil core weight over 24 hours as $\Delta W/A$ where $\Delta W$ is the change in the weight of core and A is surface area of the core.

## 3.7 Water release characteristics

### 3.7.1 Soil water potential (filter paper method)

Soil water potential was measured at Sonning, K1 and K2 using the filter paper method (Hamblin, 1981). Soil samples were taken at 0-15, 15-30 and 30-45 cm depth in three replicates from a few selected plots. Whatman No. 42 filter paper discs (55 mm diameter) were put in plastic containers that were half filled with soil. The paper dics were covered with more soil ensuring good soil-paper contact. Plastic containers were sealed with tape (to prevent soil water loss) and left to equilibrate for at least four days at constant temperature. The filter papers were removed and weighed immediately, oven dried at 70°C for at least 24 hours and later reweighed. The soil was dried at 105°C to determine the soil water content.

### 3.7.2 Water release characteristics (pressure plates)

The pressure plate apparatus was used to determine the soil water release characteristics of the soil at Kabete. Soil samples were collected at Kabete from 0-15, 15-30 and 30-45 cm depth in four replicates in close proximity to each other in steel cores (5 cm long). The bottom end of the cores were covered with fine cloth that was held in place with a rubber band. The cores were left in water for 24 hours to allow absorption to saturation. The cores were placed on ceramic plates under pressure and the pressure was gradually increased from 0.01 MPa to 1.5 MPa (0.01, 0.3, 0.6, 1.0 and 1.5 MPa). Each core was left at a given pressure for a week, to allow time for equilibration. It is recognised that the short equilibration time may lead to an overestimate of water content, though this was unavoidable because of the limited access to the equipment. The cores were weighed each time to determine the amount of water lost and then pressure was increased. Finally the cores were oven dried at 105°C for four days to determine the gravimetric water content. The results are presented in figure 3.7 below.

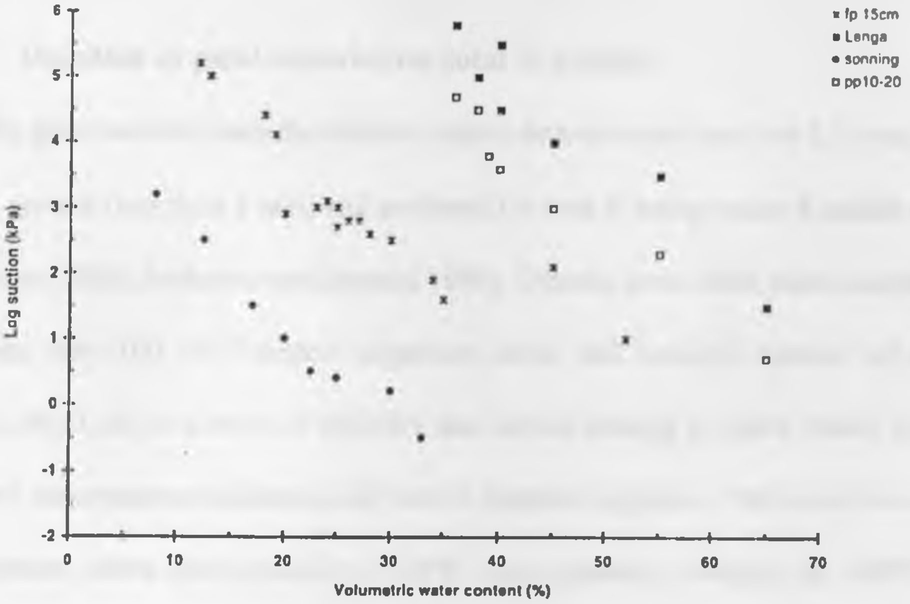


**Figure 3.7. Soil moisture characteristic curves of the Sonning and Kabete soils measured with a pressure plate (pp) and filter paper (fp) at the depths indicated. Sonning data was obtained from Naab (1994) and additional Kabete data from Lenga (1979).**

### 3.8 Soil samples to determine N analysis

Soil samples were taken to determine the soil mineral N and total N distribution in the profile in the Kabete experiments. Samples were taken one week before planting and at the end of the crop growing season, enabling seasonal N balances to be constructed. Two samples per plot were collected at 0-15, 15-30, 30-45, 45-60, and 60-75 cm and the soil was bulked. The soil samples for total N were air dried, ground manually with a (pestle and mortar) and passed through 2 mm sieve. A soil sample (0.20 g) was taken and digested in the same way as the plant material described below.

#### 3.8.1 Digestion of plant material for total N analysis.

The dry plant material used for total dry matter determination (section 3.1) was ground finely ground (less than 1 mm) and analyzed for total N using micro Kjeldhal method (Bremner, 1965; Anderson and Ingram, 1989). Ground, oven dried plant samples were weighed into 100 ml "tecator" digestion tubes and catalyst mixture of $K_2SO_4$, $CuSO_4.5H_2O$, Se in a ratio of 100:10:1 was added through a thistle funnel followed by 6 ml concentrated sulphuric acid from a Zippeter dispenser. The tubes were put in a digestion block and heated to 220°C and gradually brought to 380°C. This temperature was maintained for three hours after which the solution turned milky white or clear. The tubes were removed from the digestion block and allowed to cool to room temperature. 30 ml of distilled water was added to the digested plant material and mixed with a whirlmixer. The tubes were allowed to cool and the contents made up to 50 ml in a volumetric flask with distilled water. Total N from the Sonning samples was determined with an auto analyzer (colorimetric method). Total N forsamples from Kabete were determined by steam distillation (section 3.8.3).

### 3.8.2 Steam distillation for total N determination.

The steam distillation apparatus (Markham N still) was set up and steam allowed to pass through for 30 minutes. A steam blank (50 ml) distillate was collected and titrated with N/70 or M/140 HCl for plants and soil respectively. Aliquot measures of 5 ml from the digest (section above) were taken for distillation and the distillate collected in a solution containing 6.5 ml 0.01 N NaOH and 5 ml 1% boric acid-indicator solution. The distillate was titrated with M/140 HCl to a grey end-point using a microburette. Total N was calculated as:

$$\% \ N_{plant} = \frac{Corrected\ ml\ of\ N/70\ HCL\ x\ 0.2}{weight\ of\ sample} \qquad 3.5$$

Where $N_{plant}$ is % N in plant sample.

### 3.8.3 Soil mineral N determination

Soil samples were collected at 0-15, 15-30, 30-45, 45-60, 60-75 cm depths using an auger at the beginning and end of the season in K1. In K2, samples were taken to 75 cm depth (at 15 cm interval). Two soil profiles per plot were sampled and the replicate soil were thoroughly mixed. Soils were stored in a deep freezer shortly after sampling and thawed out for the mineral N determination. 30 g of the soil was weighed into a 200 ml plastic container and 100 ml 2 M KCl added to the soil and put in a shaker for 1 hour. The contents were filtered. Another 20 g of the soil sample was dried in the oven at 105°C for soil moisture content determination.

$NO_3^-$-N and $NH_4^+$-N was determined by steam distillation of the KCl extract using 0.4 g Devarda's alloy and 0.2 g MgO as catalysts. The distillate was collected in $H_3BO_3$

solution and titrated with dilute $H_2SO_4$ for the N determination.

### 3.9 Nitrogen fixation determination by difference method.

Nitrogen fixation was determined using the nitrogen difference method (Lyon and Bizzel, 1934; Giller and Wilson, 1991). The N derived from fixation ($N_{dfa}$) is calculated as the difference between total N in the bean crop and the total N in a non-fixing wheat crop grown in an adjacent plot at the same time (kg $ha^{-1}$). 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 bean and the reference crop.

The assumptions made in the N difference method are that the fixing and reference crops exploit the same soil volume (have access to the same N pool) and take up the same amount of soil N. The ideal reference crop would be a non-fixing isoline, or a crop grown on otherwise identical soil where no indigenous rhizobia exists. For example, uninoculated nodulating line would be an excellent control in situations where there were no indigenous rhizobia. Some of the reference crops that have been used in bean fixation studies include barley (Rennie and Kemp, 1984; Ssali and Keya, 1984), maize (Karanja, 1988; Pilbeam *et al.*, 1995a) and wheat (Alaides *et al.*, 1981). Both barley and maize were found to take up more N than beans (Ssali and Keya, 1984; Pilbeam personal communication). A wheat variety with the same maturity period as the Mwezi Moja beans was therefore selected as a reference crop.

Wheat (var. Kenya Paka) was grown along side the bean crop and subjected to the same water and fertilizer nitrogen treatments as the beans. The conventional seeding rate (100 kg seed/ha) was used. The plants were harvested at the end of the growing season and analyzed for total N as described in the section above.

# Chapter 4

## Climatic inventory of the experimental sites

### 4.1 Introduction

The objective of this chapter is to assess the differences between the three growing seasons and the meteorological variables likely to influence growth. The chapter considers some of the difficulties encountered in the analysis of daily records, when diurnal patterns of such variables as temperature and saturation deficit are required in order to account for their integral over time. The variables investigated include:

i) Temperature regime - Maximum and minimum temperature

- Accumulation of thermal time

ii) Atmospheric humidity - Mean daytime relative humidity (0600 to 1800 East African Standard Time; EAST)

- Maximum, minimum and diurnal patterns of saturation deficit.

iii) Rainfall - daily rainfall

iv) Potential evaporation - Daily values estimated using Penman-Monteith equation

v) Total solar radiation - Daily values and seasonal totals

### 4.1.1 Air Temperature regimes.

Temperature influences the rate of plant developmental processes in *Phaseolus vulgaris* (Masaya and White, 1991). The seasonal daily maximum, minimum and mean temperatures for each of the three experiments are presented in figure 4.1 and the seasonal average values summarised in table 4.1. The average seasonal temperatures in the three experiments were similar (table 4.1). However, the seasonal temperature fluctuation was highest at Sonning and least in K1.

Table 4.1 Summary of temperature seasonal average minimum, maximum and mean temperatures (°C) for the three experiments.

| Temperature(°C) | Experiment | | |
|---|---|---|---|
| | Sonning | K1 | K2 |
| Seasonal values | | | |
| Minimum | 12.1 ± 1.7 | 13.4 ± 1.0 | 13.7 ± 1.2 |
| Maximum | 24.5 ± 2.2 | 22.0 ± 1.6 | 23.8 ± 1.7 |
| Mean | 18.3 ± 1.4 | 17.8 ± 0.9 | 18.5 ± 0.5 |
| Record minimum | 5 | 7 | 8.2 |
| Record maximum | 29.4 | 25.1 | 27.4 |
| Range | 24.4 | 18.1 | 19.2 |

number after ± refers to standard deviation from the mean.

### 4.1.2 Choosing a base temperature

The dependence of developmental processes on temperature is quantified in terms of thermal time (equation 2.12), which is usually calculated using the daily mean temperature and a base temperature, $T_b$ (equation 2.12). The base temperature is the minimum temperature at which a process occurs. White and Montes-R (1993) established $T_b$ for germination of bean seeds as 8°C. In attempt to determine the $T_b$ for Mwezi Moja beans, the number of nodes on the main stem were plotted against accumulated thermal time, using different values for $T_b$. The number of nodes (basic

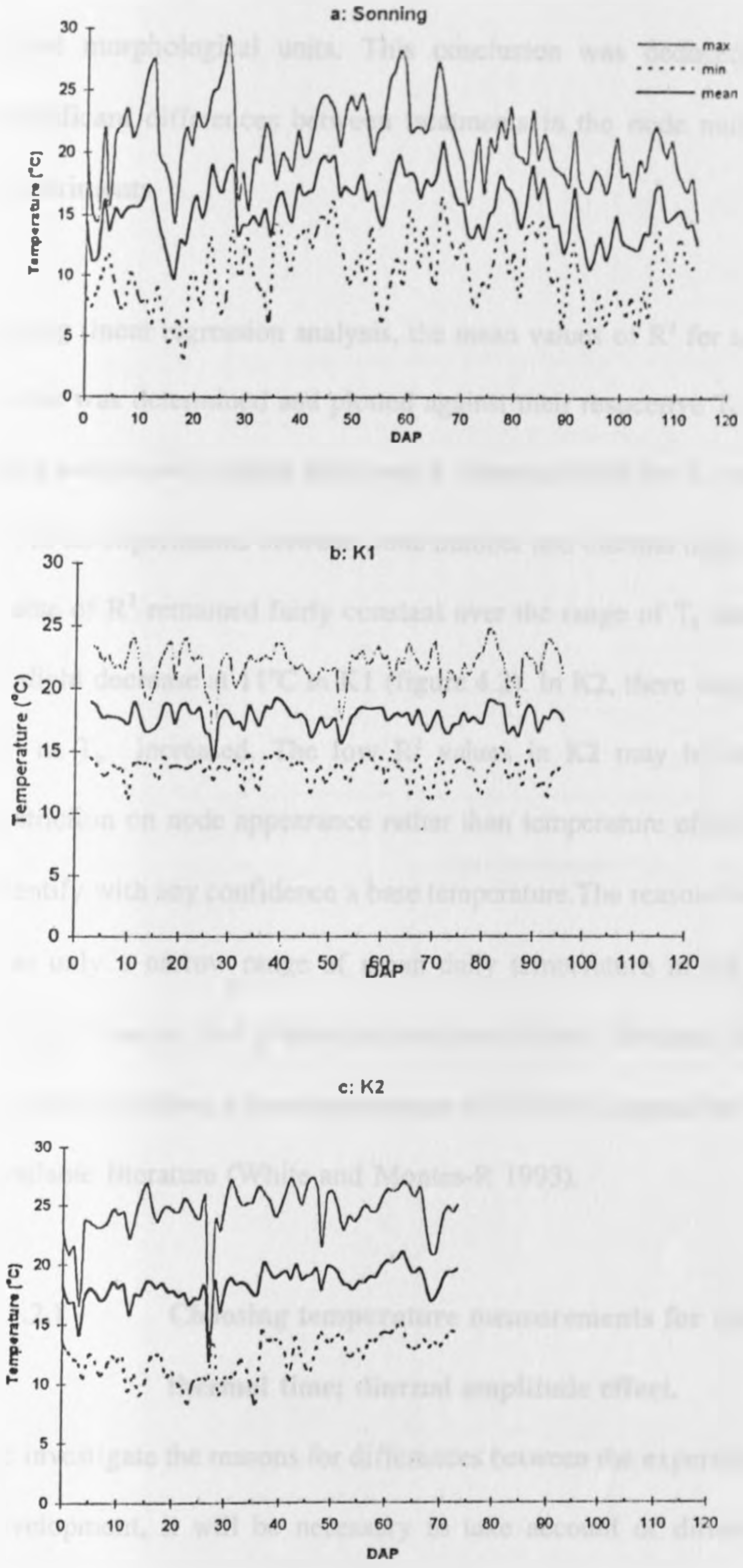


Figure 4.1. Daily minimum, maximum and mean air temperature (°C) for Sonning, K1 and K2 experiments.

developmental unit) was less dependent on other environmental conditions than other plant morphological units. This conclusion was deduced from there being non significant differences between treatments in the node number in any of the three experiments.

Using linear regression analysis, the mean values of $R^2$ for all treatments for each $T_b$ value was determined and plotted against their respective $T_b$ values (figure 4.2). The idea was to see whether there was a common value for $T_b$ which give the best linear fit in all experiments between node number and thermal time. At Sonning and K1, the value of $R^2$ remained fairly constant over the range of $T_b$ used with the exception of a slight decrease at 11°C in K1 (figure 4.2). In K2, there was an apparent decrease in $R^2$ as $T_b$ increased. The low $R^2$ values in K2 may be evidence of water stress restriction on node appearance rather than temperature effect. This analysis failed to identify with any confidence a base temperature.The reason for this failure if that there was only a narrow range of mean daily temperature in the data set, which makes extrapolation to find a base temperature difficult. Because the resultant information was not definitive, a base temperature of 8°C was adopted for Mwezi Moja, based on available literature (White and Montes-R 1993).

#### 4.1.2.1 Choosing temperature measurements for calculating accumulated thermal time; diurnal amplitude effect.

To investigate the reasons for differences between the experiments in crop growth and development, it will be necessary to take account of differences between in crop development attributable directly to the temperature regime. Although the mean daily

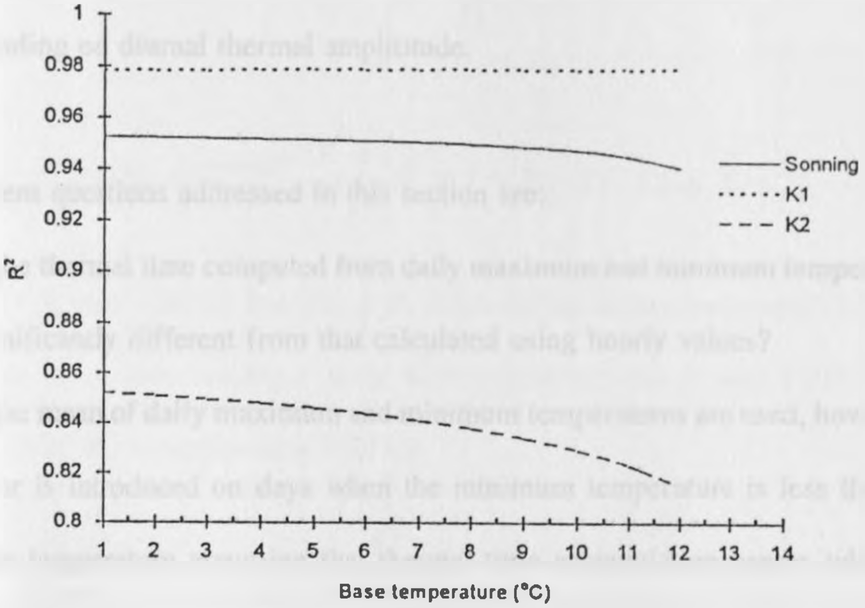


Figure 4.2. The influence of the value for base temperature used in the thermal time calculation on $R^2$ obtained from the regression of node number on accumulated thermal time . The least number of samples was 12 per experiment.

temperatures in the three experiments were similar, there were large differences in the diurnal amplitude of temperature. In particular, at Sonning there were times when the temperature was less than the base temperature for development. Loomis and Connor (1992) pointed out that the length of a particular phenostage (in chronological time) of a crop cultivar at locations with the same daily mean temperature (Tmean) may vary depending on diurnal thermal amplititude.

The pertinent questions addressed in this section are:

a) Is the thermal time computed from daily maximum and minimum temperatures significantly different from that calculated using hourly values?

b) If the mean of daily maximum and minimum temperatures are used, how much error is introduced on days when the minimum temperature is less than the base temperature assuming that thermal time accumulation ceases when the temperature is below $T_b$?

The accumulated thermal time was calculated using three different methods.

Method 1: using maximum and minimum daily temperatures (TTDAP)

$$TTDAP = \Sigma_0^{DAP}[\frac{(Tmax - Tmin)}{2}] - T_b \qquad 4.1$$

Where DAP is days after planting

Tmax is daily maximum temperature (°C)

Tmin in daily minimum temperature (°C)

$T_b$ is the base temperature, and in this case 8°C.

### Method 2: using hourly temperatures (TTHAP)

$$TTHAP = \Sigma_0^{HAP} \frac{(T - T_b)}{24} \qquad 4.2$$

Where HAP is hours after planting and T is the hourly average temperature.

### Method 3: using hourly temperatures and correcting for temperatures lower than $T_b$ (TTHAPc)

$$TTHAPc = \sum_0^{HAP} \frac{[T - T_b]}{24} \; if\ T > T_b,\ else\ [0]\ if\ T < T_b \qquad 4.3$$

Method 3 was used with the Sonning data, where the minimum temperature fell below $T_b$ at night on a few occasions early in the growing season and TTHAPc was compared with the corresponding TTHAP.

Hourly temperature records were available at Sonning but not at Kabete. However, hourly temperature values were available from Dagoretti, a meteorological station about 5 km away from Kabete. A summary of long term weather records for Kabete and Dagoretti is provided in table 4.2.

Before using the Dagoretti data to investigate the influence of diurnal patterns at Kabete, it was important to assess the predictability of temperatures at Kabete from those at Dagoretti. Temperatures at Kabete were measured at 0900 and 1500 together with daily minimum and maximum temperatures (subsequently referred to as T0900, T1500, Tmin, Tmax respectively). These were compared with corresponding values at Dagoretti in attempt to quantify the error involved in using the hourly temperature data from Dagoretti to estimate thermal time accumulation at Kabete. Estimation of

Table 4.2 Summary of long term rainfall and temperature characteristics of Kabete and Dagoretti.

| Site | Characteristic | | | |
|---|---|---|---|---|
| | Altitude (m) | Temperature (°C) | | Rainfall (mm) |
| | | Minimum | Maximum | |
| Kabete | 1942 | 13.0 | 23.9 | 985 |
| Dagoretti | 1798 | 11.9 | 23.4 | 1049 |

Source: Climatological Statistics for Kenya (1984).

any of the four temperatures at Kabete from measurements made at Dagoretti showed 50% to 75% error indicated by $R^2$ values (figures 4.3 a and b). It was difficult to predict temperature at Kabete at any one particular time from measurements made at Dagoretti, despite the two being less than 5 km apart. Nevertheless, the diurnal temperature trend at Kabete and Dagoretti are likely to be more similar than just individual point measurements on the diurnal temperature curve.

The Dagoretti temperature data were used to examine the effect of diurnal temperature fluctuations on thermal time accumulation during the experimental periods at Kabete (K1 and K2 seasons). This was used to compare and contrast the effect of diurnal thermal amplitude on accumulated on TTDAP and TTHAP at Sonning and Dagoretti in the K1 and K2 seasons. In Sonning, hourly temperature values were used to

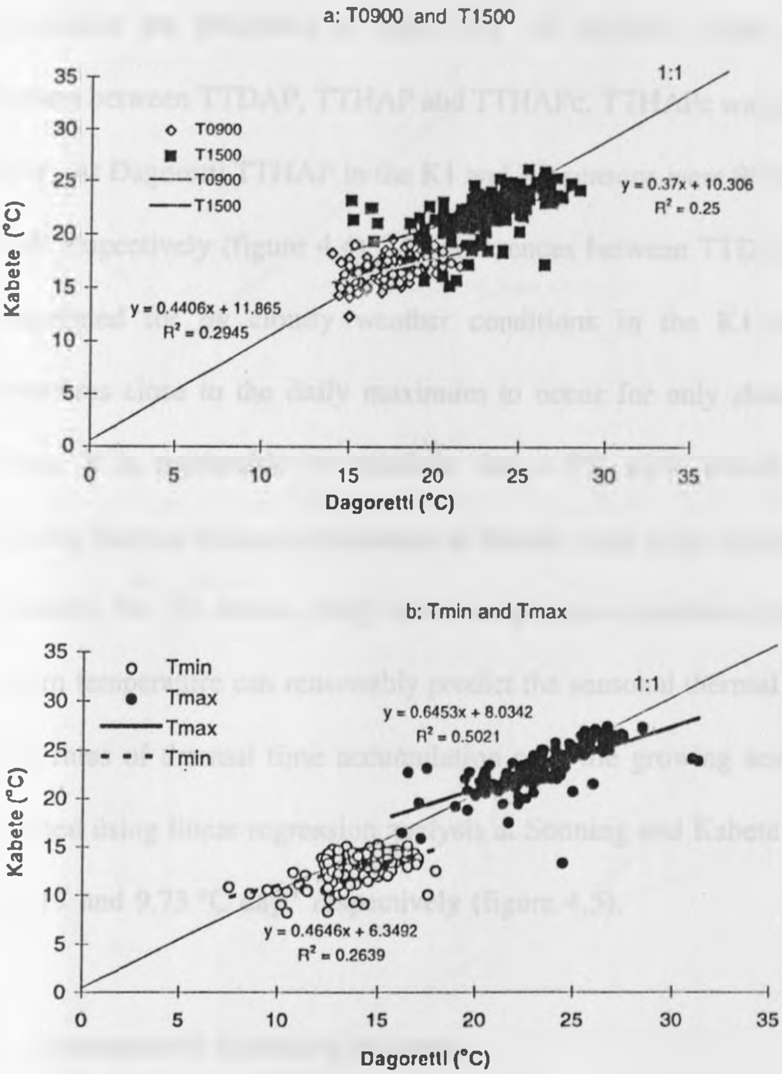


**Figure 4.3. a Comparison of temperature at Kabete and Dagoretti at 0900, 1500 and (b) daily minimum and maximum temperatures for the period of K1 and K2 experiments.**

compare all three methods (TTDAP, TTHAP, TTHAPc).

#### 4.1.2.2 Results.

The results of the comparison of the various methods of calculating thermal time accumulation are presented in figure 4.4. At Sonning, there was no significant difference between TTDAP, TTHAP and TTHAPc. TTHAPc was only 3% higher than TTHAP. At Dagoretti TTHAP in the K1 and K2 seasons were 9% and 3% higher than TTDAP respectively (figure 4.4). The differences between TTDAP and TTHAP may be accounted for by cloudy weather conditions in the K1 season that caused temperatures close to the daily maximum to occur for only short periods of bright sunshine. It is reasonable to conclude that a 9% error would be introduced by calculating thermal time accumulations at Kabete from daily maximum and minimum temperature. On the whole, daily mean temperature calculated from maximum and minimum temperature can reasonably predict the seasonal thermal accumulation. The average rates of thermal time accumulation over the growing season using TTDAP determined using linear regression analysis at Sonning and Kabete (K1 and K2) were 7.88, 9.17 and 9.73 °C day$^{-1}$ respectively (figure 4.5).

### 4.2.0 Atmospheric Humidity regimes.

Relative humidity (RH) is the ratio of actual vapour pressure to the saturation vapour pressure at the same temperature (Monteith and Unsworth, 1990). Values of SD in the three experiments were calculated from temperature (dry bulb) and RH measurements made during the experimental periods. SD is highly variable among regions, from

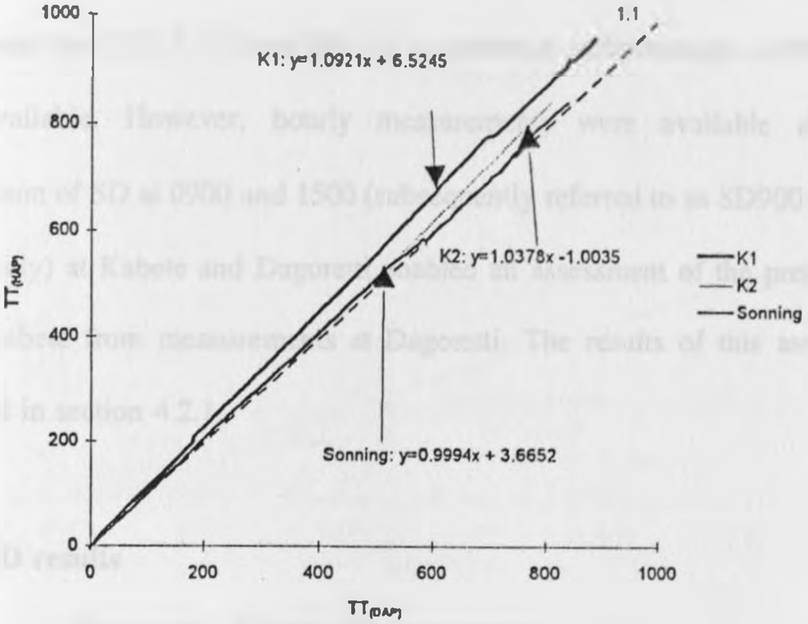


Figure 4.4. Comparison of $TT_{(DAP)}$ and $TT_{(HAP)}$ at Sonning and Dagoretti in the K1 and K2 seasons.

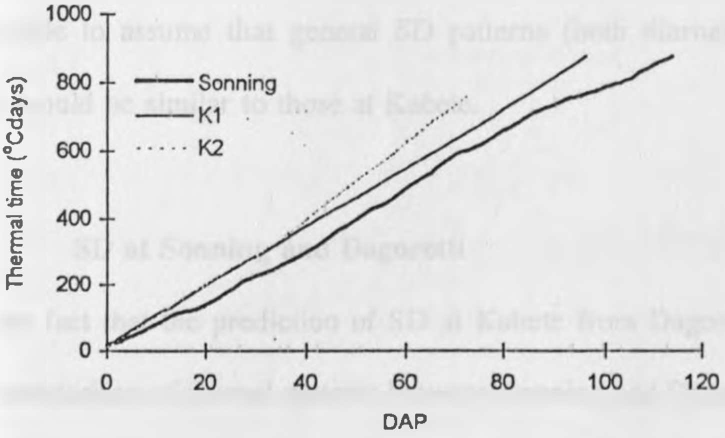


Figure 4.5. Comparison of accumulated thermal time ($TT_{(DAP)}$) at the Sonning, K1 and K2 experiments.

season to season and within a season and on a diurnal basis in a location (Stanhill, 1986). Assessment of the diurnal variation in SD requires hourly measurements of temperature and RH. At Kabete RH and temperature measurements at 0900 and 1500 were available. However, hourly measurements were available at Dagoretti. Comparison of SD at 0900 and 1500 (subsequently referred to as SD900 and SD1500 respectively) at Kabete and Dagoretti enabled an assessment of the predictability of SD at Kabete from measurements at Dagoretti. The results of this assessment are presented in section 4.2.1.

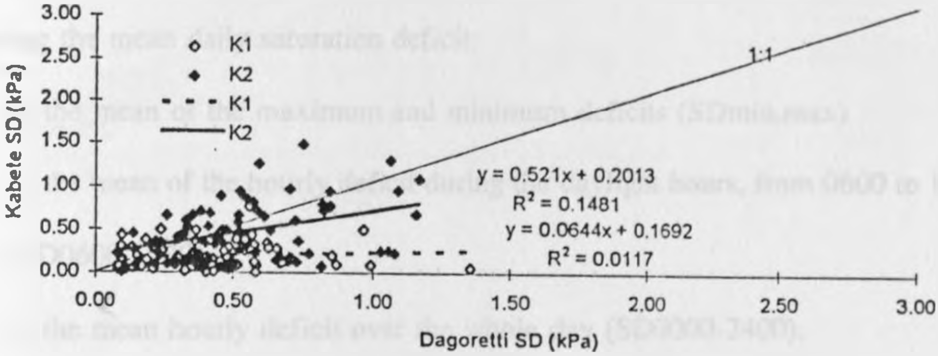
### 4.2.1 SD results

#### 4.2.1.1 Dagoretti - Kabete SD comparison.

Linear regression analysis of SD0900 and SD1500 at Dagoretti against Kabete showed high variation indicated by the low $R^2$ values (figure 4.6 a and b). In general, prediction of SD at Kabete from measurements made at Dagoretti was difficult. However, although absolute values on any given day are not well correlated, it may be reasonable to assume that general SD patterns (both diurnal and seasonal), at Dagoretti would be similar to those at Kabete.

#### 4.2.1.2 SD at Sonning and Dagoretti

Despite the fact that the prediction of SD at Kabete from Dagoretti data had large errors, a comparison of diurnal patterns between Sonning and Dagoretti was for made for the experimental period of K1 and K2, due to lack of alternative data. This provided a basis for the comparison of the SD patterns in the tropical and temperate conditions in which the experiments were conducted. Comparison of WUE under a: SD0900



b: SD1500

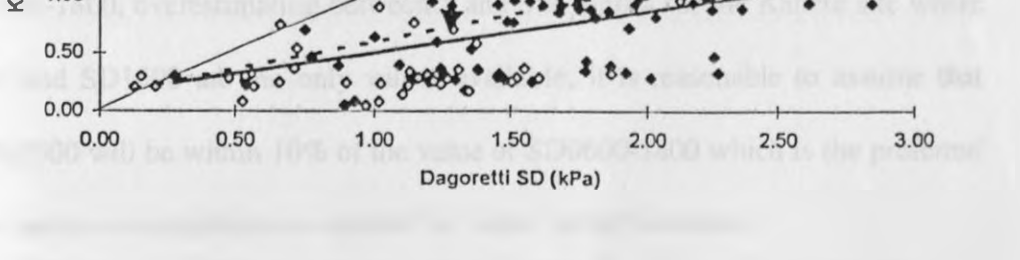


Figure 4.6 : Comparison of SD0900 and SD1500 at Dagoretti and Kabete during the experimental period (19/11/92 to 23/04/1993)

different environmental conditions requires normalisation of transpiration with an appropriate value for the mean saturation deficit (SDmean).

In the analysis which follows,comparisons are made between the mean of the values of SD at 0900 and 1500 (SD0900,1500) with the following possible ways of expressing the mean daily saturation deficit:

a) the mean of the maximum and minimum deficits (SDmin,max)

b) the mean of the hourly deficit during the daylight hours, from 0600 to 1800 (SD0600-1800)

c) the mean hourly deficit over the whole day (SD0000-2400).

Of these, perhaps SD0600-1800 is the most useful as it represents the mean deficit during the hours of daylight when transpiration is occurring, making it the most appropriate mean to use as a normalising variable in water use efficiency comparisons (Tanner and Sinclair, 1983; Stanhill, 1986).

In general daily SD0900,1500 overestimated SD0600-1800. Sdmin,max and SD0000-2400 (figure 4.7). This is because SD1500 is close to maximum SD, whereas SD0900 is substantially greater than the nighttime minimum. However, SD0900,1500 was close to SD0600-1800, overestimating between 5 and 8%. Hence for the Kabete site where SD0900 and SD1500 are the only values available, it is reasonable to assume that SD0900,1500 will be within 10% of the value of SD0600-1800 which is the preferred mean to use as a normalisation variable for water use efficiencies.

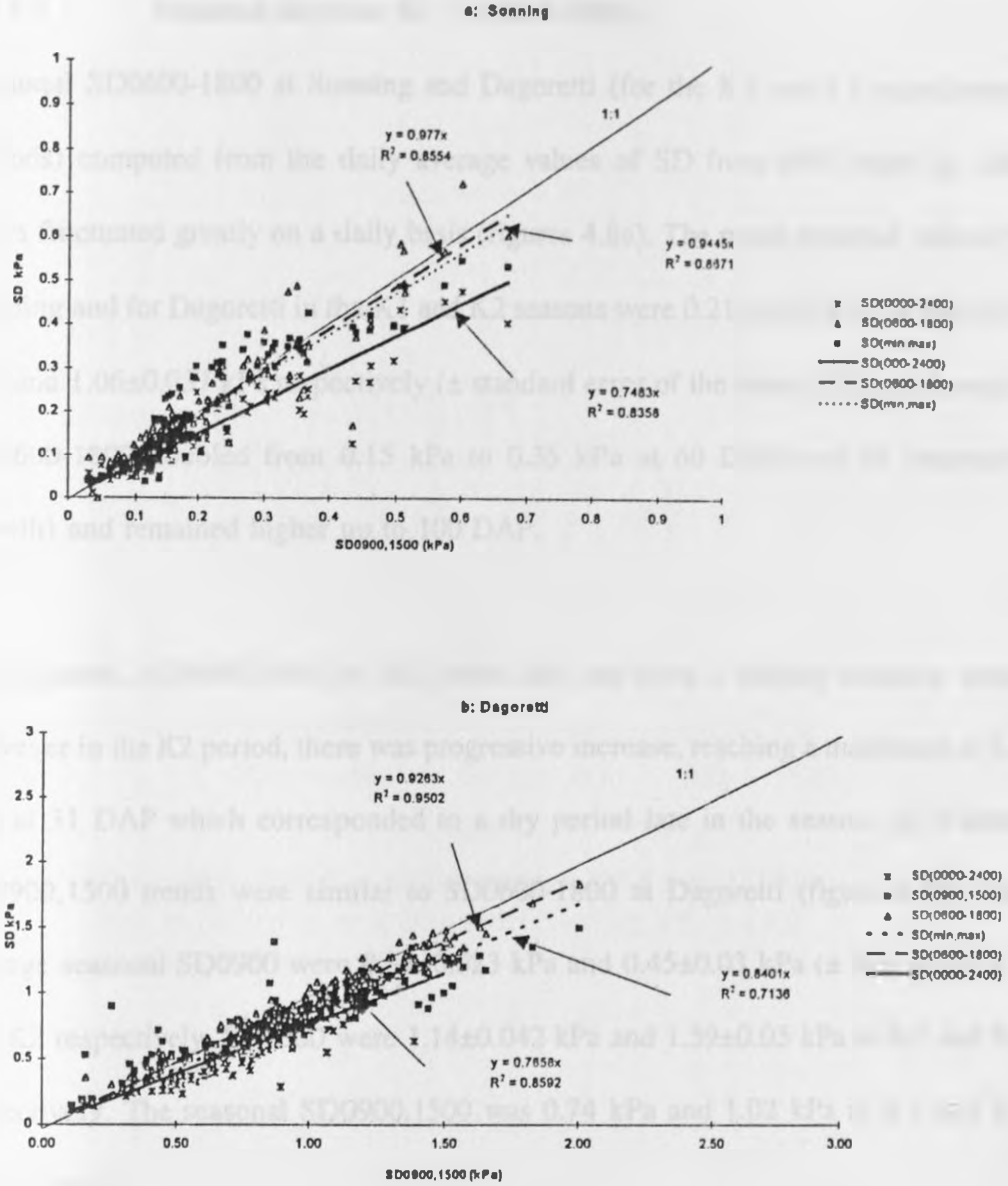


**Figure 4.7 Comparison of different methods of calculating mean daily SD at Sonning and Dagoretti. SDmin,max, SD0600-1800 and SD0000-2400 are compared to the widely available SD0900,1500 values**

#### 4.2.1.3 Seasonal daytime SD (SD0600-1800).

Seasonal SD0600-1800 at Sonning and Dagoretti (for the K1 and K2 experimental periods) computed from the daily average values of SD from 0600 hours to 1800 hours fluctuated greatly on a daily basis (figures 4.8a). The mean seasonal values for Sonning and for Dagoretti in the K1 and K2 seasons were 0.21±0.013 kPa, 0.76±0.028 kPa and 1.06±0.037 kPa respectively (± standard error of the mean; SE). At Sonning, SD0600-1800 doubled from 0.15 kPa to 0.35 kPa at 60 DAP (end of vegetative growth) and remained higher up to 100 DAP.

At Dagoretti, SD0600-1800 for K1 period did not have a distinct seasonal trend. However in the K2 period, there was progressive increase, reaching a maximum of 2.8 kPa at 31 DAP which corresponded to a dry period late in the season. At Kabete, SD0900,1500 trends were similar to SD0600-1800 at Dagoretti (figure 4.8b). The average seasonal SD0900 were 0.34±0.023 kPa and 0.45±0.03 kPa (± SE) in the K1 and K2 respectively. SD1500 were 1.14±0.042 kPa and 1.59±0.05 kPa in K1 and K2 respectively. The seasonal SD0900,1500 was 0.74 kPa and 1.02 kPa in K1 and K2 respectively.

#### 4.2.1.4 Seasonal minimum and maximum SD (SDmin and SDmax).

The importance of daytime SD has important direct implications for WUE. There is also evidence that nighttime saturation deficit has important implications for leaf growth, hence WUE. The seasonal patterns of SDmin and SDmax at Sonning and Dagoretti (K1 and K2 periods) are presented in figure 4.9. SDmax was more variable than SDmin in both locations. At Sonning, SDmax values increased threefold from

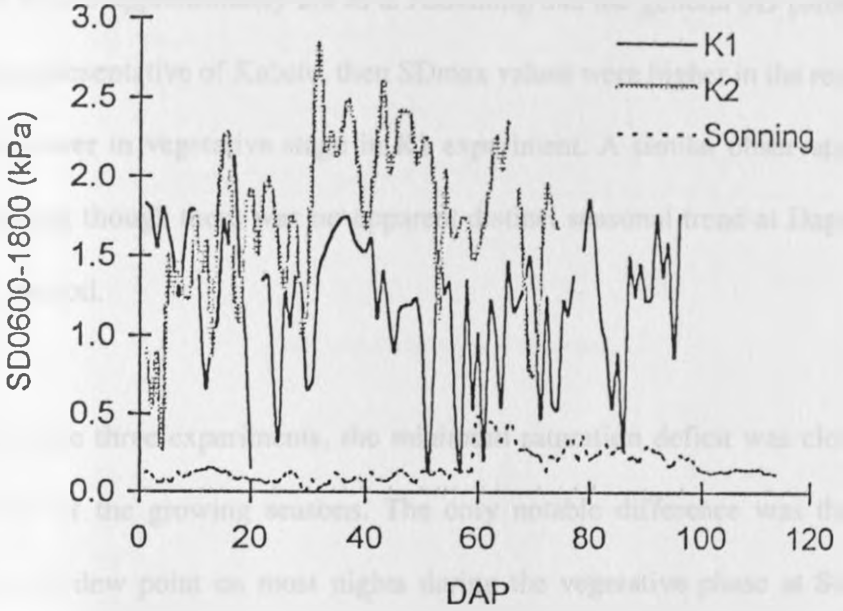


**Figure 4.8a. Relationship between DAP and SD0600-1800 at Sonning and Dagoretti during K1 and K2 experimental periods.**

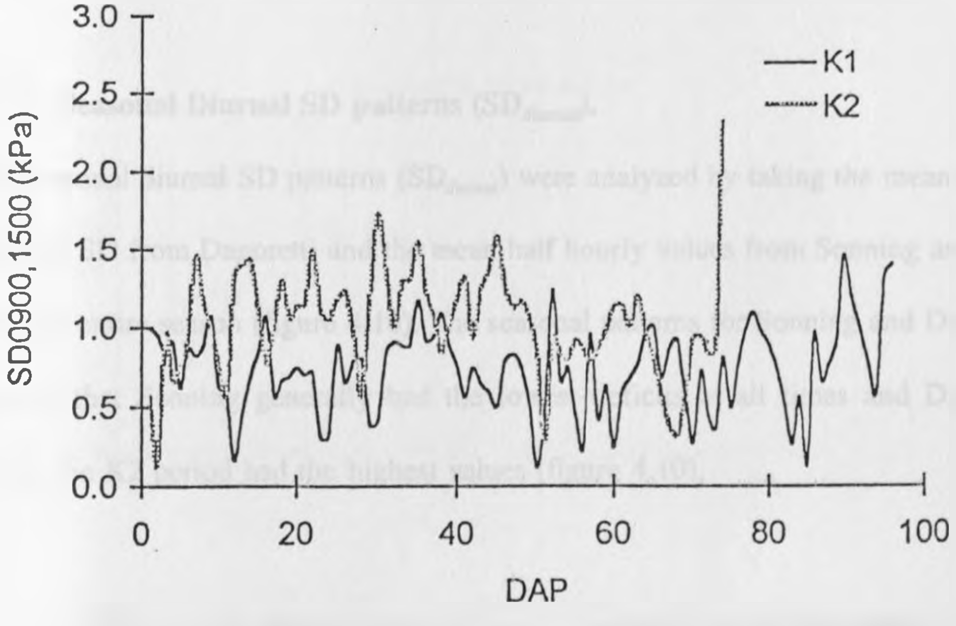


**Figure 4.8b. Relationship between DAP and SD0900,1500 at Kabete in the K1 and K2 experimental periods.**

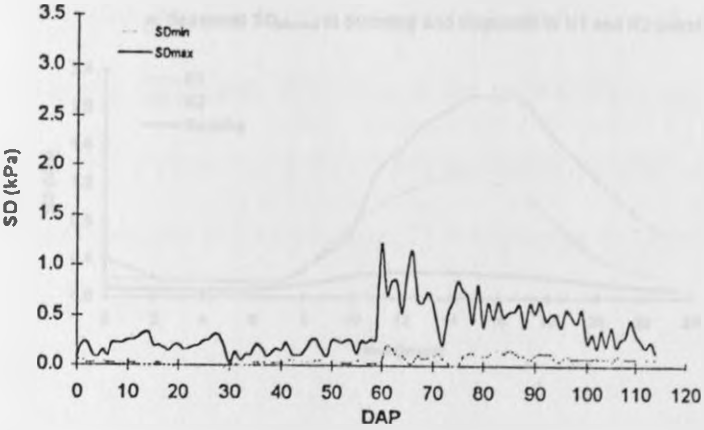
0.35 kPa early in the season to 1.2 kPa at 58 DAP. At Dagoretti in K1 and K2 periods, SDmax was 1.35±0.42 kPa and 1.81±0.5 kPa respectively. SDmax atDagoretti in the K2 period was lower early in the season (0 to 30 DAP) and increased later from 1.4 kPa to approximately 2.0 kPa. Assuming that the general SD patterns of Dagoretti are representative of Kabete, then SDmax values were higher in the reproductive phase and lower in vegetative stage in K2 experiment. A similar observation was made at Sonning though there was no apparent distinct seasonal trend at Dagoretti during the K1 period.

In all the three experiments, the minimum saturation deficit was close to zero at all stages of the growing seasons. The only notable difference was that the humidity reached dew point on most nights during the vegetative phase at Sonning, whereas after 60 DAP (and at all stage of both the Kabete growing seasons) there was a slight deficit maintained at night, with the minimum values at Kabete (0.2 kPa) being about twice those at Sonning (0.1 kPa).

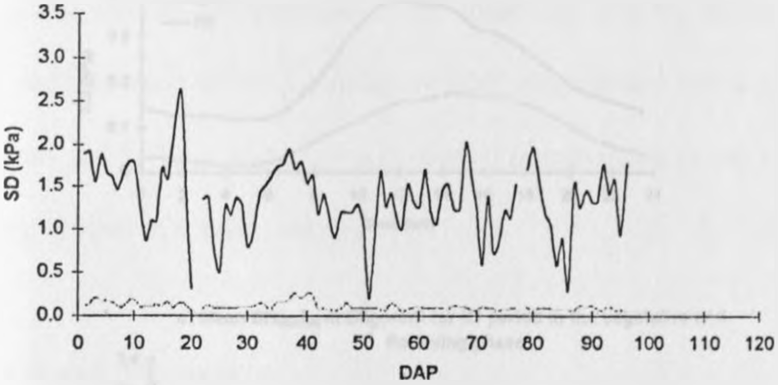
### 4.2.2 Seasonal Diurnal SD patterns ($SD_{diurnal}$).

The seasonal diurnal SD patterns ($SD_{diurnal}$) were analyzed by taking the mean hourly value of SD from Dagoretti and the mean half hourly values from Sonning averaged over the entire season (figure 4.10). The seasonal patterns for Sonning and Dagoretti showed that Sonning generally had the lowest deficits at all times and Dagoretti during the K2 period had the highest values (figure 4.10).

a) Sonning



b) Dagoretti in the K1 season



c) Dagoretti in the K2 season

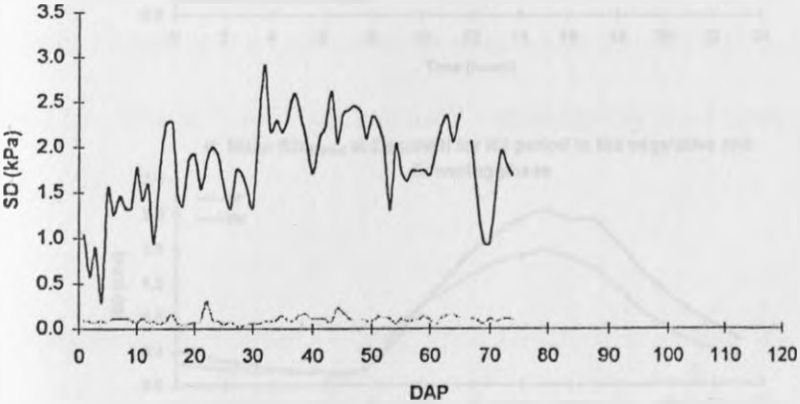
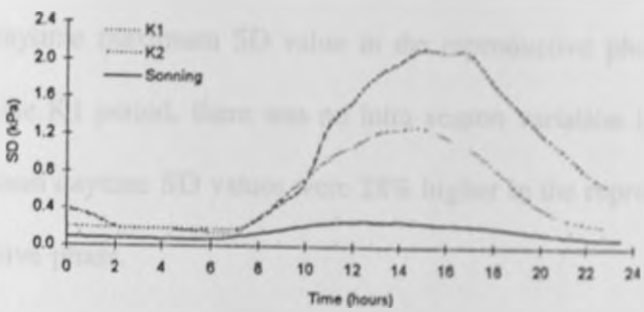
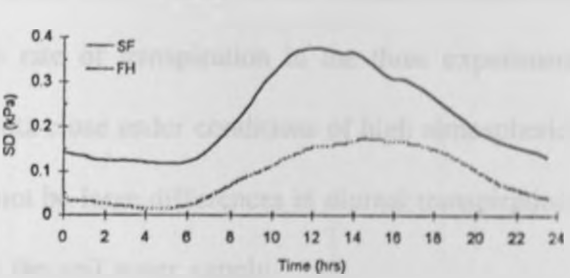


Figure 4.9 a, b, and c. Seasonal patterns of maximum and minimum saturation deficit (SDmin and SDmax) at Sonning, and Dagoretti in K1 and K2 seasons.

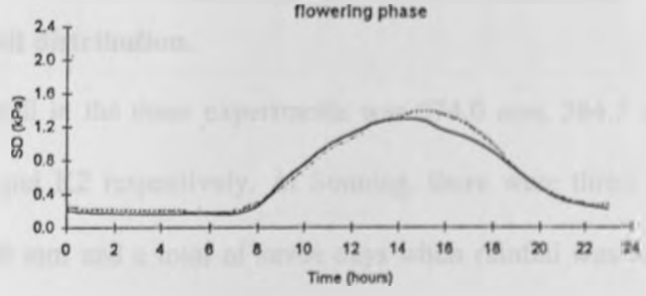
a: Seasonal SD$_{diurnal}$ at Sonning and Dagoretti in K1 and K2 seasons



b: Mean SD$_{diurnal}$ at Sonning in the vegetative and flowering phase.



c: Mean SD$_{diurnal}$ at Dagoretti for K1 period in the vegetative and flowering phase



d: Mean SD$_{diurnal}$ at Dagoretti for K2 period in the vegetative and flowering phase

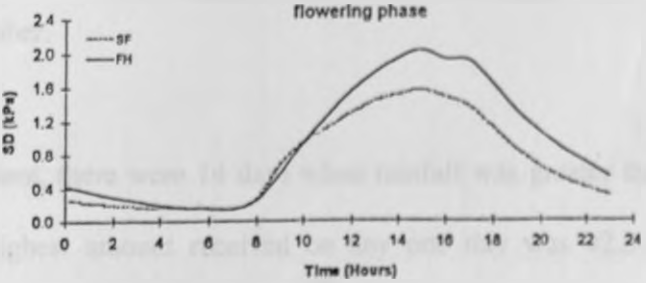


**Figure 4.10. a) Comparison of mean seasonal SD$_{diurnal}$ at Sonning and Dagoretti for K1 and K2 experimental periods. b-d Variation of SDdiurnal in the vegetative (SF) and flowering (FH) phases of growth.**

Analysis of within season $SD_{diurnal}$ patterns showed that there was variation at Sonning and Dagoretti during the K2 period. At Sonning, there was an approximately 40% increase in daytime maximum SD value in the reproductive phase of the crop. At Dagoretti in the K1 period, there was no intra season variation in SD, while in K2 period maximum daytime SD values were 28% higher in the reproductive phase than in the vegetative phase.

Atmospheric $SD_{diurnal}$ is closely related to leaf $SD_{diurnal}$ which is the driving force of transpiration when water supply is not limited. It would be an over-simplification to state that the rate of transpiration in the three experiments would follow $SD_{diurnal}$ because stomata close under conditions of high atmospheric SD (Jones, 1983). There may or may not be large differences in diurnal transpiration in the three experiments depending on the soil water supply.

## 4.3 Rainfall distribution.

The total rainfall in the three experiments was 274.0 mm, 384.1 and 105.6 mm for Sonning, K1 and K2 respectively. At Sonning, there were three days with rainfall greater than 40 mm and a total of seven days when rainfall was higher than 10 mm (figure 4.11a). The early part of the season was relatively dry followed by late season rain in September.

In K1 experiment, there were 14 days when rainfall was greater than 10 mm (figure 4.11b). The highest amount received on any one day was 42.3 mm at 60 DAP, corresponding to pod growth stage. There were 3 dry spells when average daily

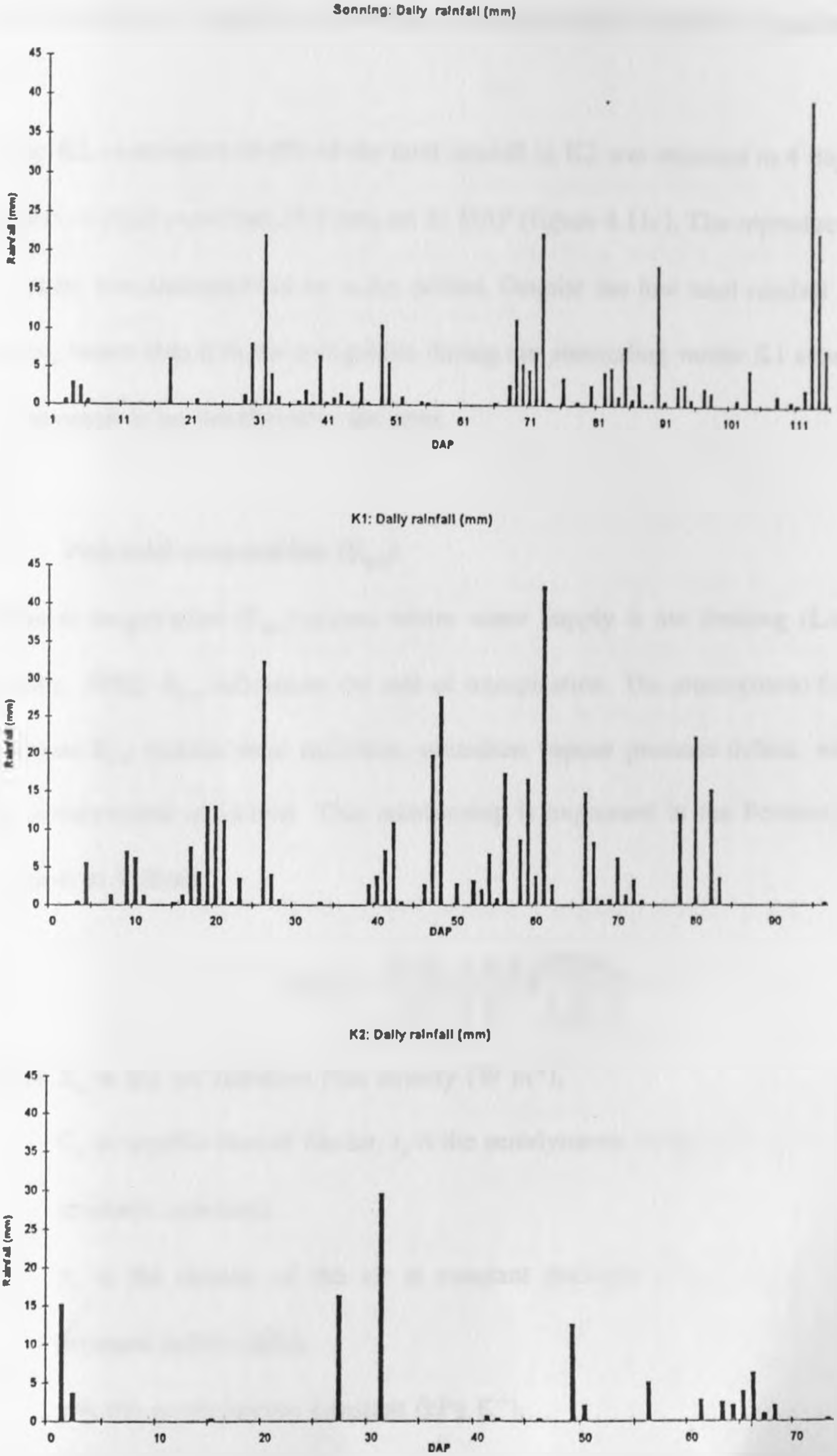


Figure 4.11. Daily rainfall distribution pattern in Sonning, K1 and K2.

rainfall was less than 10 mm (0 to 19 DAP, 29 to 47 DAP and 83 to 95 DAP) corresponding to vegetative, flowering and physiological maturity respectively.

In the K2 experiment 69.6% of the total rainfall in K2 was received in 4 days and the highest rainfall event had 29.5 mm on 31 DAP (figure 4.11c). The reproductive phase of beans was characterised by a dry period. Despite the low total rainfall in the K2 season, water stored in the soil profile during the preceeding wetter K1 season would be expected to be beneficial to the crop.

## 4.4 Potential evaporation ($E_{pot}$).

Potential evaporation ($E_{pot}$) occurs where water supply is not limiting (Loomis and Connor, 1992). $E_{pot}$ influences the rate of transpiration. The atmospheric factors that influence $E_{pot}$ include solar radiation, saturation vapour pressure deficit, wind speed and aerodynamic resistance. This relationship is expressed in the Penman-Monteith equation as follows:

$$ET_o = \frac{\Delta R_n + \rho_a C_p (SD)/r_a}{\Delta + \gamma(1 + r_c/r_a)} \qquad 4.4$$

Where $R_n$ is the net radiation flux density (W $m^{-2}$),

$C_p$ is specific heat of the air, $r_a$ is the aerodynamic resistance and $r_c$ is the bulk stomatal resistance.

$\rho_a$ is the density of the air at constant pressure, SD is saturation vapour pressure deficit (kPa),

$\gamma$ is the psychometric constant (kPa $K^{-1}$),

$\Delta$ is the slope of the saturation vapour pressure versus temperature (kPa $K^{-1}$)

$r_a$ in the above equation is calculated as (Jones, 1983).

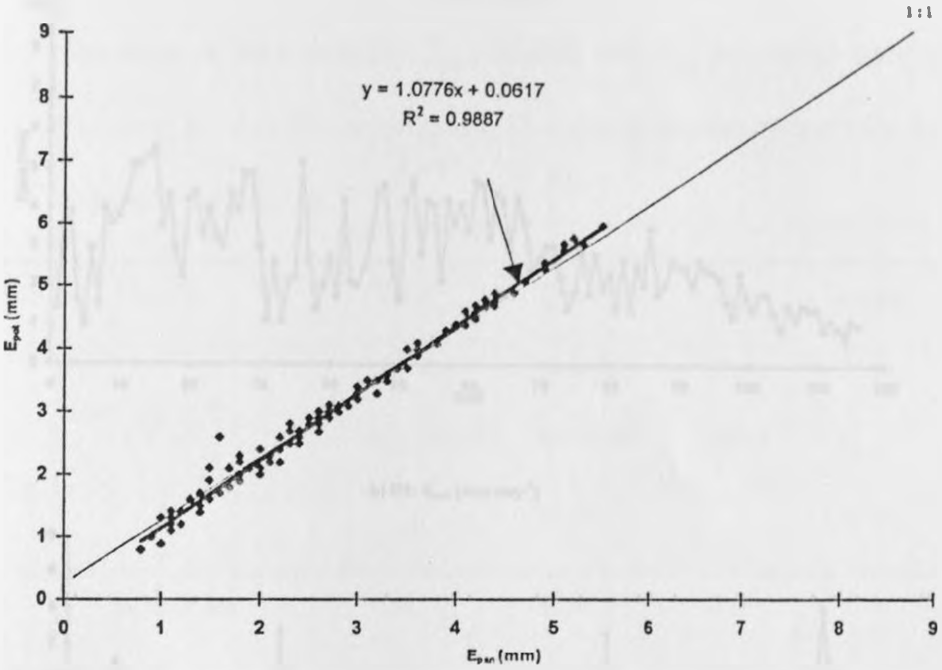
$$r_a = \frac{(\ln[(z - d)/z_o])^2}{k^2 u} \qquad 4.5$$

where z is the height at which wind speed is measured (usually 2 m); $z_o$ is the roughness length (m), d is the zero plane displacement, u is the wind speed at height z (m $s^{-1}$), k is the von Karman constant (0.41).

In some circumstances, evaporation from an open water surface in a pan, ($E_{pan}$) reasonably estimates $E_{pot}$ (Doorenbos and Pruitt, 1977). Comparison of $E_{pot}$ and $E_{pan}$ values for Sonning showed that $E_{pan}$ values were 8% higher than $E_{pot}$ (figure 4.12). There was linear relationship between $E_{pan}$ and $E_{pot}$ at Kabete. $E_{pot}$ tended to exceed $E_{pan}$, though there was a large, apparently random error, giving rise to considerable scatter. The analysis which follows is based on $E_{pan}$ measurements, because of the uncertainty in the appropriate value of SD to use in the calculation of $E_{pot}$ for Kabete. The daily $E_{pan}$ values in the three experiments fluctuated greatly (figure 4.13). The mean daily $E_{pan}$ in the three experiments was 2.8±1.2 mm (± standard deviation), 4.0±1.4 mm and 5.0±1.2 mm for Sonning, K1 and K2 respectively. Seasonal total $E_{pan}$ were 321.3 mm 378.6 mm, and 357.6 mm for Sonning, K1 and K2 respectively. Total $E_{pan}$ exceeded rainfall by a factor of 3.4 in the K2 experiment but the ratio was close to 1:1 in the Sonning and K1 experiments.

At Sonning, total monthly $E_{pan}$ in the experimental period was highest in June and decreased thereafter to a minimum in September (table 4.3). The maximum daily evaporation was 5.5 mm on 15/06/92. The minimum daily evaporation was 0.8 mm

a: Sonning



b: Kabete

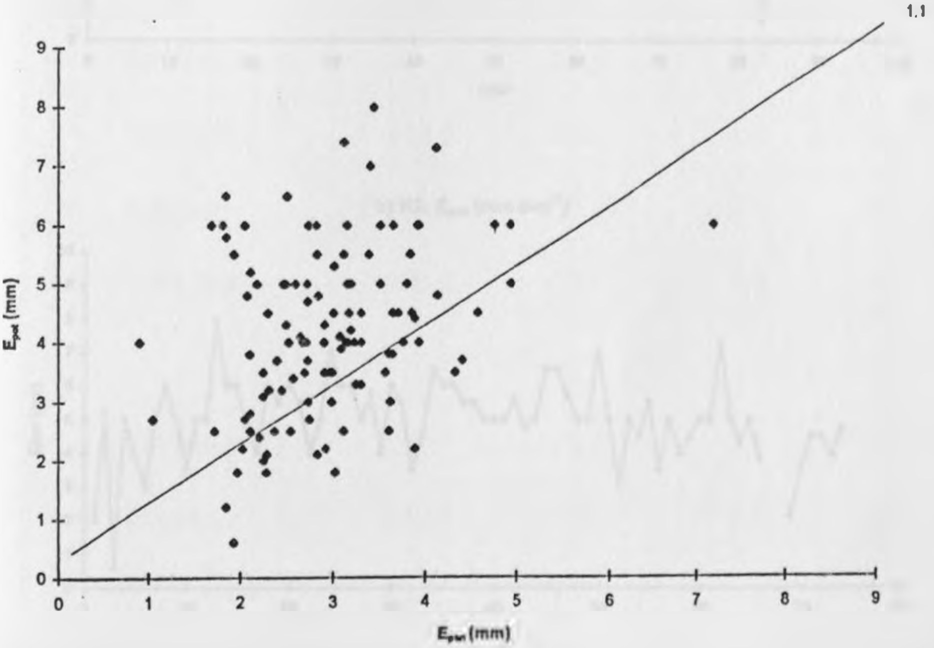
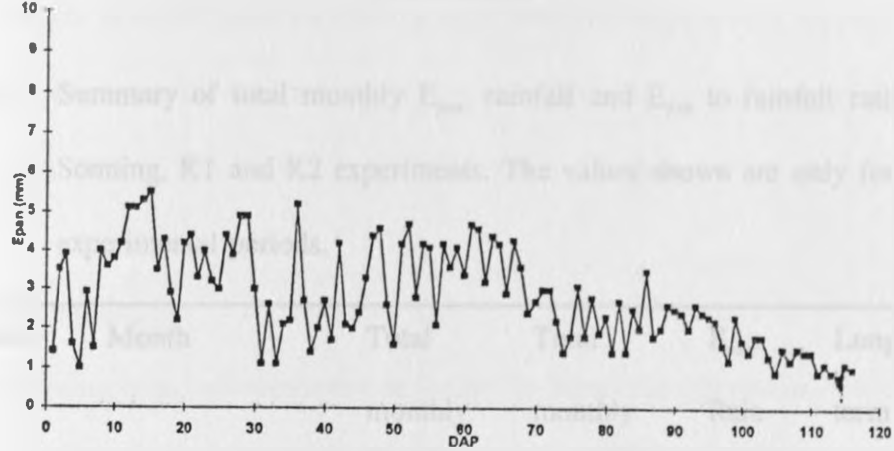
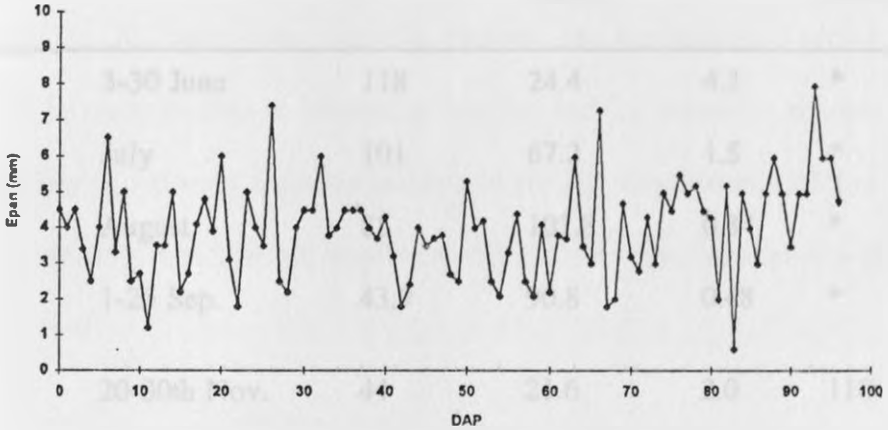


Figure 4.12. The relationship between Epan and Epot at Sonning and Kabete

Sonning: $E_{pan}$ (mm day$^{-1}$)



b) K1: $E_{pan}$ (mm day$^{-1}$)



b) K2: $E_{pan}$ (mm day$^{-1}$)

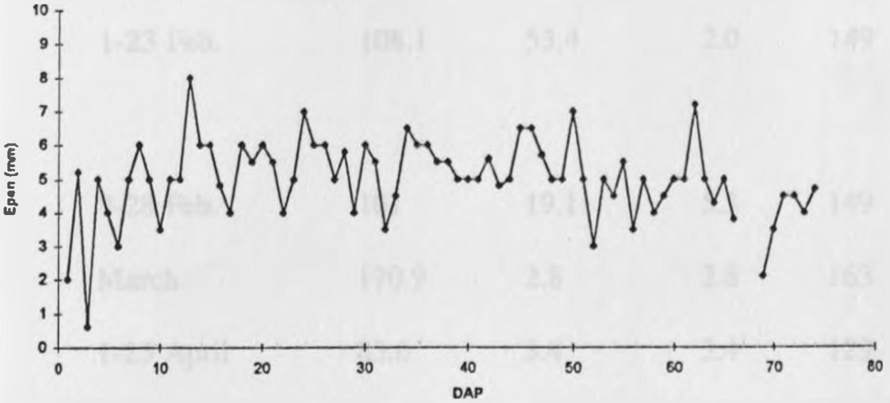


Figure 4.13. Daily $E_{pan}$ (mm day$^{-1}$) at the Sonning, K1 and K2 experiments.

on 23/09/92. Evaporation exceeded rainfall in June and July (vegetative phase) but was lower than rainfall in August and September (reproductive phase).

Table 4.3 Summary of total monthly $E_{pan}$, rainfall and $E_{pan}$ to rainfall ratio in Sonning, K1 and K2 experiments. The values shown are only for the experimental periods.

| Experiment | Month | Total monthly $E_{pan}$ (mm) | Total monthly Rainfall (mm) | $E_{pan}$: Rain ratio | Long term $E_{pan}$ (mm) |
|---|---|---|---|---|---|
| Sonning | 3-30 June | 118 | 24.4 | 4.3 | * |
| | July | 101 | 67.2 | 1.5 | * |
| | August | 85 | 101.8 | 0.84 | * |
| | 1-25 Sep. | 43.9 | 90.8 | 0.48 | * |
| K1 | 20-30th Nov. | 44 | 21.6 | 2.0 | 118 |
| | December | 122.5 | 116 | 1.1 | 124 |
| | January | 108.4 | 193.1 | 0.6 | 142 |
| | 1-23 Feb. | 108.1 | 53.4 | 2.0 | 149 |
| K2 | 9-28 Feb. | 101 | 19.1 | 5.3 | 149 |
| | March | 170.9 | 2.8 | 2.8 | 163 |
| | 1-23 April | 85.6 | 3.4 | 3.4 | 129 |

* Data not available

At Kabete, total monthly $E_{pan}$ for K1 was highest in December. The maximum daily value was 8 mm on 20/06/93 and a minimum value of 0.6 mm on 09/02/93. $E_{pan}$ exceeded rainfall in all the months except January, which corresponded to reproductive phase of the beans. In K2, total monthly $E_{pan}$ was higher than rainfall throughout the entire growing season. The highest $E_{pan}$:rainfall was in February.

## 4.5 Solar radiation

The total incoming solar radiation received during the three experiments was presented in figure 4.14. Sonning had higher day-to-day fluctuations of total incoming radiation than the Kabete experiments (figure 4.14). The daily average was highest in K2, and daily receipts in K2 were least variable because the experimental period was characterised by clear weather in contrast to Sonning and K1 where the weather was cloudy and rainy. Total solar radiation incident in the K2 season was 13% and 15% lower compared to K1 and Sonning despite the high daily receipts because of a shorter season (table 4.4).

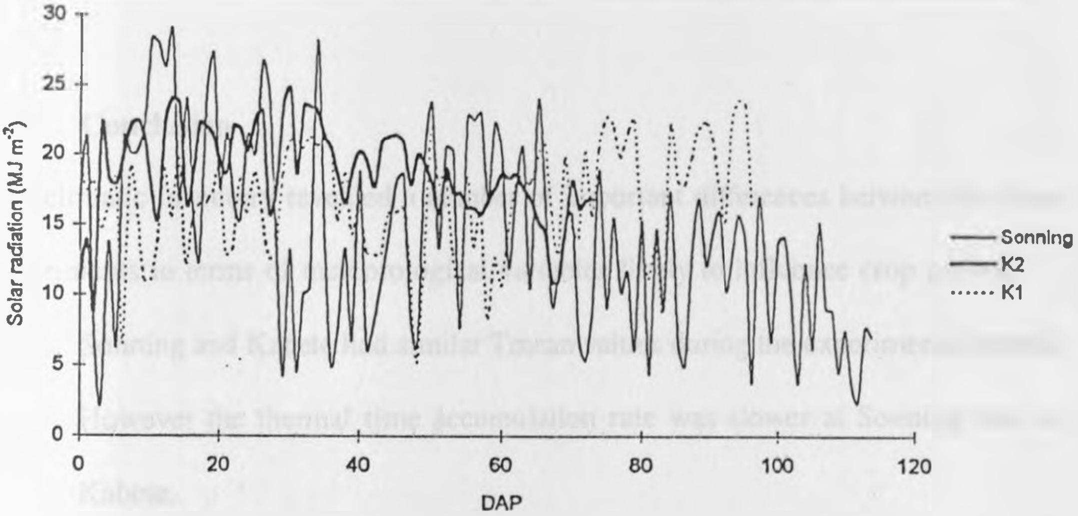


Figure 4.14. Daily total solar radiation (MJ m$^{-2}$) in Sonning, K1 and K2 .

Table 4.4: Summary of the incident radiation during the crop growing season in the three experiments.

| Total solar radiation<br>(MJ $m^{-2}$) | Experiment | | |
|---|---|---|---|
| | Sonning | K1 | K2 |
| Total radiation | 1639 | 1606 | 1392 |
| Daily average | 14.4 | 16.9 | 18.8 |

## 4.6 Conclusion

The climatic inventory revealed a number of important differences between the three experiments in terms of meteorological variables likely to influence crop growth.

1) Sonning and Kabete had similar Tmean values during the experimental period. However the thermal time accumulation rate was slower at Sonning than at Kabete.

2) Average saturation deficits were higher at Kabete than Sonning, which was largely responsible for the faster potential evaporation rate at Kabete. The daytime saturation deficits were greatest in K2 and least at Sonning. The nighttime saturation deficits were similar in the two Kabete experiments, and higher at Kabete than Sonning.

3) Radiation receipts were slightly higher at Kabete than Sonning, and slightly greater in K2 than K1. Day-to-day fluctuations were much less in K2 where

there was less cloudiness.

4) There were major differences between rainfall, and in the ratio of potential evaporation to rainfall in the three experiments. The differences in the ratios accounted for differences in the theoretical soil moisture deficit; highest in K2 and least in the K1 experiment.

# Chapter 5

# The effect of water, nitrogen and planting density on canopy expansion

## 5.1 Introduction

The objective of this chapter is to assess the effect of irrigation, nitrogen fertilizer and planting density on LAI development at Sonning, K1 and K2 experiments by taking account of factors at plant level and at individual leaf level.

Green leaf area index is used as a measure of photosynthetic potential (Watson, 1947). Crop growth rate (CGR), has been expressed as a product of LAI and the efficiency of dry matter production per unit leaf area. The relationship between LAI and CGR or total dry matter production is curvilinear in many crops (Anguilar *et al.*, 1977; Hay and Walker, 1989) being non responsive to change in LAI after an optimum LAI. Anguilar *et al.*, (1977) reported an optimum LAI of 3.5 in *Phaseolus vulgaris.* LAI at the end of vegetative growth and its duration through the reproductive phase) is positively related to seed yield in *Phaseolus vulgaris* (Laing *et al.*, 1984). The LAI determines the source capacity for dry matter production through the reproductive phase. Duarte and Adams (1972) showed that leaf numbers and leaf size influence number of pods/plant and seed size. The number of pods/plant is a key component that determines yield (Chung and Goulden, 1971) which in turn is dependent on the size of individual plant.

LAI may be expressed as a product of individual leaf size, the total number of leaves and the plant population density as:

$$LAI = \frac{LA}{leaf} * \frac{No.\ of\ leaves}{Plant} * \frac{No.\ of\ plants}{area} \qquad 5.1$$

Where LAI = leaf area of a single leaf.

Leaf area per plant (the first two components of equation 5.1) at any given time depends on the rate of leaf appearance, rate of expansion after appearance, the duration of leaf expansion, the rate of branching and the rate of senescence (Dale, 1982; Hay and Walker, 1989).

The rate of leaf appearance is solely controlled by air temperature provided crop growth is not limited by severe water or nutrient stress (Dennett *et al.*, 1983; Leong and Ong, 1983; Milford *et al.*, 1985). The rate of leaf expansion (after appearance) is influenced by air temperature (Gallagher and Biscoe, 1979), plant nitrogen (Squire, 1990) and plant water status (Acevedo *et al.*, 1971). Plant nitrogen status influences the rate of leaf expansion, the final leaf size (Hay and Walker, 1989), the number of leaves per plant (due to increased branching) and leaf longevity if the effect self-shading is severe enough to hasten leaf senescence (Pearman *et al.*, 1977). The number of leaves per plant and leaf size are also reduced by high atmospheric saturation vapour pressure deficit; especially under limited soil moisture supply (Ong *et al.*, 1985).

Assessment of treatment effects on leaf area development in the three experiments over time were based on accumulated thermal time (°C days). This provided a unifying time scale because of variation in crop duration in the field in the three experiments.

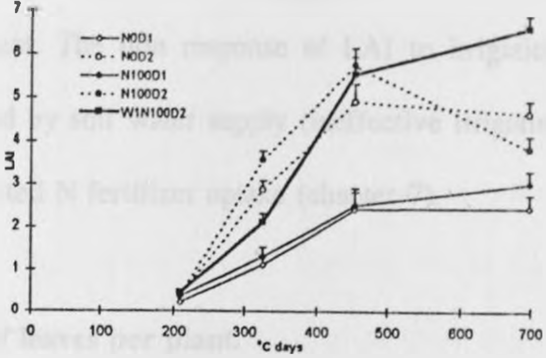
## 5.2 Results and discussion

### 5.2.1 Effect of irrigation, nitrogen and planting density on LAI

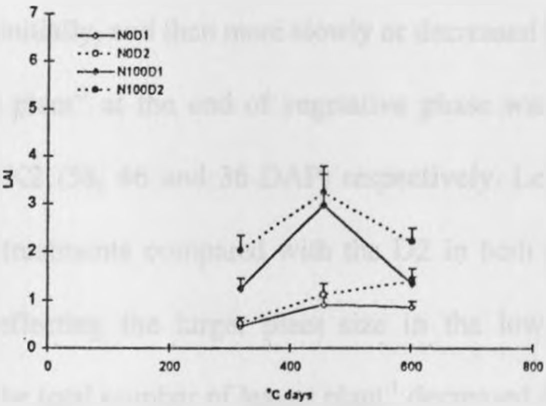
LAI increased with time to a maximum value and then either decreased or remained constant in all three experiments (figure 5.1). LAI was highest at Sonning and lowest in K2. At Sonning, D2 treatments had significantly higher LAI ($p<0.05$) than D1 treatments (figure 5.1a). Nitrogen fertilizer did not have a significant effect on LAI throughout the measurement period. Although irrigation did not significantly increase LAI in the Sonning experiment, it is notable that LAI was larger at the final harvest in the irrigated treatments than in the rainfed treatments. The positive late season irrigation effect on LAI was through reduced leaf abscission in the irrigated treatments, particularly the W1N100D2 treatment.

Fertilizer nitrogen increased LAI in the three harvests ($p\leq0.07$) in the K1 experiment (figure 5.1b). High planting density increased LAI in the first and 3rd harvest ($p<0.07$) (figure 5.1b). Irrigation did not have a significant effect on LAI in K1 (data not shown). This is not surprising because when irrigation was applied in the dry periods, the quantities of water applied were probably too small to influence leaf area development. Also heavy late season rains nullified irrigation effect. It is likely that the amount of fertilizer N applied in K1 experiment was not high enough to influence the LAI.

a: Sonning



b: K1



c: K2

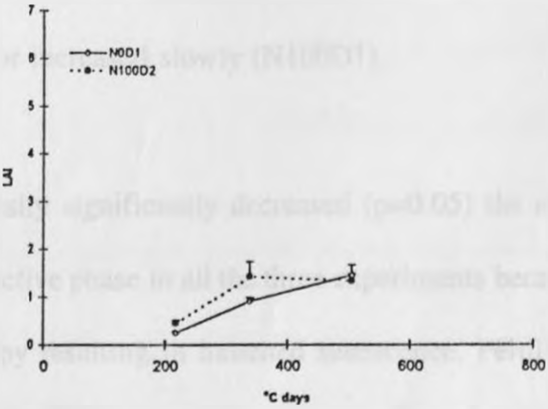


Figure 5.1. Change in LAI with thermal time (°C days) in the Sonning, K1 and K2 experiments. Bars represent standard errors of mean.

Neither irrigation nor nitrogen significantly increased LAI in the K2 experiment. LAI was significantly higher ($p<0.01$) early in the season in the D2 treatment compared to the D1 treatment. The non response of LAI to irrigation and fertilizer N was presumably limited by soil water supply (ineffective irrigation and low rainfall; see table 3.4) and limited N fertilizer uptake (chapter 7).

### 5.2.2 Number of leaves per plant.

On the premise that the air temperature is the most important determinant of leaf production in the three experiments, the number of leaves produced over time was expressed on accumulated thermal time basis. The number of leaves per plant increased rapidly initially, and then more slowly or decreased (figure 5.2). The average number of leaves plant$^{-1}$ at the end of vegetative phase was 17.2, 12.6 and 10.3 at Sonning, K1 and K2 (58, 46 and 36 DAP) respectively. Leaf numbers plant$^{-1}$ were higher in the D1 treatments compared with the D2 in both experiments where data were available, reflecting the larger plant size in the low density treatments. At Sonning and K1, the total number of leaves plant$^{-1}$ decreased after 350$^{0}$C days (58 and 41 DAP respectively) in the high planting density (D2) in both N0 and N100 treatments, in contrast to the D1 treatments where the number of leaves remained constant (N0D1) or increased slowly (N100D1).

High planting density significantly decreased ($p=0.05$) the number of leaves plant$^{-1}$ during the reproductive phase in all the three experiments because of shading of leaves lower in the canopy resulting in hastened senescence. Fertilizer nitrogen seemed to have **no** effect on the leaf number in the vegetative phase at Sonning and K2, but increased leaf number later in the season (figure 5.2). In K1, nitrogen increased leaf number at all stages of development. Irrigation alone did not increase the number of leaves plant$^{-1}$ significantly in the three experiments (figure 5.2 shows the pooled data from both the irrigated and rainfed treatments). Each of the plots of leaf number per plant against thermal time had a period during which the slope was at a maximum and approximately constant (harvest 1-4 at Sonning, 1-3 in KI and 2-4 in K2). These maximum rates were estimated by linear regression analysis, and are summarised in table 5.1. The K2 experiment had the highest average rate of leaf appearance (leaves plant$^{-1}$ °C day$^{-1}$ and K1 the lowest. The inverse of numbers in table 5.1 the time to leaf appearance (°C day$^{-1}$)

Table 5.1 Relationship between thermal time and total leaves plant$^{-1}$ at Sonning, K1 and K2 experiments for D1 treatments.

| Treatment | leaves/plant/°C day$^{-1}$ | | |
|---|---|---|---|
| | Sonning | K1 | K2 |
| N0D1 | 0.073 | 0.058 | 0.134 |
| N0D2 | 0.074 | 0.049 | 0.111 |
| N100D1 | 0.098 | 0.107 | 0.195 |
| N100D2 | 0.098 | 0.070 | 0.111 |

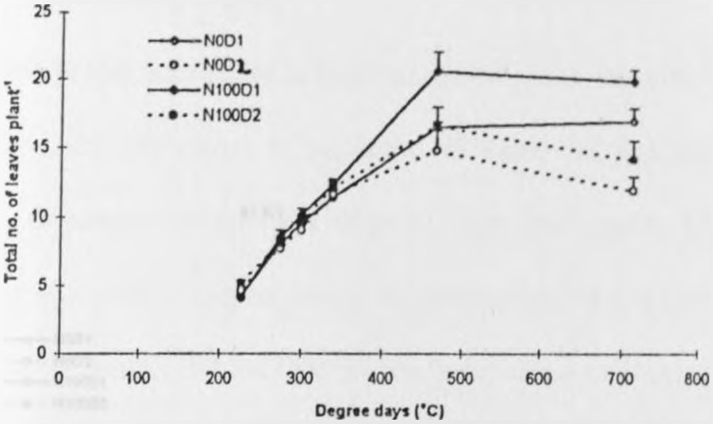
In general, N100 treatments had higher rates of leaf production/°C day than N0 treatments in all the three experiments, probably due to increased branching in N100 treatments (see section 5.2.3). At Kabete, Plants grown at the lower density had the faster rate of leaf production per plant, but there was no apparent effect of density at Sonning.

### 5.2.3 Number of mainstem nodes and branches per plant.

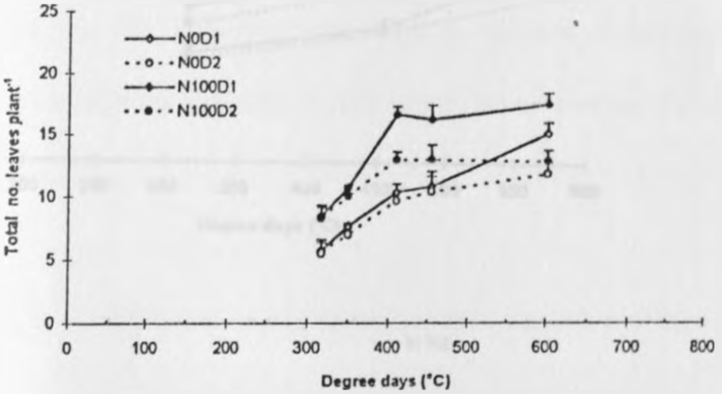
The rate of leaf appearance is determined by the number of nodes and branches from which leaves develop. Mainstem nodes are the plant basic morphological unit on which branches are supported. The numbers of mainstem nodes and branches per plant were monitored in K1 and K2 experiments. Irrigation, nitrogen and planting density did not have significant effect on the number of mainstem nodes per plant (data not shown). The average number of mainstem nodes per plant was 5.7 and 4.9 at K1 and K2 respectively. Plants were smaller in the K2 experiment compared to K1.

Branching occurred after the appearance of the fourth trifoliate leaf on the first mainstem node (close to cotyledon leaves) and progressed acropetally. Irrigation did not have a significant effect on the number of branches per plant in K1 and K2. The number of branches per plant were significantly higher in the N100 treatments in K1 (44 DAP) but not in K2 (figure 5.3). High planting density did not have a significant effect on the number of branches per plant in K1. On the contrary, the number of branches per plant was significantly lower (p=0.05) in D2 in the K2 experiment at 51 DAP (4.9 branches per plant) compared to D1 (6.4 branches per plant). Water stress may have slowed the rate production and development of branches in the D2 treatment.

a: Sonning



b: K1



c: K2.

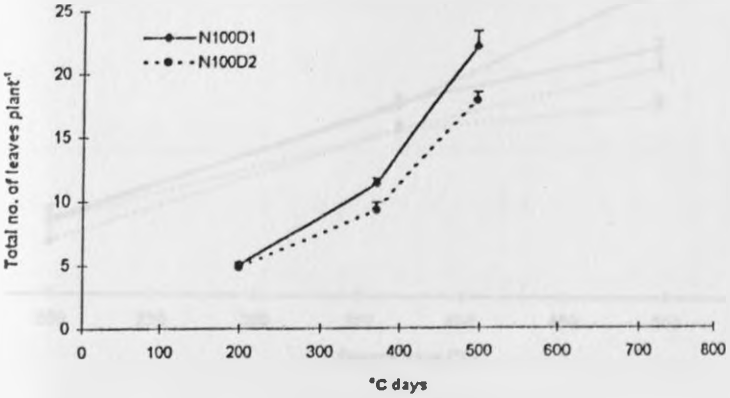


Figure 5.2 Changes in total number of leaves plant$^{-1}$ with thermal time (° C days ) at the Sonning, K1 and K2 experiments. Bars represent SE of mean. Half of the bars shown for clarity.

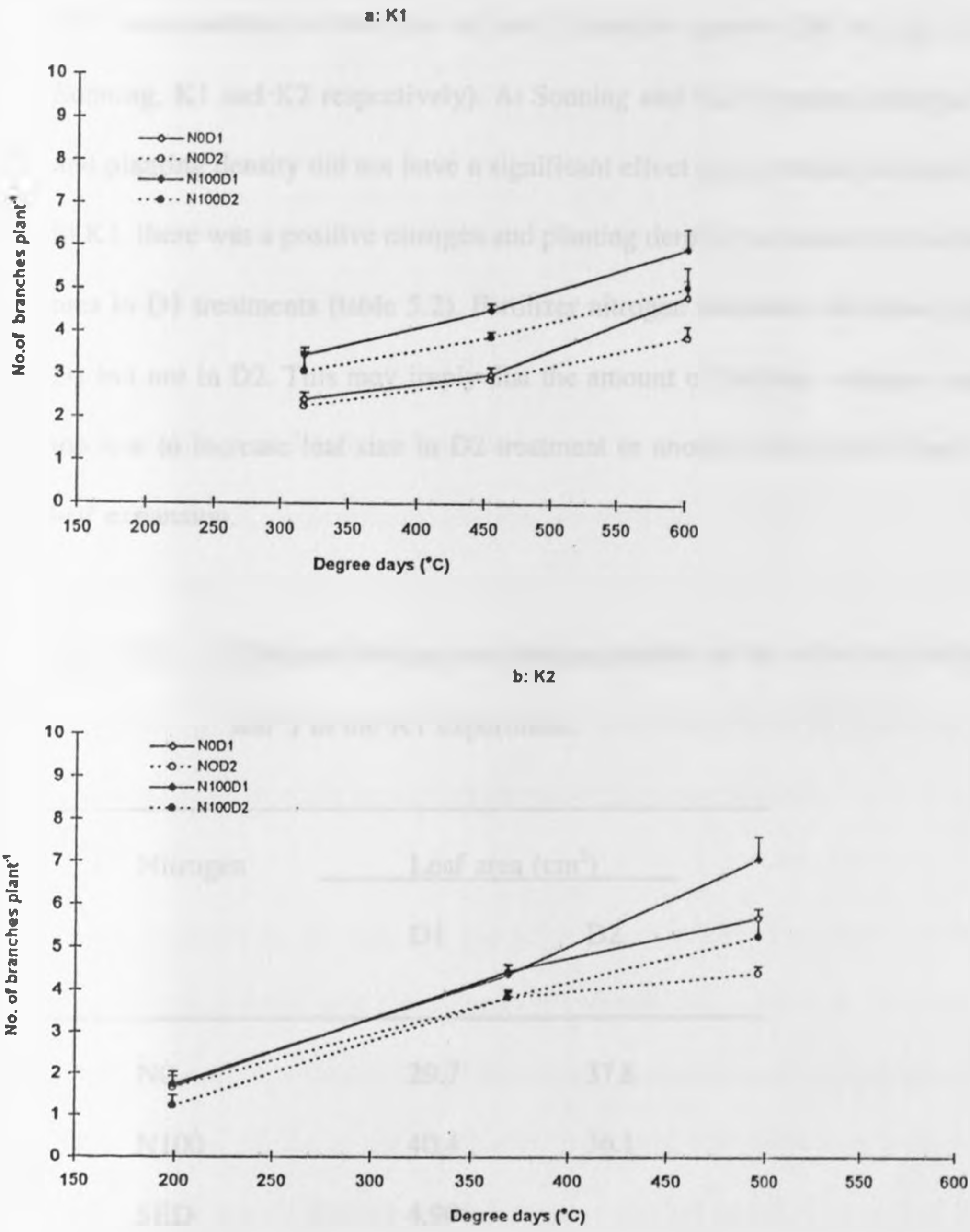


Figure 5.3. Changes in total number of branches plant$^{-1}$ with thermal time in the K1 and K2 experiments. Bars represent SE of mean.

### 5.2.4 Individual leaf area

The average leaf area (total LA/No. of leaves) is an important factor in determining total leaf area. The effects of irrigation, nitrogen and planting density on mean leaf area were assessed at the time of peak vegetative growth (58, 46 and 36 DAP in Sonning, K1 and K2 respectively). At Sonning and K2, irrigation, nitrogen fertilizer and planting density did not have a significant effect on individual leaf size. However in K1, there was a positive nitrogen and planting density interaction on individual leaf area in D1 treatments (table 5.2). Fertilizer nitrogen increased individual leaf area in D1 but not in D2. This may imply that the amount of fertilizer nitrogen applied was too low to increase leaf size in D2 treatment or another factor other than N limited leaf expansion.

Table 5.2 Effect of nitrogen and planting density on the individual leaf area (cm$^2$ leaf$^{-1}$) in the K1 experiment.

| Nitrogen | Leaf area (cm$^2$) | |
|---|---|---|
| | D1 | D2 |
| N0 | 29.7 | 37.8 |
| N100 | 40.4 | 36.1 |
| SED | 4.90 | |

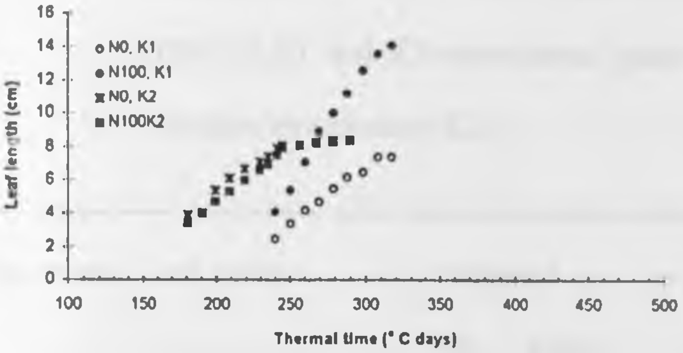
Further investigation of leaf characteristics involved assessment of specific leaf area (SLA) which is the ratio of leaf area to leaf mass ($cm^2\ g^{-1}$). SLA is an index of leaf structure; the lower the ratio, the greater the leaf thickness. Average SLA values for Sonning, K1 and K2 were 257, 217 and 201 $cm^2\ g^{-1}$ respectively implying that leaves were thinner and broader at Sonning than at Kabete and thickest in K2. The higher SLA may explain the larger LAI at Sonning compared to K1 and K2. SLA decreases under stressful environments (water stress, high light intensity, low N) (Bjorkman, 1975; Boardman, 1975).

### 5.2.5 Individual leaf length extension

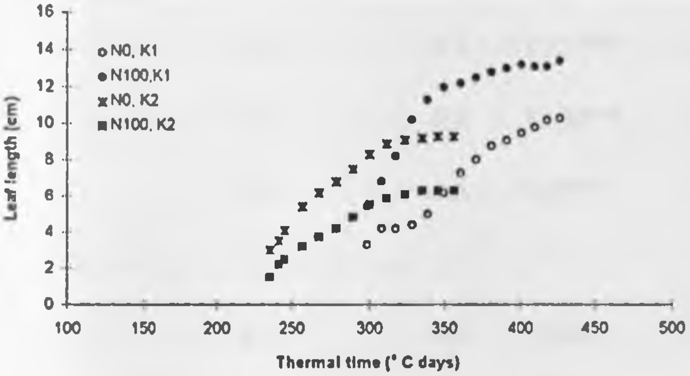
In the K1 and K2 experiments, leaf length extension was used as an indicator of area expansion rate. Leaf length increased slowly initially, then at a rapid linear rate and finally stopped (figure 5.4). The rapid rate of leaf extension lasted approximately 7 days after the leaves emerged and extension was complete in 10 days. Extension rate was most rapid at night in both experiments (data not shown).

The final length of the 2nd, 3rd and 4th trifoliate leaflets was significantly larger in the N100 treatments in K1 but not in K2 (figure 5.4; table 5.3). The 3rd leaflet in N100 treatment was smaller than N0 treatment in the K2 experiment (figure 5.4). This effect did not persist in the 4th leaflet, indicating that there may have been other factors other than N limiting the expansion of the 3rd leaflet. The ratio of leaf length in N0:N100 leaflets in K1 treatments was between 1:1.6 and 1:2.1 in the 2nd and 4th trifoliate leaflets (table 5.3). The final leaflet size decreased acropetally (table 5.3).

a: 2nd trifoliate leaflet



b: 3rd trifoliate leaflet



c: 4th trifoliate leaflet

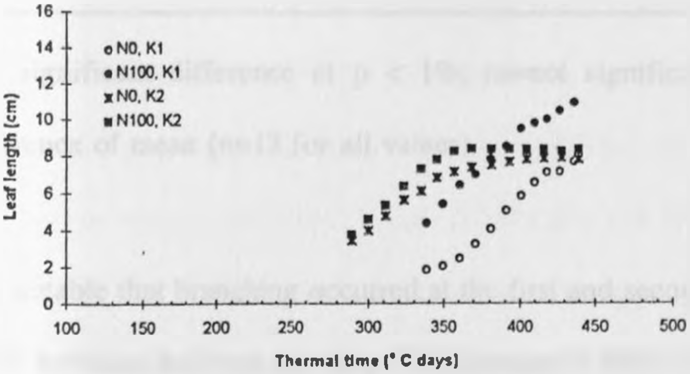


Figure 5.4. Leaf length extension with time (°C days) of the 2nd, 3rd and 4th middle trifoliate leaflets in the K1 and K2 experiments (all treatments are rainfed, D1).

Table 5.3 Average length of the lamina of fully-expanded 2nd, 3rd and 4th mid-trifoliate leaflet of *Phaseolus vulgaris* grown at low planting density (D1) in K1 and K2 experiments (pooled values for irrigation and nitrogen treatments in K2).

| Experiment | leaf position | Treatment |  |  |  |
|---|---|---|---|---|---|
|  |  | N0 | N100 | SED | Mean |
|  |  | -----Leaf length (cm)--- |  |  |  |
| K1 | 2 | 6.1 | 11.5*** | 0.27 | 8.8 |
|  | 3 | 8.2 | 13.2*** | 0.45 | 10.7 |
|  | 4 | 4.6 | 9.5*** | 0.42 | 7.0 |
| K2 | 2 | 8.0 | 7.7ns | 0.33 | 7.9 |
|  | 3 | 9.1 | 8.5ns | 0.39 | 8.8 |
|  | 4 | 8.1 | 8.3ns | 0.42 | 8.2 |

*** significant difference at $p < 1\%$; ns=not significant; SED = standard error difference of mean (n=12 for all values).

It is notable that branching occurred at the first and second node at the time that the fourth trifoliate leaf was growing. The decrease in final size and rate of extension of the 4th trifoliate leaflet was probably due to competition between the leaves and the developing branch for assimilates. Milford *et al.*, (1985) reported acropetal decrease in leaf size in sugar beets.

Leaf extension rates in K1 decreased significantly acropetally in N100 treatments (table 5.4). There was a two-fold difference between the extension rate of the second leaflet and the fourth leaflet (table 5.4). The extension rates of the fourth trifoliate leaflet of N0 and N100 treatments in K1 are comparable. This seems to indicate that the effect of fertilizer nitrogen on leaf extension rate over time decreased. It is likely that as the plant size increased, competition for N by actively growing parts (ie branches) reduced the N effect on the extension rate of individual leaves. The absence of N effect on the extension rate of individual leaflets in the K2 experiment (table 5.4) might be explained by water rather than N limiting expansion.

### 5.2.6 Water potential isotherms

Nitrogen may increase leaf extension rate by increasing the elastic modulus of leaves, thereby increasing the rate of expansion per unit turgor pressure. The primary assumption is that leaf extension is driven by turgor pressure.

This was tested by plotting leaf water potential ($\psi$) against the RWC. The slope in the linear part of the curve (RWC ≥ 95%) estimates the leaf elastic modulus (Hsiao and Bradford, 1983). From the water potential isotherms, all the treatments had a water potential of ranging between 0.2 and 0.3 MPa at 100% RWC (figure 5.5). The leaves did not fully  equilibrate with the water, possibly due to presence of solutes in the leaves. This result is similar to that observed by Boyer (1968). Differences in slopes among treatments were not apparent, indicating that N fertilizer did not alter tissue elastic modulus. These results are contrary to those of Taylor *et al.*, (1993) who reported that N fertilization increased tissue elastic modulus in *Salix viminalis.*

Table 5.4 Relationship between thermal time and leaf length extension rates (mm °C day$^{-1}$) in K1 and K2 (for rainfed D1 treatments) obtained from regression equations of thermal time against leaf length.

| Experiment | Nitrogen | Extension rates (mm °C day$^{-1}$<br>Leaf position<br>2 | <br><br>3 | <br><br>4 |
|---|---|---|---|---|
| K1 | N0 | 0.66 | 0.67 | 0.67 |
| | N100 | 1.49 | 1.55 | 0.72 |
| K2 | N0 | 0.67 | 0.77 | 0.57 |
| | N100 | 0.68 | 0.56 | 0.69 |

Plots of 1/ψ against RWC of actively growing leaves indicated that the N100 treatments maintained higher turgor at 100% RWC than the N0 treatments in K1 experiment (figure 5.6). Differences between the treatments in solute potential (ψπ) at 100% RWC within the K1 and K2 experiments were not detectable (figure 5.6). This may have been due to difficulties in determining the point of inflection of the water potential isotherm, i.e the point where pressure potential is zero. Direct measurement of osmotic potential would have resolved the problem.

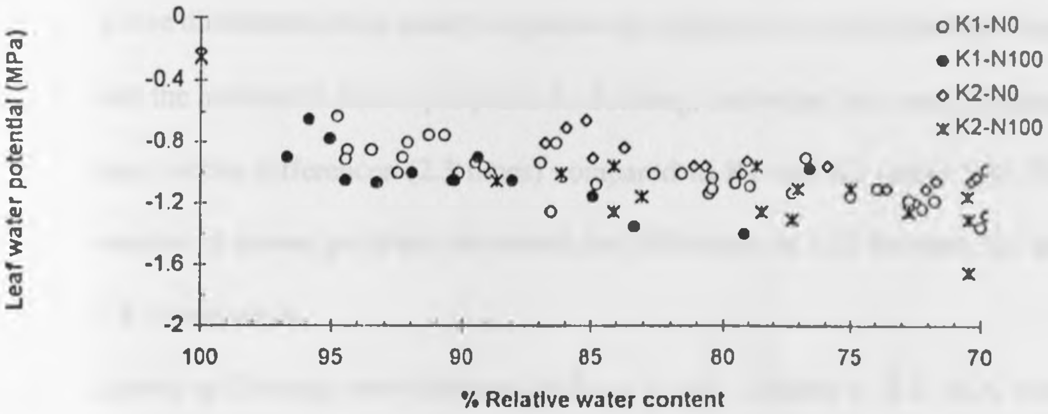


Figure 5.5. The effect of fertilizer N on relationship between relative water content and water potential in actively growing leaves in the K1and K2 experiments.

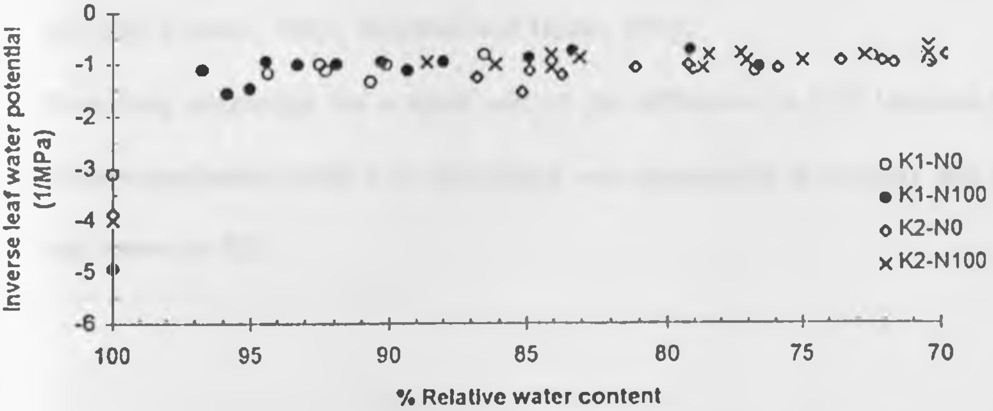


Figure 5.6. The effect of fertilizer N on relationship between leaf relative water content and inverse leaf water potential in actively growing leaves in the K1 and K2 experiments.

## 5.4 Summary and conclusions

Tables 5.5 is a summary of the various components that influenced LAI in the three experiments. The ratios of the maximum LAI (taking the mean values across all treatments) in the three experiments were 2.6:1.3:1 at Sonning:K1:K2 respectively.

1) These differences were mainly explained by differences in individual leaf sizes and the number of leaves per plant. At Sonning, individual leaf area explained most of the differences (2.3 times) compared to K1 and K2 (table 5.5). The number of leaves per plant accounted for differences in LAI between K1 and K2 experiments.

2) Leaves at Sonning were thin and wide and were thickest in K2; SLA were highest at Sonning and lowest in K2 (table 5.5). At Sonning, there may have been a photoperiod effect on leaf area, particularly the leaf width (as the slope of the leaves in terms of the ratio of length to width) was different than for plants grown at Kabete (data not shown). SLA observed in K2 is characteristic adaptation of leaves grown under droughty conditions to reduce the transpiring surface (Kramer, 1983; Bradford and Hsiao, 1982).

3) Branching accounted for a small part of the difference in LAI between the three experiments (table 5.5). Branching was comparable at Sonning and K1 but lowest in K2.

Table 5.5 Mean values across all treatments of various canopy size parameters at the time of peak vegetative growth (58, 46 and 36 DAP in Sonning, K1 and K2 respectively).

| Parameter | Sonning | K1 | K2 |
|---|---|---|---|
| Nodes plant$^{-1}$ | nd | 5.7 | 4.9 |
| Branches plant$^{-1}$ | 5.5 | 4.9 | 5.6 |
| Mean leaf area (cm$^{-2}$) | 84.4 | 36.4 | 36.0 |
| Leaves plant$^{-1}$ | 17.2 | 14.1 | 10.3 |
| Plant leaf area (cm$^{-2}$) | 1452 | 513 | 371 |
| Mean specific leaf area cm$^2$ g$^{-1}$ | 257 | 217 | 201 |
| Time to leaf appearance (°C days) | | | |
| N0 | 13.6 | 18.8 | 8.3 |
| N100 | 10.2 | 11.8 | 7.0 |
| Leaf extension rates (mm °C day$^{-1}$) | | | |
| N0 | nd | 0.66 | 0.67 |
| N100 | nd | 1.25 | 0.64 |

nd - no data available for the period

4) High planting density was the most effective factor in increasing LAI at flowering in the Sonning and K2 experiments (table 5.6). The low LAI in the K2 experiment was because of water-limited leaf area expansion. High planting

density did not increase LAI significantly in the K1 experiment (table 5.6) because of the overriding N limitation on LAI (figure 5.1b).

Nitrogen effects on LAI was primarily through increased leaf emergence and extension rate (table 5.5). In conclusion, planting density was the most effective factor in increasing LAI if water and N supply were not limiting.

Table 5.6. Summary of the effect of planting density on LAI in the Sonning, K1 and K2 experiments at flowering (58, 46 and 40 DAP respectively).

| Experiment | ------ Treatment ------ | | | |
|---|---|---|---|---|
| | D1 | D2 | SED | mean |
| Sonning | 2.6 | 5.5*** | 0.51 | 4.05 |
| K1 | 2.0 | 2.2ns | 0.44 | 2.1 |
| K2 | 0.9 | 1.6*** | 0.18 | 1.25 |

*** significant difference at p < 1%. SED = standard error difference of mean (n=12 for all values).

# Chapter 6

# Bean development, dry matter production and partitioning

## 6.0 Introduction.

Crop development refers to changes in the organ formation and is manifested as the onset or termination of different phases of the plant life cycle (i.e. germination, flowering, pod growth, seed growth, leaf senescence and maturity: Masaya and White, 1991). The key developmental stages (phenostages) considered in this chapter are emergence, vegetative growth, flowering, pod growth and physiological maturity. The latter three stages can be collectively referred to as the reproductive phase. Flowering marks the transition from vegetative growth (end of vigorous leaf production) to reproductive growth. Crop development rate is influenced by temperature, water stress and photoperiod.

Dry matter production is proportional to the total amount of incident PAR that is intercepted by foliage and the efficiency with which it is converted to dry matter by green leaves. Total radiation incident on the canopy varied between locations and within seasons in a given location. The amount of total radiation intercepted is a function of crop leaf area index and leaf area duration while efficiency of conversion of solar radiation is less variable (Squire, 1990). Irrigation, planting density, fertilizer nitrogen application, cultivar selection and planting dates are management strategies which influence LAI and leaf area duration.

## 6.1 Objectives

Total dry matter production over time and the final seed yield in the three experiments are presented. The central hypothesis is that application of nitrogen and increasing planting density will increase yield through increased PAR interception. Water is expected to influence productivity through radiation interception and through influence on the conversion efficiency brought about by stomatal response to plant water balance. Temperature influences the rate of crop development and so will influence LAI duration, and hence radiation interception. The total daily incident solar radiation determine the potential radiation available for interception.

## 6.2 Results and discussion

### 6.2.1 Crop phenological development

Accumulated thermal time (°C days) was used to evaluate the effect of temperature on bean development in the three experiments and results are summarised in table 6.1.

Table 6.1 Relationship between crop phenological stages and thermal time (°C days since zero DAP) in the Sonning and Kabete experiments (assuming a base temperature of 8°C).

| Phenological stage | Phenological duration (°C days) | | |
|---|---|---|---|
| | Sonning | K1 | K2 |
| Emergence | 66 | 116 | 71 |
| Anthesis | 336 | 364 | 329 |
| 50% flower | 384 | 405 | 382 |
| Pod growth | 610 | 541 | 506 |
| Physiological maturity | 771 | 779 | 676 |
| Final harvest | 859 | 845 | 749 |

Emergence was slower in K1 (12 DAP) compared to Sonning (10 DAP) and K2 (8 DAP) respectively. The average final percentage emergence was 80%, 89% and 87% at Sonning, K1 and K2 respectively. The minimum thermal time at which emergence occurred was 66°C days at Sonning. The difference in thermal time to emergence between K1 and K2 experiments indicates that factors other than temperature influenced emergence. In K1, two rainfall events occurred at 3 DAP (5.5 mm) and 9 DAP (6.2) after a prolonged dry spell. On the contrary, at Sonning and K2, 10.2 mm and 15.2 mm rain fell as single events at sowing. Although a total of 11.7 mm of rain fell in K1 prior to emergence, its effectiveness may have been reduced by evaporation due to shallow depth of penetration. Itabari *et al.*, (1993) reported that low soil moisture content delayed emergence of maize seeds. This was probably the case in K1.

The vegetative stage (emergence to 50% flowering) was 318, 289 and 311°C days accumulated over 40, 33 and 32 days in the Sonning, K1 and K2 experiments respectively. The difference in the duration of the vegetative stage may be explained by the difference in the thermal time accumulation rate. The average thermal time accumulation rate was 7.8, 9.2 and 9.7°C day$^{-1}$. Though differences were small (all values were within 5% of the overall mean), the slightly shorter thermal time requirement in K1 may have been because, in contrast to Sonning and K2, there was very frequent rain during this phase.

The thermal duration of the reproductive phase (50% flowering to physiological maturity) in the three experiments was 387, 374, 294°C days accumulated in 50, 43 and 26 days at the Sonning, K1 and K2 experiments respectively. Sonning and K1 had similar thermal duration for the reproductive phase though it was much shorter in K2, probably due to soil water deficit (table 3.4) hastening maturity (Kramer, 1983).

### 6.2.2 Total dry matter (TDM)

TDM in the three experiments increased from planting and reached a maximum at harvesting (figure 6.1). The average TDM produced at the end of the season at Sonning, K1 and K2 was 752, 584 and 339 g m$^{-2}$ respectively. The differences in TDM are attributable to the crop duration; 114, 95 and 73 days at Sonning, K1 and

K2 respectively. TDM increased linearly during the vegetative phase and at slower rate in the reproductive phase at the Sonning and K2 experiments (figure 6.1). At Sonning, the rate of TDM increase slowed down between 58 and 86 DAP (figure 6.1a). This coincided with the end of the vegetative phase and onset of pod growth. The lag in growth was due to slower leaf production which was not compensated for by pod growth (presumably lag phase of pod growth). The sudden increase in TDM between 86 and 114 DAP at Sonning corresponded to rapid seed growth.

The crop growth rates for the three experiments were 11.9, 8.6 and 6.0 g $m^{-2}$ $day^{-1}$ averaged over the main part of season when dry matter increase with time was approximately linear (fig 6.1). Maximum crop growth rates reported for beans are 14 to 18 g $m^{-2}$ $day^{-1}$ (White and Izquierdo, 1991). The values of crop growth rate of Mwezi Moja beans in the three experiments showed high variability, being 43% higher in Sonning compared to K2. This difference is attributed to water; rainfall in K1 was 384.1 mm compared to 105.6 mm in K2. The more rapid crop growth rate at Sonning might be explained by long day length (16 and 12 hours at Sonning and Kabete). At Sonning, photosynthesis occurred for four extra hours per day for 50 days (between June and July) compared to Kabete. Although the daily total radiation receipts were lower at Sonning compared to Kabete (table 4.4), the distribution over a longer time, resulting in lower intensity, might have increased daily dry production. Beans have a low light saturation point (Laing *et al.*, 1984).

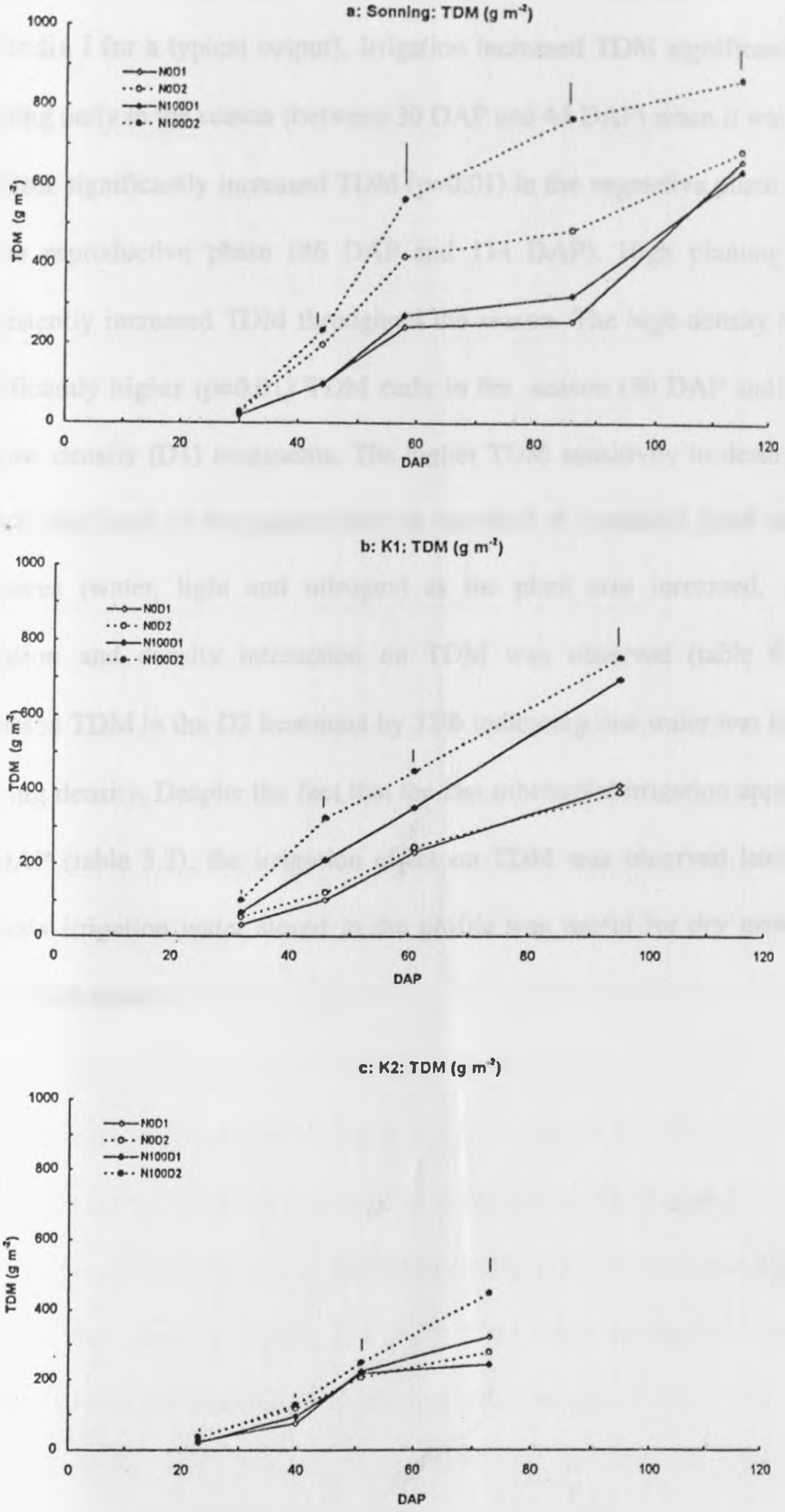


Figure 6.1. Change in total dry matter (g m$^{-2}$) over time at Sonning, K1 and K2 experiments in the rainfed treatments. SED bars shown.

Treatment effects on TDM were analyzed statistically (ANOVA) (see table 1, Appendix I for a typical output). Irrigation increased TDM significantly (p=0.05) at Sonning early in the season (between 30 DAP and 44 DAP) when it was dry. Nitrogen fertilizer significantly increased TDM (p=0.01) in the vegetative phase (30 DAP) and in the reproductive phase (86 DAP and 114 DAP). High planting density (D2) consistently increased TDM throughout the season. The high density treatments had significantly higher (p=0.01) TDM early in the season (30 DAP and 44 DAP) than the low density (D1) treatments. The higher TDM sensitivity to density early in the season than later in the season may be ascribed to increased plant competition for resources (water, light and nitrogen) as the plant size increased. At 114 DAP, irrigation and density interaction on TDM was observed (table 6.2). Irrigation increased TDM in the D2 treatment by 32% indicating that water was limiting at high planting density. Despite the fact that the last substantial irrigation application was at 56 DAP (table 3.2), the irrigation effect on TDM was observed later at 114. This suggests irrigation water stored in the profile was useful for dry matter production later in the season.

Table 6.2. The effect of irrigation and planting density on TDM at 114 in the Sonning experiment.

| Irrigation | TDM (g $m^{-2}$) | |
|---|---|---|
| | D1 | D2 |
| W0 | 665 | 764 |
| W1 | 565 | 1016 |
| SED | 80.3 | |

Fertilizer nitrogen and high planting density significantly (p=0.05) increased TDM in K1 (figure 6.1b). Fertilizer nitrogen significantly (p=0.05) increased TDM at 32, 46 and 95 DAP in K1. D2 treatments has significantly higher (p≥0.05) TDM than D1 at 46 and 95 DAP. Irrigation did not have a significant effect on TDM in the entire growing season in K1 experiment. Nitrogen and planting density had a significant (p=0.05) interaction on TDM in K1 at 46 DAP (table 6.3). There was a greater TDM response to N fertilizer application in the D2 treatment (162%) compared to the D1 treatment (124%), implying a greater N limitation on TDM in D2. The higher TDM response to planting density in the N100 treatments (48% compared to 27% in N0) indicates that planting density increased TDM when N was not limiting. N x D interaction was not maintained to the end of the season in K1.

Table 6.3. The effect of nitrogen and planting density on TDM in the K1 experiment at 46 DAP and K2 at 73 DAP.

| Nitrogen | TDM (g $m^{-2}$) | | | |
|---|---|---|---|---|
| | K1 | | K2 | |
| | 46 DAP | | 73 DAP | |
| | D1 | D2 | D1 | D2 |
| N0 | 89.2 | 113.5 | 336 | 284 |
| N100 | 200.2 | 297.5 | 312 | 423 |
| SED | 18.9 | | 32.7 | |

The difference in the interactions in the K1 and the K2 experiments was that fertilizer nitrogen increased TDM at D1 and D2 in K1 but increased growth in D2 in K2 (table 6.3). This difference may be explained by the soil water supply in the two experiments. In K1, ample soil water supply increased N uptake resulting in increase dry matter production. The higher crop demand for N in the K2 experiment resulted in higher N uptake compared to D1 (see figure 7.3).

On the whole, planting density and nitrogen fertilizer had opposing effects on plant size (figure 6.2). High planting density decreased plant size; the relative decrease at the final harvest was least at Sonning (18%) and highest in the K2 experiment (44%). Nitrogen fertilizer significantly increased plant size at the final harvest in all the three

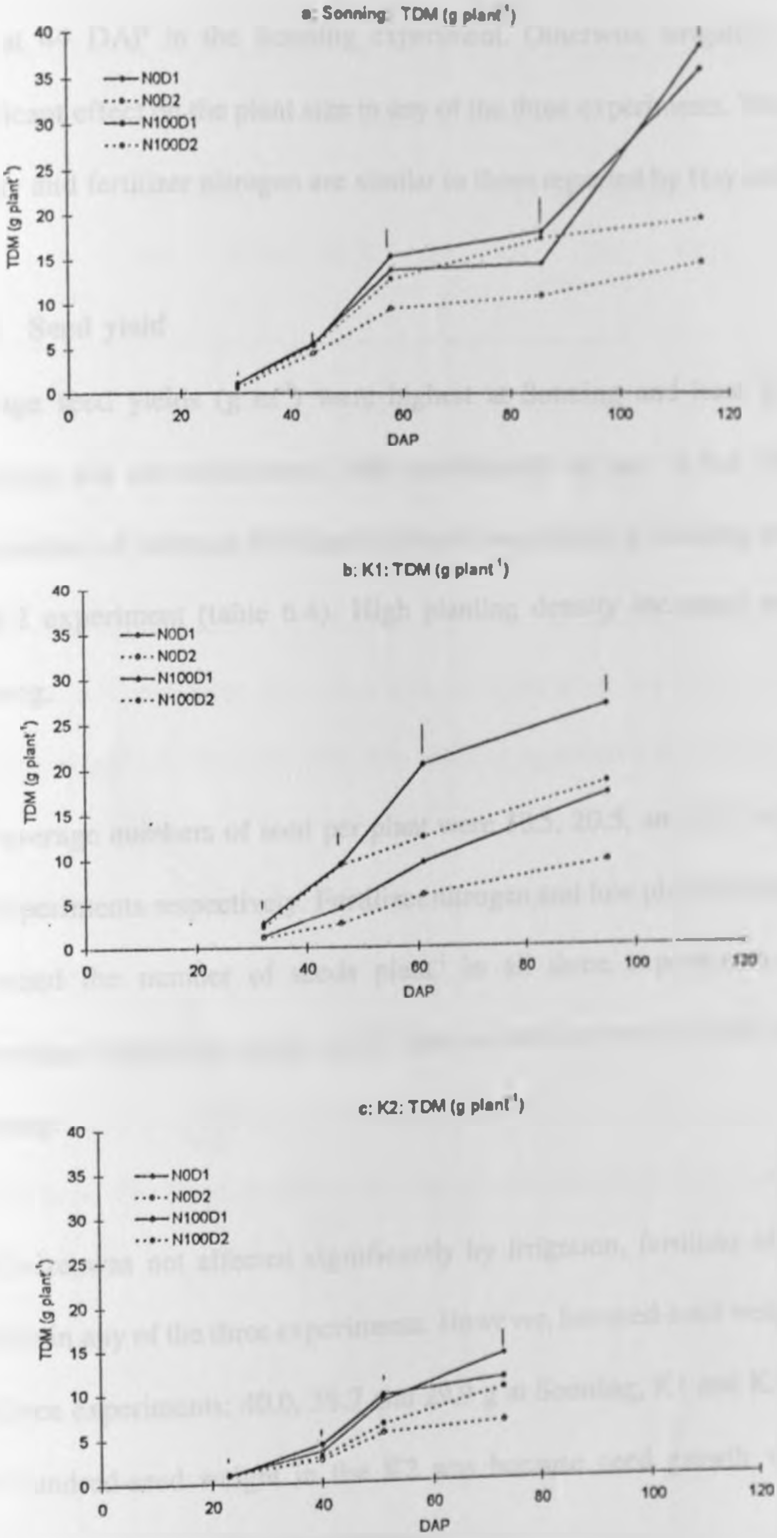


Figure 6.2. Change in plant dry matter (g plant$^{-1}$) with time at Sonning, K1 and K2; bars represent SED.

experiments. Plant size was most responsive to fertilizer N in the K1 experiment (71%) and least responsive in K2 (24%). Irrigation increased plant size significantly only at 44 DAP in the Sonning experiment. Otherwise irrigation did not have a significant effect on the plant size in any of the three experiments. The effects planting density and fertilizer nitrogen are similar to those reported by Hay and Walker (1989).

### 6.2.3 Seed yield

Average seed yields (g $m^{-2}$) were highest at Sonning and least in K2 (table 6.4). Irrigation did not affect seed yield significantly in any of the three experiments. Application of nitrogen fertilizer increased seed yield at Sonning and K1 but not in the K2 experiment (table 6.4). High planting density increased seed yield only at Sonning.

The average numbers of seed per plant were 30.5, 20.5, and 15.7 at Sonning, K1 and K2 experiments respectively. Fertilizer nitrogen and low planting density significantly increased the number of seeds $plant^{-1}$ in all three experiments (table 6.5). The percentage increase in seeds $plant^{-1}$ due to fertilizer was in 47% in K1 and 17% at Sonning.

Seed size was not affected significantly by irrigation, fertilizer nitrogen or planting density in any of the three experiments. However, hundred-seed weight differed among the three experiments; 40.0, 38.7 and 29.9 g at Sonning, K1 and K2 respectively. The low hundred-seed weight in the K2 was because seed growth was limited by the prevalent soil water stress conditions.

Table 6.4 Effect of nitrogen fertilizer and planting density of seed yield (g $m^{-2}$) at Sonning, K1 and K2.

| Experiment | Seed yield (g $m^{-2}$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Nitrogen | | | Planting density | | | |
| | N0 | N100 | SED | D1 | D2 | SED | Mean |
| Sonning | 289 | 375 | 25.2† | 278 | 386 | 23.9** | 332 |
| K1 | 196 | 295 | 14.9* | 239 | 252 | 9.4ns | 246 |
| K2 | 128 | 132 | 11.3ns | 128 | 131 | 13.5ns | 130 |

SED = significant error difference between treatments, n=12 for all SED values. †, *, **, ns= significant at 10%, 5%, 1%, and not significant respectively.

The differences in seed yield (g $m^{-2}$) among the three experiments may be explained by differences in the number of seeds $plant^{-1}$ and seed weight. At Sonning, larger plants may have produced either more more pods $plant^{-1}$ and/or more seeds $pod^{-1}$ (data not available) and heavier seeds than K1 and K2. The differences in the seed filling duration in the three experiments explain the differences in final hundred weight (section 6.5).

Table 6.5 Effect of nitrogen fertilizer and planting density the number of seeds plant$^{-1}$ at Sonning, K1 and K2 experiments

| Experiment | Number of seeds plant$^{-1}$ | | | | | | |
|---|---|---|---|---|---|---|---|
| | Nitrogen | | | Planting density | | | |
| | N0 | N100 | SED | D1 | D2 | SED | Mean |
| Sonning | 28.1 | 32.9 | 0.8* | 38.1 | 23.0 | 2.8* | 30.5 |
| K1 | 16.6 | 24.4 | 0.7** | 24.4 | 16.6 | 2.1** | 20.5 |
| K2 | 14.2 | 17.3 | 0.6** | 20.3 | 11.1 | 0.8** | 15.7 |

SED = significant error difference between treatments, n=12 for all SED values. *, **, ns = significant at 5%, 1%, and not significant respectively.

## 6.3 TDM partitioning

About 75% of the total dry matter produced was allocated to leaves (lamina and petioles) during the vegetative phase in all the three experiments. This decreased to about 15% at the end of the season (figure 6.3). The decrease in allocation to leaves occurred at flowering. In all the experiments and at all harvests, the average allocation to petioles was 15%. Stem weight constituted 25% of TDM during the vegetative phase in all three experiments. This proportion decreased to 21.3% at the final harvest; an average decrease of 1.5% of stem weight in the course the growing season. At the end of the growing season, about 70% of TDM was allocated to reproductive parts (seeds and haulm).

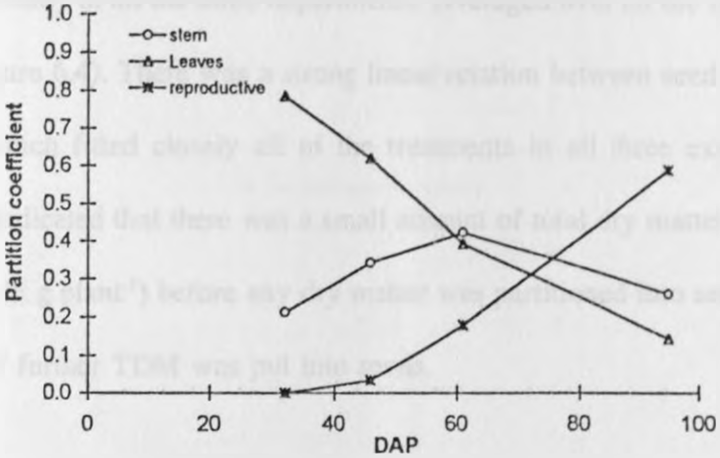


**Figure 6.3. Total dry matter partitioning over time among leaves, stem and reproductive parts in beans in K1 experiment (W0NOD1 treatment).**

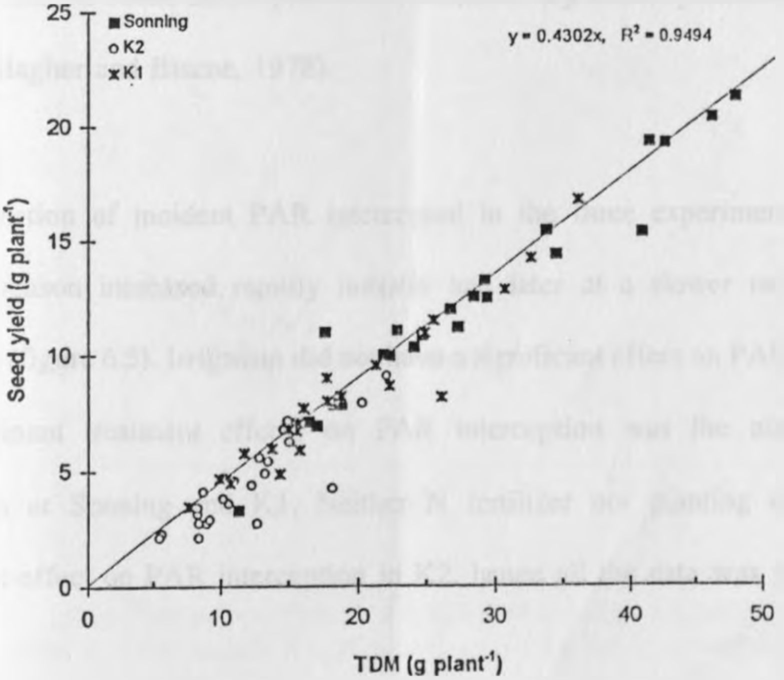


**Figure 6.4 Relationship between plant TDM and seed yield at Sonning, K1 and K2.**

The proportion of TDM allocated to seed was not significantly affected by nitrogen or planting density in all the three experiments. Averaged over all the experiments, HI was 0.43 (figure 6.4). There was a strong linear relation between seed yield and total dry matter which fitted closely all of the treatments in all three experiments. The relationship indicated that there was a small amount of total dry matter that had to be accumulated (5 g plant$^{-1}$) before any dry matter was partitioned into seeds; thereafter, about 45% of further TDM was put into seeds.

## 6.4 Physiological basis of TDM production

### 6.4.1 Solar radiation interception and light use efficiency

The differences in TDM in the three experiments may be attributed to differences in the amount and duration of leaf area index. The relationship between the duration of crop growth and the dry matter yield may be attributed to the total amount of solar radiation that the beans intercepted and utilised for dry matter production (Monteith, 1977; Gallagher and Biscoe, 1978).

The proportion of incident PAR intercepted in the three experiments during the growing season increased rapidly initially and later at a slower rate and finally decreased (figure 6.5). Irrigation did not have a significant effect on PAR interception. The dominant treatment effects on PAR interception was the nitrogen-density interaction at Sonning and K1. Neither N fertilizer nor planting density had a significant effect on PAR interception in K2, hence all the data was pooled (figure 6.5b).

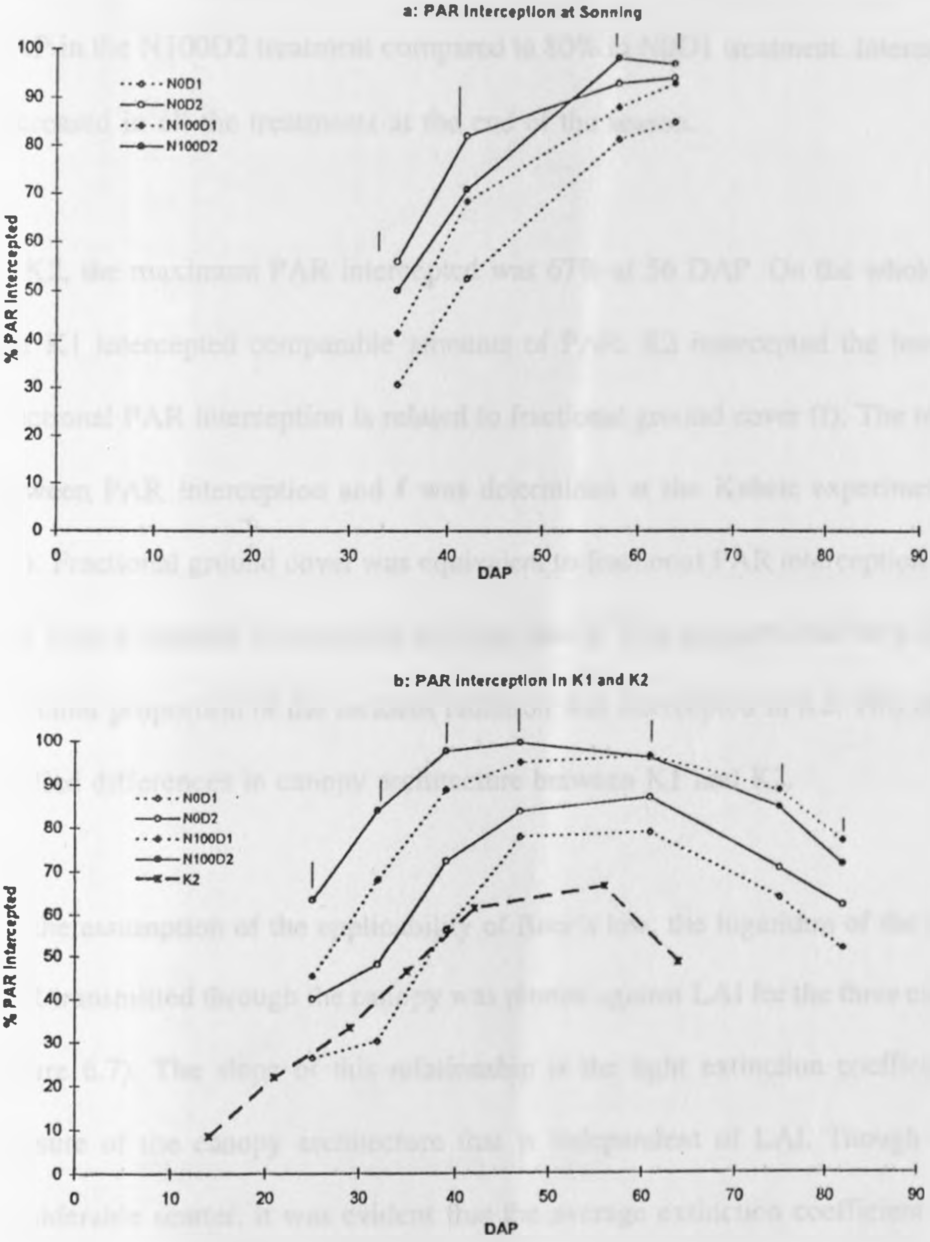


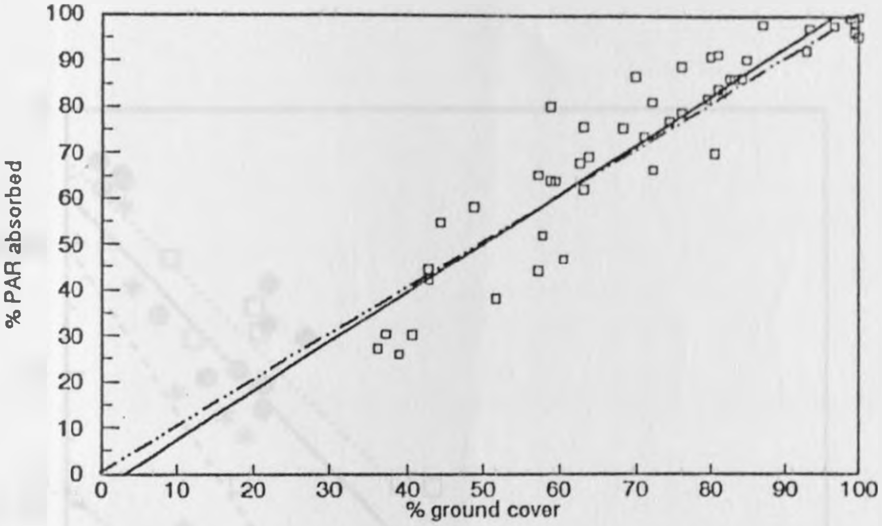
Figure 6.5. Canopy PAR interception over time at the Sonning, K1 and K2 experiments. Data pooled for all treatments in K2. SED bars shown for the K1 experiment.

Positive and significant N x D interaction on PAR interception was apparent early in the season (figure 6.5a) at Sonning. However by 64 DAP, N100D1, N0D2 and N100D2 treatments all intercepted approximately 90% of the incident PAR. Similar trends occurred in K1 (figure 6.5b). The canopy intercepted approximately 95% at 47 DAP in the N100D2 treatment compared to 80% in N0D1 treatment. Intercepted PAR decreased in all the treatments at the end of the season.

In K2, the maximum PAR intercepted was 67% at 56 DAP. On the whole, Sonning and K1 intercepted comparable amounts of PAR. K2 intercepted the least amount. Fractional PAR interception is related to fractional ground cover (f). The relationship between PAR interception and f was determined at the Kabete experiments (figure 6.6). Fractional ground cover was equivalent to fractional PAR interception in K1, but in K2 the fractional interception was less than f. This suggests that for a given LAI, a smaller proportion of the incident radiation was intercepted in K2. This observation implied differences in canopy architecture between K1 and K2.

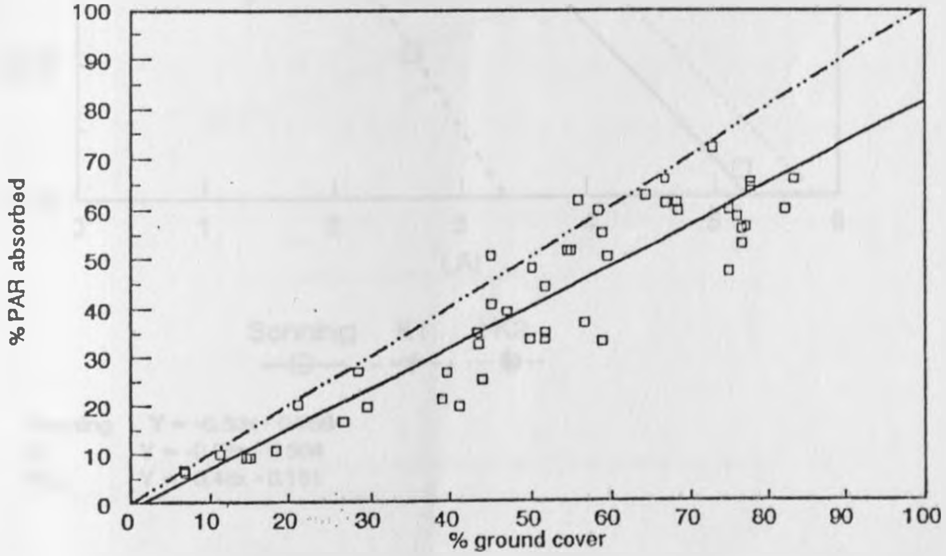
On the assumption of the applicability of Beer's law, the logarithm of the fraction of PAR transmitted through the canopy was plotted against LAI for the three experiments (figure 6.7). The slope of this relationship is the light extinction coefficient (K), a measure of the canopy architecture that is independent of LAI. Though there was considerable scatter, it was evident that the average extinction coefficient in the K1 experiment (0.75) was somewhat greater than the values at Sonning (0.53) and K2 (0.48) (figure 6.8). These results imply that canopies in the K1 experiment were rather planophile. This is to be expected because of the high frequency and amount of

a) K1



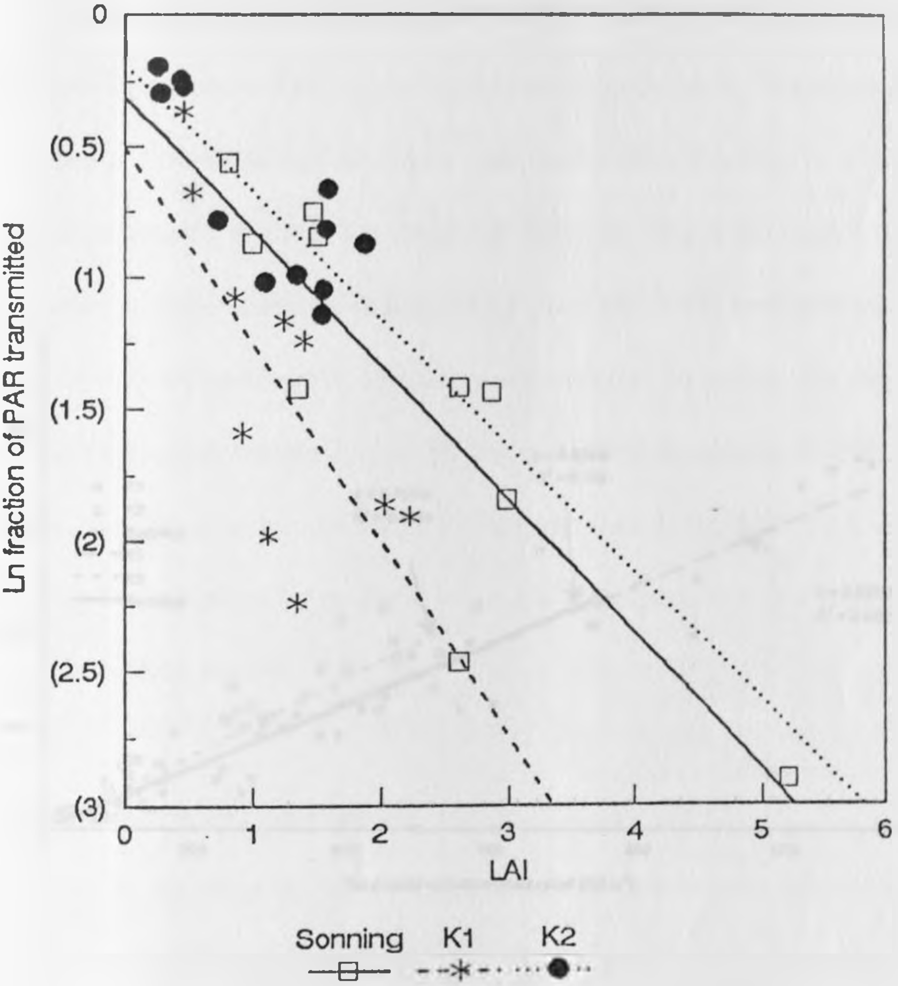
Y = 1.0680918x - 3.208364

b) K2



—··—·· 1:1 line Y = 0.8270336x - 1.208802

Figure 6.6. Relationship between % ground cover and % PAR intercepted in the K1 and K2 experiments (data pooled for all treatments and a single regression line fitted).



Sonning Y = -0.53x - 0.168
K1 Y = -0.75x - 0.504
K2 Y = -0.48x - 0.181

**Figure 6.7. Relationship between LAI and the natural logarithm of the fraction of PAR transmitted through the canopy at the Sonning, K1 and K2 experiments.**

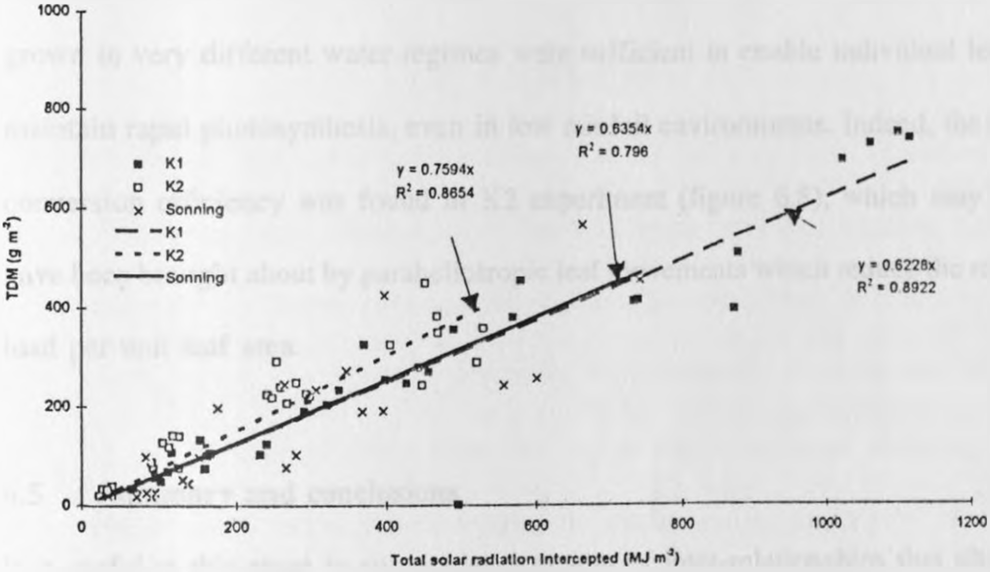


Figure 6.8. Relationship between total radiation intercepted (MJ m$^{-2}$) and total dry matter production (g m$^{-2}$) at Sonning, K1 and K2 experiments.

rainfall in K1 resulting in smaller tissue water deficits (data not shown) and no need to reduce the heat load on leaves by vertical orientation.Solar radiation conversion efficiency were remarkably similar in the three experiments (figure 6.8). However, beans, grown in the K2 experiment had 51 days less than those grown at the Sonning experiment to intercept PAR, and thereby produce dry matter. The similarity between experiments in conversion efficiency was remarkable bearing in mind the large differences in soil water stress resulting from the different rainfall regimes. The implication is that variations in LAI and extinction coefficient between bean crops grown in very different water regimes were sufficient to enable individual leaves to maintain rapid photosynthesis, even in low rainfall environments. Indeed, the highest conversion efficiency was found in K2 experiment (figure 6.8), which may in part have been brought about by paraheliotropic leaf movements which reduce the radiation load per unit leaf area.

## 6.5 Summary and conclusions

It is useful at this stage to summarise a system of inter-relationships that ultimately determine yield. Seed yield is a function of plant size, HI (partitioning coefficient) and planting density (see equation 6.1).

$$\frac{S_y}{De} = (\frac{Y}{De} - Y_o) * HI \qquad 6.1$$

where $S_y$ = seed yield (g $m^{-2}$),

Y = total dry matter (g $m^{-2}$)

De = plant density (plants $m^{-2}$) (hence $S_y$/De and Y/De are the yield and total dry matter expressed per plant basis)

$Y_o$ = minimum individual plant dry matter required for seed yield

HI = harvest index

The rate of dry matter production is equal to the total amount of incoming solar radiation that is intercepted and the efficiency with which it is converted to dry matter by the canopy (equation 2.8). The amount of radiation intercepted by the foliage ($S_i$) depends of the daily incident solar radiation (S) and the fraction of incident radiation intercepted by the foliage (f) (equation 6.2).

$$S_i = \Sigma_0^n (S * f) \qquad 6.2$$

f depends on the light extinction coefficient and the leaf area index (equation 2.10).

1) There were large differences between treatments and experiments in seed yield and total dry matter, but some the parameters in the system of equations above were remarkably stable. In particular, the partitioning of dry matter into seed in all experiments was described by a single equation showing strong conservatism in the harvest index (HI) which was not apparently affected by the very different environments. Hence differences in seed yield were directly attributable to the differences in dry matter production per plant.

2) The analysis of radiation interception revealed that differences in dry matter production were due primarily to differences in the amount of radiation intercepted. there were no significant effects of treatments <u>within</u> an experiment on conversion efficiency. The average conversion efficiencies in the three experiments were also remarkably similar, with evidence of a slightly higher (20% higher) conversion efficiency in K2 (although yield was smaller)

compared to K1 and Sonning

3) Differences in the amounts of radiation intercepted between treatments and between experiments had by far the most important influence on crop productivity. These differences were brought about by a number of factors:

   a) crop duration

   b) leaf area index

   c) incident radiation

   d) extinction coefficient

Crop duration varied between experiments because of differences in the rate of accumulation of thermal time, which was most rapid in K2 and slowest at Sonning. However there was evidence also of shortening of thermal time requirement in K2 due to water stress (tables 3.2 to 3.4), which was an additional factor causing crop duration to be reduced in K2.

The leaf area index (as well as its duration) was a major factor influencing radiation interception, and was the largest single contributor to differences between treatments and experiments in radiation, interception, and hence growth. Details were discussed earlier (chapter 5).

4) The three experiments differed in the amount of incident radiation received. The mean daily incident radiation ranged from 14.1 MJ $m^{-2}$ at Sonning to 18.8 MJ $m^{-2}$ at K2, but the lower daily receipts at Sonning were compensated for

by the longer crop duration. The result was that the accumulated incident radiation during the growing season was least in K2 (1392 MJ $m^{-2}$) and most at Sonning (1639 MJ $m^{-2}$) (chapter 4).

5) Finally, difference in canopy architecture between experiments had a small influence on radiation interception. The main effect noted was that during the wet season at Kabete, the canopy was apparently more planophile, which would have resulted in a slight increase in radiation interception during the early vegetative phase where there was relatively small mutual shading between the leaves.

# Chapter 7

## Bean nitrogen uptake and partitioning

### 7.1 Introduction

Plant N uptake over time depends on the crop demand for N, the supply of available N ($NO_3^-$-N and $NH_4^+$-N) to the plant and the efficiency with which the plant takes up N. Plant N demand may be estimated by the crop growth rate and duration. Management practices (other than fertilizer N application) and environmental factors that increase dry matter production would increase plant N uptake. Some of the factors affecting the efficiency with which the plants take up N include, splitting fertilizer-N applications so that small quantities are applied at times of high demand to minimise loss, selection of cultivars with a long growth cycle and prolific root development, eliminating competition from weeds and adequate soil water supply (Bock, 1984). In this thesis, the effects of irrigation and planting density as strategies to optimise N-use in beans were assessed.

The sources of N in the bean plant tissue are soil mineral N, fertilizer derived N and atmospheric-N (through symbiotic fixation). This can be summarised as:

$$N_{pl} = N_f + N_s + N_{dfa} \qquad 7.1$$

where $N_{pl}$ is total plant N uptake, $N_f$ is plant N derived from fertilizer, $N_s$ is plant N derived from soil mineral N supply and $N_{dfa}$ is plant N derived from atmospheric nitrogen fixation.

### 7.2.1 Fertilizer derived nitrogen ($N_f$).

Bean production (*Phaseolus vulgaris* L) is often limited by inadequate nitrogen supply as attested by the widespread response of bean yield to fertilizer N application (Muigai and Ndegwa, 1991; Ruschel *et al.*, 1981; Buttery *et al.*, 1987). Beans take up N at higher rates during the vegetative phase of growth (7.5 mg N $pot^{-1}$ $day^{-1}$) than they do in the reproductive phase (1.0 mg N $pot^{-1}$ $day^{-1}$) (Karanja, 1988). Fertilizer-N is an expensive input, and in the case of excessive use it can be a pollutant. Management strategies that would optimize fertilizer-N use for bean production would reduce production costs and improve the farmers' profits. Therefore it is important to understand the factors that affect fertilizer-N use efficiency.

Craswell and Godwin (1984) classified nutrient use efficiency into three categories; agronomic efficiency, physiological efficiency and apparent recovery efficiency. The agronomic efficiency (AE) is defined as the economic production obtained per unit of fertilizer applied.

$$AE = \frac{Y_f - Y_{f0}}{F} \qquad 7.1$$

Where $Y_f$ is grain yield of a fertilized crop (kg), $Y_{f0}$ is grain yield of unfertilized crop (kg) and F is the quantity of fertilizer applied (kg). AE can be determined from the application of fertilizer at several rates and their associated yields.

Physiological efficiency (PE) is the biological production obtained per unit of nutrient absorbed (also called biological efficiency) as:

$$PE = \frac{TDM_f - TDM_{f0}}{U_f - U_{f0}} \qquad 7.2$$

where $TDM_f$ is the total dry matter yield in a fertilized crop (kg), $TDM_{f_0}$ is the total dry matter yield in an unfertilized crop (kg), $U_f$ and $U_{f_0}$ are the amounts of nutrient uptake up by the fertilized and unfertilized crop respectively (kg).

Apparent recovery efficiency (ARE) is the quantity of nutrient absorbed per unit of nutrient applied.

$$ARE = \frac{U_f - U_{f0}}{F} \qquad 7.3$$

F is the quantity of fertilizer applied (kg $ha^{-1}$).

ARE is the index that was used in this study to assess the efficiency of fertilizer N use. Two strategies (high planting density and irrigation) were used to increase ARE. High planting density (that would not reduce plant size to the extent of reducing root size) would be expected to increase ARE due to the exploration of a larger soil volume by the root systems. Irrigation may increase plant size and therefore N uptake.

ARE (calculated by difference between N in fertilized and a non-fertilized plants) considers only above ground dry matter. The method does not consider possible alterations in the root:shoot ratio that may arise from application of N fertilizer which enhance root growth or alterations indigenous soil N transformations (Bock, 1984).

Stimulation of N uptake by fertilizer application would lead to over-estimation of ARE whereas an increase in root:shoot ratio would result in under-estimation.

### 7.2.2 Soil derived nitrogen ($N_s$).

$N_s$ in a crop-soil system can be determined from a crop receiving no fertilizer (Broadbent, 1981) and making correction for $N_{dfa}$. Hence, $N_s$ is calculated by rearranging equation 7.1 as follows:

$$N_s = N_{pl} - N_f - N_{dfa} \qquad 7.5$$

The quantity of available soil N for plant uptake ($N_s$) depends on the net effects of mineralization and immobilization of soil mineral N. For a cropped-system $\Delta N_{min}$ may be defined as:

$$\Delta N_{\min} = N_{dfa} + N_f + (N_{\min} - N_{imm}) - N_{pl} \qquad 7.6$$

$\Delta N_{min}$ is the total change in soil mineral N between the end and the beginning of the season,

$N_{min}$ and $N_{imm}$ are the total soil-N mineralised and immobilised in the season respectively

Seasonal net mineralisation can be estimated from a bare soil, assuming mineralisation and immobilisation are the dominant processes and losses through volatilization, clay fixation, leaching and denitrification are minimal. A positive $\Delta N_{min}$ value would indicate a net gain in soil mineral N (net mineralization) while a negative value would indicate a net loss (net immobilisation). The changes in soil mineral N in K1 and K2 are considered and results presented in section 7.3.4.

### 7.2.3 Nitrogen derived from fixation ($N_{dfa}$).

The amount of $N_{dfa}$ is influenced by fertilizer N application, planting density, crop phenological stage and soil moisture supply. Fertilizer application (greater than 15 kg ha$^{-1}$) has been found to reduce both nodulation and N fixation in beans under field (Graham, 1981; Rennie and Kemp, 1984; Ssali and Keya, 1986) and glass house conditions (Tsai *et al.*, 1993; Muller *et al.*, 1992). $N_{dfa}$ increased under limited fertilizer-N supply and high planting density (Graham and Rosas, 1978; Sprent and Bradford, 1977), although Hardy and Halveka (1976) found that fixation per plant decreased with increasing planting density in soybeans. Nevertheless, total N fixed per unit area remained constant. In the experiments carried out in this thesis, N fertilizer applied at 100 kg ha$^{-1}$ was intended to reduce N fixation and increase crop dependence on fertilizer-N uptake.

Nodulation in beans (a rough indicator of nitrogen fixation) increased with time reaching a peak between flowering and pod filling and then decreasing at physiological maturity (Rennie and Kemp, 1984). Ssali and Keya (1986) did not observe a significant increase in the weight of nodules in Mwezi Mola beans between flowering and pod-fill stage at different N and P levels. Soil moisture stress reduced nodulation (Abdel Ghaffar *et al.*, 1982; Pena-Cabriales and Castellanos, 1993) and nitrogen fixation (Kirda *et al.*, 1989).

### 7.2.4 Nitrogen partitioning and remobilization.

The ultimate objective of improving plant N status is to increase seed yield and quality. The partitioning of $N_{pl}$ to different plant components and its redistribution during seed production is important in determining seed yields and will therefore be considered. Chapin *et al.*, (1987) noted that "limited availability of any resource required for plant growth rouses a response that tends to ameliorate the limitation through resource allocation to procure more of the limiting resource, increased longevity of the procuring organs and increasing the efficiency of use of the limiting resource." Within the context of the experiments conducted in this thesis, the efficiency of nitrogen use (NUE) for seed production is considered. Nitrogen use efficiency is defined as the proportion of $N_{pl}$ allocated to seed (seed-N). Seed-N represents the quantity of N removed from a soil-plant system (assuming all other crop residues remain in the field), and is important when considering the N budget of a soil system and crop fertilizer requirement.

Plants increase NUE by sequestering N and concentrating it in vegetative organs and afterward redistributing it to reproductive parts. Redistribution would be expected to occur if N supply (from outside of the plant) does not meet the requirements of developing seeds (Sinclair and de Wit, 1976). N remobilization is influenced by N availability, soil water status, planting density and the sink strength (i.e. numbers of reproductive structures) (Engels and Marschner, 1995).

$N_{pl}$ and NUE decreases under conditions of soil water stress in cowpeas, lalab beans (Chapman and Muchow, 1985), soybeans, pigeon peas, groundnuts (DeVries *et al.*, 1989), beans (Foster *et al.*, 1995) due to limited N uptake and poor redistribution to seeds under water stress. Foster *et al.*, (1995) observed that under moderate soil moisture stress, vegetative tissue-N concentration in beans decreased more than under severe moisture deficit.

## 7.3 Hypotheses.

i) Plant N uptake will increase over time to match the plant N demand.

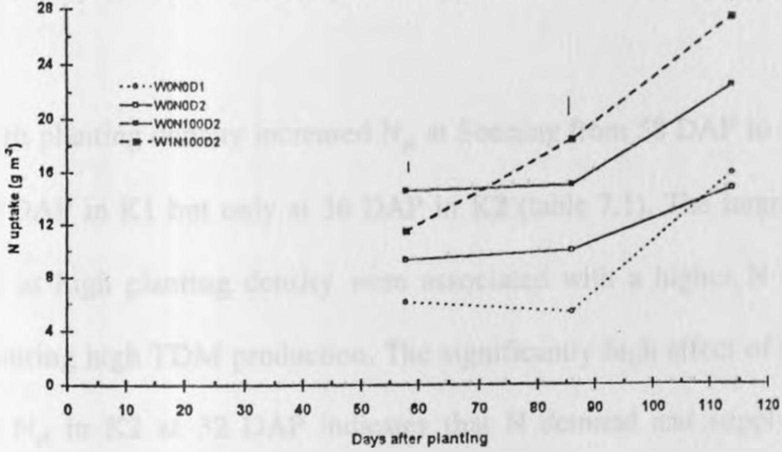
ii) Irrigation will increase $N_{pl}$ through increased N uptake in fertilized and non-fertilized treatments.

iii) Under limited N supply conditions, high plant N demand will stimulate uptake of $N_s$, increase net mineralization, increase nitrogen fixation and more efficient use of internally available N (N redistribution) for seed production.

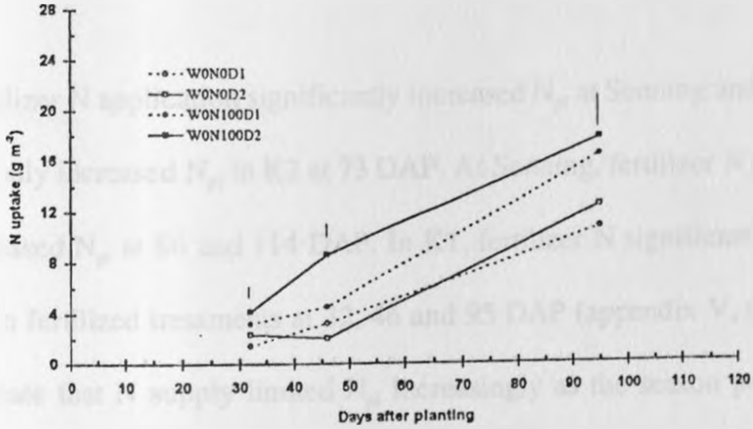
## 7.4. Results and discussion

### 7.4.1 Plant N uptake

The amount of N in the plant ($N_{pl}$) increased with time in all three experiments (figure 7.1). The average $N_{pl}$ at the end of the season at Sonning, K1 and K2 was 17.9, 14.4 and 8.2 g N $m^{-2}$ respectively. These results may be partly explained by differences in the crop duration in the three experiments (114, 95 and 73 days at Sonning, K1 and K2 respectively) which influenced N uptake. The average daily N uptake rate at Sonning, K1 and K2 was 0.16, 0.15 and 0.11 g N $m^{-2}$ $day^{-1}$ respectively. The average CGR (crop growth rates) in the three experiments were 7.1, 6.1 and 4.6 g $m^{-2}$ at Sonning, K1 and K2 respectively. It is evident that average rates of dry matter a: N uptake by beans at Sonning (g m$^{-2}$).



b: N uptake by beans in the K1 (g m$^{-2}$) rainfed treatments.



c: N uptake by beans and wheat in K2

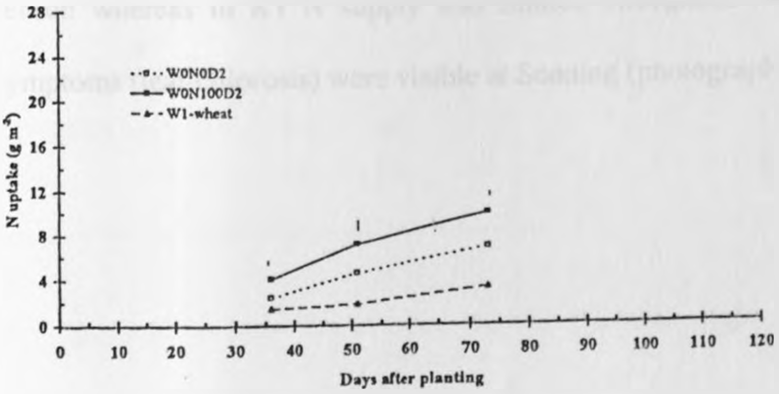


Figure 7.1. Plant nitrogen uptake in the season at Sonning, K1 and K2 in . selected treatments. Bars represent standard errors of differences of means.

production per unit N taken up in the three experiments were similar; 43.5, 40.0, 41.7 g TDM $m^{-2}$/ g N at Sonning, K1 and K2 respectively. This implies that the crop efficiency of use of N for dry matter production was similar in the three experiments.

High planting density increased $N_{pl}$ at Sonning from 58 DAP to 114 DAP and 32 and 46 DAP in K1 but only at 36 DAP in K2 (table 7.1). The larger $N_{pl}$ at Sonning and K1 at high planting density were associated with a higher N demand by the crop ensuring high TDM production. The significantly high effect of high planting density on $N_{pl}$ in K2 at 32 DAP indicates that N demand and supply was influenced by density at that time but that other factors limited plant N uptake later in the season.

Fertilizer N application significantly increased $N_{pl}$ at Sonning and K1 at different times but only increased $N_{pl}$ in K2 at 73 DAP. At Sonning, fertilizer N significantly ($p \leq 0.05$) increased $N_{pl}$ at 86 and 114 DAP. In K1, fertilizer N significantly increased ($p \leq 0.05$) $N_{pl}$ in fertilized treatments at 32, 46 and 95 DAP (appendix V, table 1). These results indicate that N supply limited $N_{pl}$ increasingly as the season progressed in the three experiments. At Sonning, $N_{pl}$ was limited by N supply from 86 DAP to the end of the season whereas in K1 N supply was limited throughout the season. N-deficiency symptoms (leaf chlorosis) were visible at Sonning (photograph 2) but not in K1 or K2.

Table 7.1 Total plant N uptake by beans over time at Sonning, K1 and K2

| Treatment | Total N (g $m^{-2}$) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Sonning | | | K1 | | | K2 | | |
| DAP | 58 | 86 | 114 | 32 | 46 | 95 | 36 | 51 | 73 |
| W0N0D1 | 6.1 | 5.4 | 15.9 | 1.4 | 3.2 | 10.7 | 2.1 | 5.4 | 6.7 |
| SE | 0.6 | 0.2 | 1.1 | 0.1 | 0 | 0.4 | 0.4 | 0.4 | 1.6 |
| W0N0D2 | 9.3 | 10 | 14.8 | 2.4 | 2 | 12.4 | 2.5 | 4.6 | 6.9 |
| SE | 1.6 | 1.5 | 1 | 0.2 | 0 | 0.3 | 0.1 | 1.3 | 0.9 |
| W0N100D1 | 7.6 | 6.9 | 16.4 | 3.2 | 4.5 | 16.4 | 3.4 | 6.4 | 7 |
| SE | 1.2 | 1 | 2.2 | 0.3 | 0 | 0.6 | 0.4 | 2.1 | 0.9 |
| W0N100D2 | 14.6 | 15 | 22.5 | 4.1 | 8.6 | 17.8 | 4.1 | 7.2 | 9.9 |
| SE | 0.2 | 1.4 | 0.8 | 0.3 | 0 | 0.4 | 1.1 | 0.5 | 0.3 |
| W1N0D1 | 4.7 | 6 | 10 | 1.4 | 2.3 | 9.9 | 2.3 | 6.6 | 8.4 |
| SE | 0.9 | 0.4 | 0.7 | 0.1 | 0 | 0.1 | 0.2 | 0.6 | 0.8 |
| W1N0D2 | 7.9 | 10.2 | 19.7 | 1.7 | 2.8 | 9 | 4.7 | 6 | 7.6 |
| SE | 1.4 | 2.2 | 1.3 | 0.3 | 0 | 0.4 | 1.1 | 0.7 | 0.8 |
| W1N100D1 | 7.0 | 11.3 | 16.3 | 2.6 | 5.7 | 19.2 | 3 | 9 | 8.7 |
| SE | 1.0 | 3.5 | 1.4 | 0.4 | 0.2 | 0.7 | 0.3 | 1.5 | 0.5 |
| W1N100D2 | 11.5 | 18.5 | 27.4 | 4.0 | 8.2 | 19.5 | 3.9 | 5.9 | 9.1 |
| SE | 2.0 | 2.2 | 1.3 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 1.5 |

S.E represents the standard error of the mean of three replicates

Photograph 2. Beans at the Sonning experiments showing nitrogen deficiency symptoms.

In K2 the lack of $N_{pl}$ response to fertilizer N application may have arisen from a combination of limited bean growth and reduced N uptake because of limited soil water supply.

Irrigation as a main factor did not significantly increase $N_{pl}$ over time in the three experiments except in K2 at 51 and 73 DAP when $N_{pl}$ was 18% higher in irrigated than in the rainfed treatment (table 7.1). This observation might indicate that irrigation was probably ineffective (due to loss of water by evaporation; table 3.4) or N supply was limited so that the applied water did not increase the availability of N to the plant.

**Interactions**

Interactions between water, nitrogen and planting density on $N_{pl}$ occurred in all of the three experiments at different times. At Sonning, there was a significant interaction (p=0.05) between irrigation and planting density on $N_{pl}$ at the end of the season (114 DAP). $N_{pl}$ was 21% higher in the irrigated, high planting density treatment (W1D2) than the rainfed high planting density treatment (W0D2) (figure 7.1a). The increase in $N_{pl}$ in W1D2 indicated that soil moisture applied through irrigation early in the season was stored in the profile and used up later in the season (table 3.2). The stored soil moisture improved N uptake.

There was highly significant interaction (p=0.01) between irrigation and nitrogen (W x N) on $N_{pl}$ in K1 at 46 and 95 DAP (table 7.2). $N_{pl}$ in the unfertilized irrigated treatment was the same or less than in the irrigated treatment. Application of N fertilizer increased $N_{pl}$ more in the irrigated than in the rainfed treatments.

Table 7.2 Interaction of irrigation and fertilizer N application on total plant N uptake ($N_{pl}$) at 46 and 95 DAP in K1.

| Irrigation | $N_{pl}$ (g $m^{-2}$) | | | |
|---|---|---|---|---|
| DAP | 46 | | 95 | |
| | N0 | N100 | N0 | N100 |
| W0 | 2.8 | 6.4 | 11.6 | 17.1 |
| W1 | 2.6 | 6.9 | 9.5 | 19.3 |
| SED | 0.88 | | 1.34 | |
| CV% | 0.9 | | 0.5 | |

At 46 DAP in K1, there was highly significant N x D interaction ($p=0.01$) (table 7.3). $N_{pl}$ was unaffected by density in the absence of N fertilizer, implying that N was limiting at the higher density. An application of 100 kg N $ha^{-1}$ increased $N_{pl}$ more in the higher density (223% increase) than in the low density treatment (79%). In the N0 treatments, N supply limited $N_{pl}$. When N supply was not limiting $N_{pl}$ (N100 treatment), increasing plant demand for N through high planting density increased $N_{pl}$.

Table 7.3 Effect of nitrogen and planting density on $N_{pl}$ in K1 at 46 DAP.

| Nitrogen | | $N_{pl}$ (g m$^{-2}$) | |
|---|---|---|---|
| | Density | D1 | D2 |
| N0 | | 2.8 | 2.6 |
| N100 | | 5.0 | 8.4 |
| SED | | 0.77 | |
| CV% | | 14.3 | |

### 7.4.2 Apparent fertilizer N recovery efficiency (ARE; %)

Apparent fertilizer N recovery efficiency (calculated on an area basis; g N m$^{-2}$) increased with time in all three experiments to a maximum at or near the end of the season and either levelled off or decreased (figure 7.2). Average seasonal ARE at Sonning, K1 and K2 was 55, 77 and 13 % respectively (table 7.4). The differences in ARE may be attributed to the soil N supply, plant size and soil water content. The seasonal rainfall was highest in K1 and lowest in K2. The low ARE under low rainfall conditions in K2 may be because of the reduced N demand arising from poor crop growth (low TDM).

Table 7.4 Apparent N recovery efficiency (%) with time in beans at Sonning, K1 and K2.

| Treatment | Sonning | | | K1 | | | K2 | | |
|---|---|---|---|---|---|---|---|---|---|
| DAP | 58 | 86 | 114 | 32 | 46 | 95 | 36 | 51 | 73 |
| W0D1 | 14.3 | 15.7 | 4.4 | 17.7 | 11 | 57 | 13.4 | 10 | 3.6 |
| SE | 10.6 | 8.5 | 23.8 | 5.5 | 9.9 | 19.1 | 3.7 | 17.6 | 24.9 |
| W0D2 | 52.8 | 50.6 | 77.1 | 17.6 | 62.8 | 53.5 | 16.1 | 25.8 | 30.5 |
| SE | 18.2 | 6.6 | 5.5 | 7.7 | 6.6 | 10 | 11.1 | 15.2 | 5.4 |
| W1D1 | 22.9 | 52.2 | 62.6 | 12.2 | 34.4 | 92.5 | 6.6 | 23.9 | 2.9 |
| SE | 19 | 37.7 | 21.2 | 6.5 | 9.9 | 21.8 | 1.7 | 15.9 | 9.9 |
| W1D2 | 35.3 | 83.1 | 77.2 | 36.7 | 53.2 | 104.7 | -7.5 | -0.7 | 15 |
| SE | 33.1 | 12.5 | 25.1 | 8.7 | 4.1 | 17.4 | 7.8 | 8 | 16.6 |
| Mean | 22.5 | 50.4 | 55.3 | 21.1 | 40.4 | 77 | 7.2 | 14.9 | 13.0 |
| SED | 27.6 | 29.1 | 37.2 | 11.2 | 6.1 | 21.1 | 10.9 | 12.8 | 30.6 |
| CV | 126 | 69 | 53 | 69 | 29 | 21 | 176 | 18 | 111 |

Irrigation and high planting density increased ARE at Sonning and K1, though not significantly (table 7.4). The non-significant fertilizer and planting density effect on ARE may be ascribed to variability in plant N content resulting in high ARE covariance (table 7.4). ARE at 95 DAP in K1 in W1D2 was 105% (figure 7.2b). This is evidence that there was an increased N uptake from the soil N pool; indicating that the application of fertilizer N stimulated the uptake of soil N.

Irrigation and planting density effects on ARE were complex in K2. On the whole ARE was higher in rainfed treatments than in the irrigated treatments. In the rainfed treatments, ARE was higher in D2 treatments compared to D1. However in the irrigated treatments, ARE was higher in D1 compared to D2. The decrease in ARE in the irrigated treatment is difficult to explain. The low fertilizer recovery under irrigation was either due to denitrification or immobilization because of intermittent wetting and drying of soil.

Unrecovered fertilizer N was either immobilized, left in the soil as mineral N, fixed by soil clay minerals, leached or volatilized. It is unlikely that N was leached in K2 because rainfall was limiting. The possibilities of N being left in the soil were examined in section 7.4.4. On the whole, the ARE results were very variable in all three experiments probably due to confounded soil N variability, plant size and N concentration. Use of labelled fertilizer N would reduce errors due to spatial soil N distribution.

### 7.4.3 Nitrogen derived from biological fixation ($N_{dfa}$)

The quantity of $N_{dfa}$ was calculated by the difference method (section 3.9). At Sonning, nitrogen fixation did not occur (there were no nodules on the beans throughout the season). The lack of nodulation at Sonning might indicate the absence of effective *Rhizobium* in the soil; the plot was not sown with a legume for six years prior to the experiment (Jones, pers. comm). At Kabete, there was prolific nodulation observed as early as 7 days after emergence in both K1 and K2. In K1, $N_{dfa}$ was measured only at the end of the season (95 DAP). In K2, $N_{dfa}$ measurements were made at different times in the season. The average $N_{dfa}$ in K1 and K2 at the end of the season was 3.8 and 5.2 g N $m^{-2}$ respectively.

Irrigation on effect on $N_{dfa}$ was not significant in either K1 (95 DAP) or K2. Nitrogen fertilizer N did not have a significant effect on $N_{dfa}$ in either K1 or K2. This suggests that fertilizer application did not stop the N fixation process. There was however a highly significant interaction ($p=0.004$) between irrigation and fertilizer N in K1 at 95 DAP (table 7.5).

Table 7.5 Interactive effect of irrigation and N fertilizer on $N_{dfa}$ at 95 DAP in K1.

| Irrigation | $N_{dfa}$ (g $m^{-2}$) | |
|---|---|---|
| Nitrogen | N0 | N100 |
| W0 | 3.3 | -1.1 |
| W1 | 2.1 | 10.9 |
| SED | 1.53 | |

$N_{dfa}$ was similar for the unfertilized beans in the irrigated and rainfed treatments. Assimilate supply to the nodules in these unfertilized beans may be limited by the small canopy size. TDM production was N limited as attested by low TDM in unfertilized treatments. Application of fertilizer N to rainfed beans, apparently improved N uptake by wheat (data not shown) thus reducing the values of $N_{dfa}$ (reference crop was greater than that of beans. Nevertheless, it is possible that in W0N100 treatment, water uptake by the plants was greater so that the nodules were subject to water stress, which resulted in a reduction in activity (Sprent, 1976).

High planting density significantly (p=0.1) increased $N_{dfa}$ in K2 only at 32 DAP (figure 7.3). In K2, average $N_{dfa}$ increased rapidly between 36 and 51 DAP (flowering and pod growth stage) and more slowly between 51 and 73 DAP (seed growth to maturity stage) (figure 7.3). The hypothesis that high planting density would increase $N_{dfa}$ due increased plant N demand was not proven in these experiments because there was ample soil mineral N to accommodate the increased N demand in the high planting density (section 7.4.4). $N_{dfa}$ was measured in K1 at the end of the season, any density effects earlier on in the season may have escaped notice. Sprent (1976) noted that self-shading under high planting density later in the growing season depressed N fixation.

The number of nodules may be used as a rough indicator of N fixation. The number of effective nodules (pink) per plant at flowering in K1 and K2 (46 and 36 DAP) were 10.7 and 6.2 respectively. In K1, irrigation significantly increased (p=0.05) the number of nodules plant$^{-1}$ (12.9) compared to rainfed treatment (8.5). Planting density did not influence the number nodules plant$^{-1}$ in either K1 or K2. There was a significant interaction (p=0.05) between irrigation and planting density (table 7.7) on nodulation in K2. The increase in nodulation due to irrigation was higher in D2 (106%) compared to D1 (50%). The increase in number of nodules plant$^{-1}$ in W1D2 (table 7.6) did not correspond to significant increase in the amount of fixed-N.

Table 7.6 Interaction of irrigation and N planting density on the number of nodules plant$^{-1}$ at 36 DAP in K2.

| Irrigation | Number of nodules plant$^{-1}$ | | |
|---|---|---|---|
| | Density | D1 | D2 |
| W0 | | 5.8 | 3.4 |
| W1 | | 8.7 | 7.0 |
| SED | | 1.8 | |
| CV% | | 14.2 | |

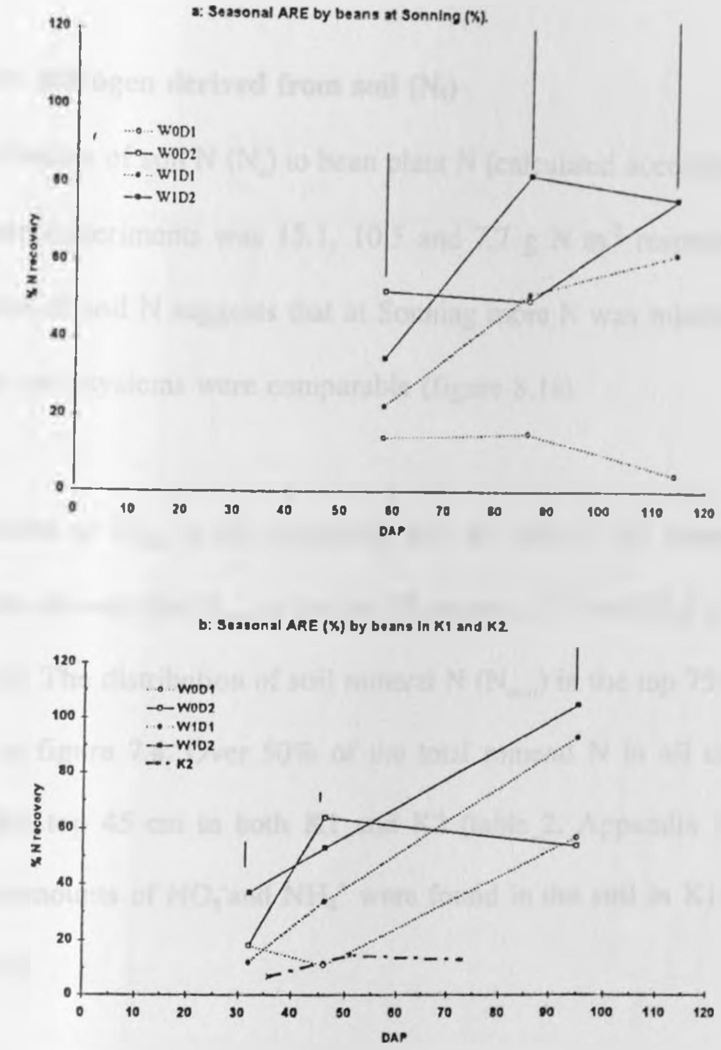


Figure 7.2. Effect of irrigation and planting density on apparent fertilizer recovery efficiency (ARE) at Sonning, K1 and K2 (pooled data) in the season. Bars represent SED.

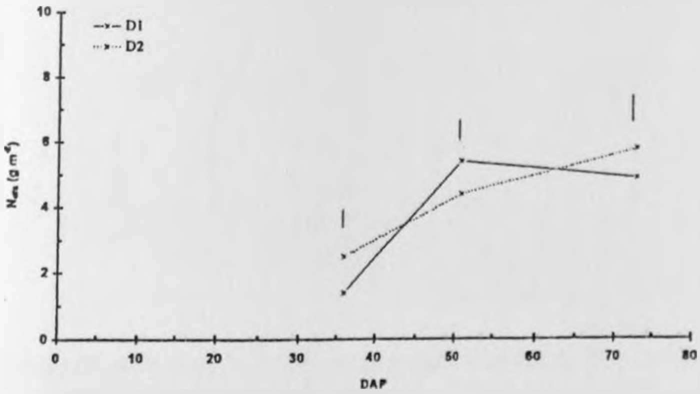


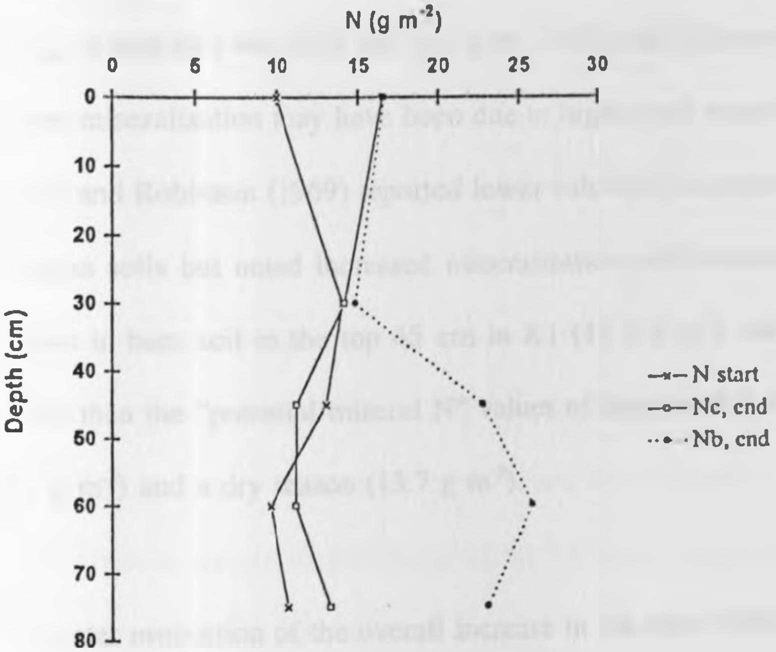
Figure 7.3. Density effect on seasonal N fixation in K2 (pooled data). Bars represent SED.

### 7.4.4 Plant nitrogen derived from soil ($N_s$)

The contribution of soil N ($N_s$) to bean plant N (calculated according to equation 7.5) in the three experiments was 15.1, 10.5 and 7.7 g N $m^{-2}$ respectively. The greater contribution of soil N suggests that at Sonning more N was mineralized because the size of the root systems were comparable (figure 8.1a).

Measurements of $N_{min}$ at the beginning and the end of the season in K1 and K2 experiments showed that $N_{start}$ in the top 75 cm was 57.7 and 55.4 g $m^{-2}$ in K1 and K2 respectively. The distribution of soil mineral N ($N_{start}$) in the top 75 cm in K1 and K2 is shown in figure 7.4. Over 50% of the total mineral N in all the treatments was found in the top 45 cm in both K1 and K2 (table 2, Appendix I). Approximately equivalent amounts of $NO_3^-$ and $NH_4^+$ were found in the soil in K1 and K2 (table 2, Appendix I).

a: K1



b: K2

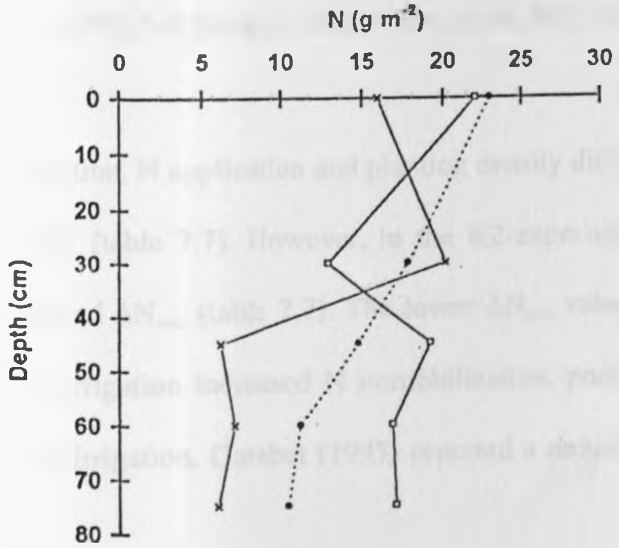


**Figure 7.4. Change in mineral N in the soil profile in bare (Nb) and cropped (Nc) at the beginning (start) and end of the season in the K1 and K2 experiments.**

There was an increase in soil mineral N in the bare plots by the end of the season ($N_{start}$ and $N_{end}$) in both K1 and K2 (103.4 and 88.3 g $m^{-2}$ respectively). Consequently, $\Delta N_{min}$ in bare soil was 45.6 and 32.9 g $m^{-2}$ in K1 and K2 respectively. The difference in net mineralisation may have been due to higher soil water content in K1 than K2. Semb and Robinson (1969) reported lower values of net mineralization in a range of Kenyan soils but noted increased mineralization with increased rainfall. The $\Delta N_{min}$ values in bare soil in the top 45 cm in K1 (15.7 g $m^{-2}$) and K2 (11.8 g $m^{-2}$) were lower than the "potential mineral N" values of Semb and Robinson (1969) for a wet (27 g $m^{-2}$) and a dry season (13.7 g $m^{-2}$).

A greater proportion of the overall increase in the total mineral N in K1 occurred in the layers below 30 cm (figure 7.4) suggesting that mineral N was leached from above during the season. Moreover, most of the increase in mineral N was in the form of $NO_3^-$-N (table 2, Appendix I). By contrast, most of the increase in mineral N occurred in the $NH_4^+$-N fraction rather than in the $NO_3^-$ fraction in the K2 experiment.

Irrigation, N application and planting density did not have a significant effect on $\Delta N_{min}$ in K1 (table 7.7). However, in the K2 experiment, irrigation significantly ($p=0.01$) reduced $\Delta N_{min}$ (table 7.7). The lower $\Delta N_{min}$ values in the irrigated treatment indicate that irrigation increased N immobilization, possibly through increased soil biomass after irrigation. Garabet (1995) reported a reduction in $\Delta N_{min}$ in irrigated plots also.

The high levels of $N_{min}$ at the beginning of the season in both K1 and K2 were high enough to meet plant N demands. The insensitivity of $\Delta N_{min}$ to treatments was probably due to the large variation in $\Delta N_{min}$ among individual samples (i.e large standard deviation). This may be corrected by collecting more samples. Plant N uptake at the end of the season represented about 20% of the total soil mineral N content in the profile at Kabete. However, the increase in $N_{pl}$ response to fertilizer N application in K1 indicates that soil N supply was limited.

$\Delta N_{min}$ represents a snap-shot view of what was happening at the beginning and at the end of the season with no information of mineral N availability during the course of the growing season. The effect of fertilizer application and N fixation on net N mineralization may be studied better using $^{15}N$ isotope labelling techniques with more frequent sampling in the course of the season.

Table 7.7 Effect of irrigation on $\Delta N_{min}$ in the top 75 cm in K1 and K2 (g $m^{-2}$).

| Experiment/ irrigation | Treatment N0D1 | N0D2 | N100D1 | N100D2 | mean |
|---|---|---|---|---|---|
| | ---------- g $m^{-2}$ ---------- | | | | |
| K1 | | | | | |
| W0 | 3.3 | 7.2 | 13.8 | 7.7 | 8.0 |
| W1 | 20.2 | -4.0 | -3.2 | 14.4 | 6.9 |
| SED | | | | | 12.2 |
| K2 | | | | | |
| W0 | 16.9 | 31 | 37.9 | 51.8 | 34.4 |
| W1 | 10.3 | -2.5 | 0.5 | -2.1 | 1.6 |
| SED | | | | | 9.4 |

SED = standard error of difference, mean of 3 values.

### 7.4.5 Nitrogen partitioning and re-mobilization patterns.

The average NUE (calculated using above ground TDM) was 0.69, 0.58 and 0.46 at Sonning, K1 and K2 respectively. The differences in NUE in the three experiments may be ascribed to the differences in seed production and seed-N concentration. The seed-N concentrations were 3.8, 3.7 and 2.8% at Sonning, K1 and K2 respectively; i.e. a combination of low seed yields and low seed-N concentrations resulted in low NUE in K2.

At Sonning and K1, irrigation, nitrogen or planting density treatments did not have a significant effect on NUE. Nevertheless there was a tendency for lower NUE in fertilized treatments all three experiments (table 7.8). Chapin *et al.*, (1987) showed that NUE increased in low N supply.

Table 7.8 Effect of fertilizer N on nitrogen use efficiency (NUE) in the Sonning, K1 and K2 experiments.

| Experiment | Treatment | NUE (g seed N/g total N) |
|---|---|---|
| Sonning | N0 | 0.70 |
| | N100 | 0.69 |
| K1 | N0 | 0.59 |
| | N100 | 0.58 |
| K2 | N0 | 0.49 |
| | N100 | 0.45 |

The site differences on NUE may be explained by differences in factors that influence redistribution. At Sonning, the long crop duration allowed redistribution of N from vegetative parts to the seed. Water stress in the K2 experiment may have limited N redistribution.

### Tissue N concentration

A decrease in N concentration in the vegetative parts over time is assumed to mean that N is transferred to the reproductive parts (seeds and pod walls) which act as stronger N sinks later in the season. N concentration in leaves and stem decreased with time in all three experiments (figure 7.5). Decreases in leaf-N concentration were significantly greater in fertilized than unfertilized treatments at Sonning and K2, but not in K1 (figure 7.5). Average leaf-N concentration at final harvest was highest in K2 (2.2%) compared to Sonning (1.4%) and K1 (1.8%). This might indicate that there was a reduced ability to re-mobilise leaf-N under the water stressed conditions of K2.

Stem-N concentration decreased over time in all three experiments (figure 7.5) although the decrease was less than that in the leaves. The decrease in stem-N indicates that there was remobilization from the stem in all three experiments. Stem-N concentration at the final harvest was highest in K2 (1.9%) and lowest at Sonning (1.1%). This might indicate that remobilization from the stem was more efficient at Sonning (high TDM, hence N demand) and least in K2 (due to water stress). It is noteworthy that although stem-N concentration at the beginning of the season in N100 (all three experiments) were higher than in N0, the concentrations at the end of season were similar (figure 7.5). These results suggest that N fertilization resulted in the accumulation of N in the stem early in the season. This N was then remobilized later in the season. The amount of N which is remobilized depends the on soil water status. Less N was remobilized in the drier K2 experiment than in the others.

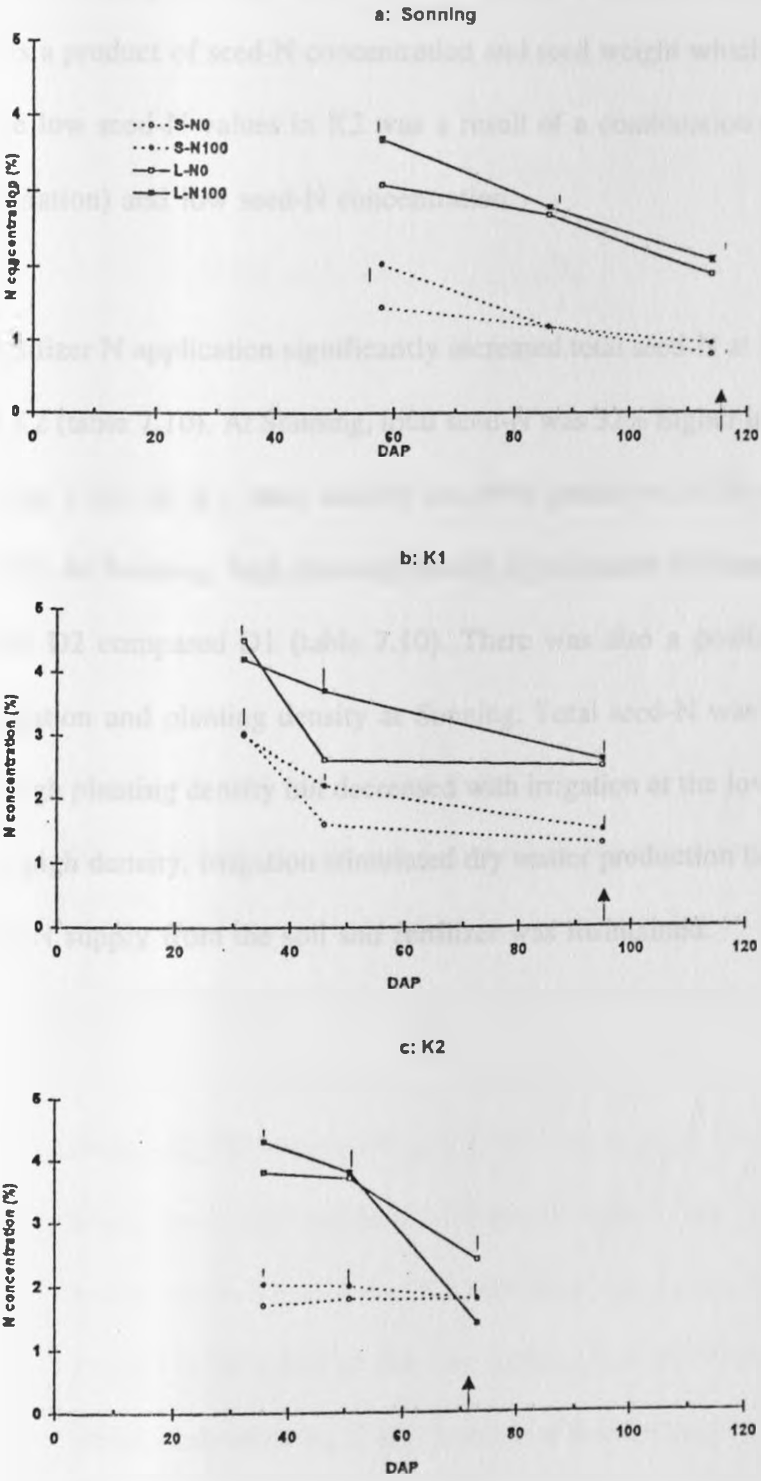


Figure 7.5. Nitrogen concentrations (g N 100 g TDM) in leaves (L) and stems (S) in non-fertilized (N0) and fertilized (N100) treatments at Sonning, K1 and K2. Bars represent SED at a given time. Arrows indicate the final harvest dates.

Total seed-N is influenced by N uptake and N-redistribution. Total seed-N was 12.4 g N $m^{-2}$, 8.2 g N $m^{-2}$, and 3.7 g N $m^{-2}$ at Sonning, K1 and K2 respectively. Total seed-N is a product of seed-N concentration and seed weight which is dependent on TDM. The low seed-N values in K2 was a result of a combination of low seed yield (sink limitation) and low seed-N concentration.

Fertilizer N application significantly increased total seed-N at Sonning and K1 but not in K2 (table 7.10). At Sonning, total seed-N was 32% higher in N100 compared to N0 (table 7.10). In K1, total seed-N was 64% greater in N100 compared to N0 (table 7.10). At Sonning, high planting density significantly increased (p=0.01) seed-N by 48% D2 compared D1 (table 7.10). There was also a positive interaction between irrigation and planting density at Sonning. Total seed-N was increased by irrigation at high planting density but decreased with irrigation at the low density (table 7.9). At the high density, irrigation stimulated dry matter production (increased sink capacity) and N supply from the soil and fertilizer was maintained.

Table 7.9 Interactive effect of irrigation and planting density total seed-N recovery at Sonning at 114 DAP

| Sonning | Total seed-N ($g\ m^{-2}$) | | |
|---|---|---|---|
| | Density | D1 | D2 |
| W0 | | 11.0 | 12.9 |
| W1 | | 9.0 | 16.7 |
| SED | | 0.86 | |

## 7.5 Summary and conclusions

1) The differences in total dry matter and $N_{pl}$ among the three experiments may be explained partially by the difference in the length of the growth period of the experiments; 114, 95 and 73 days at Sonning, K1 and K2 respectively.

2) Plant daily N uptake ($N_{dpl}$, $g\ N\ m^{-2}\ day^{-1}$) were similar for N0 in all three experiments but less in K2 for N100 (table 7.10). The greater $N_{pl}$ in N100 treatments at Sonning and K1 increased $N_{dpl}$. Lower $N_{dpl}$ in K2 was probably a result of the effect of low soil water content on N availability. High planting density increased $N_{pl}$ if soil water was not limiting (section 7.4.1). The lower $N_{dpl}$ values in K2 were probably due to water-limited growth, which reduced N uptake. $N_{dpl}$ values for Mwezi Moja beans in these experiments were lower

than those reported for other crops (Engels and Marschner, 1995; Devries *et al.*, 1989). This may be an indicator that beans are less efficient in taking up N compared to other crops.

3) Irrigation did not increase $N_{pl}$ in any of the three experiments nor did it stimulate net mineralization. However it did stimulate immobilization in K2. Net mineralization at Kabete was not driven by plant N demand ($N_{pl}$) because there was no response to planting density. However, this result would need verification with both/either a more sensitive method of measuring net mineralization (i.e $^{15}N$ isotope) and/or with repeated measurements of mineral N during the course of the crop growth season.

4) High levels of soil mineral N at the beginning of the season reduced N fixation and fertilizer N recovery in K1 and K2. Probably larger fertilizer recoveries results would be obtained if fertilizer was applied later in the season, rather than at sowing time when the plant N demand was low and other sources of N (i.e . from seed and soil mineral N) were available . The higher $\Delta N_{min}$ values for the fertilized treatments in K2 compared to K1 (table 7.10) may result from the low fertilizer recovery in K2 compared to K1.

5) N redistribution and remobilization from vegetative parts to the seed was reduced by soil moisture stress in K2 resulting in seeds with low N content. The implication of this observation is that low quality seeds are produced under water stress, and that a larger proportion of N is lost through straw in

a drier season than in a wet season.

6) The proportion of $N_{pl}$ derived from $N_{dfa}$, $N_f$ and $N_s$ showed that $N_{dfa}$ was 10% higher in K1 than K2 and that N fertilizer application did not reduce $N_{dfa}$ in K1. Probably the fertilizer application rate was not high enough to meet all of the plant N demand. The contribution of fertilizer N to the total crop N budget in the N100 treatment was 26%, 42% and 11% at Sonning, K1 and K2 respectively (figure 7.6).

7) At Sonning the unfertilized beans derived all of their N from the soil because no nodulation occurred (lack of *Rhizobium*). Although N deficiency symptoms (leaf chlorosis) were observed, it is apparent that the soil had a high mineral N supply. In K1, the non-fertilized beans derived approximately 60% of their total N from the soil compared to only 16% in N100. The proportion on $N_{dfa}$ in both K1 and K2 was similar and was not influenced by fertilizer N application. The partitioning of $N_{pl}$ among the different N sources at Kabete was similar to the results obtained by Ssali and Keya (1986).

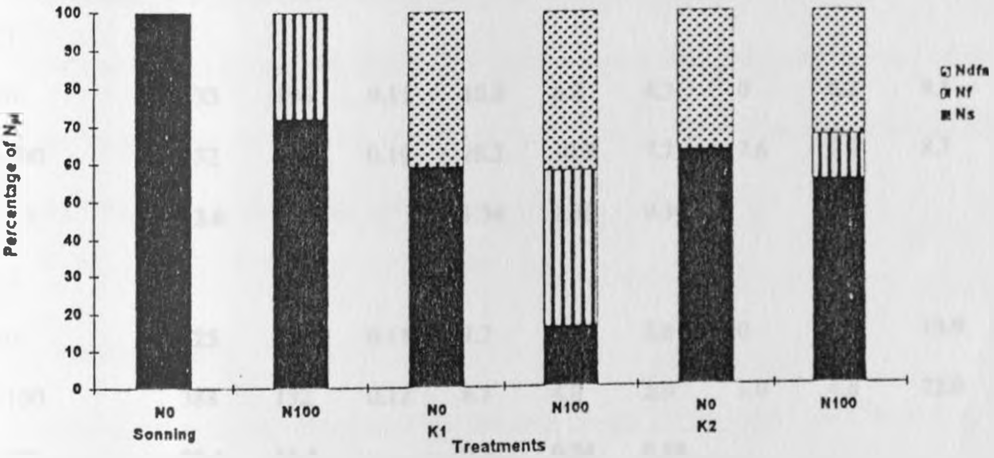


Figure 7.6. The proportion of total plant N derived from soil ($N_s$), fixation ($N_{dfa}$) and fertilizer ($N_f$) at the end of the season in Sonning, K1 and K2.

Table 7.10 Total plant uptake, seed N and N sources at the final harvest at Sonning, K1 and K2.

| Experiment/ Treatment | TDM | Seed | $N_{dpl}$ | $N_{pl}$ | Seed-N | $N_{dfa}$ | $N_f$ | $N_s$ | $\Delta N_{min}$ | $N_l$ |
|---|---|---|---|---|---|---|---|---|---|---|
| | $g\ m^{-2}$ | | | | | | | | | |
| Sonning | | | | | | | | | | |
| N0 | 678 | 289 | 0.13 | 15.1 | 10.7 | 0 | 0 | 15.1 | * | * |
| N100 | 936 | 375 | 0.19 | 21.1 | 14.1 | 0 | 6.0 | 15.1 | * | * |
| SED | 77.4 | 25.2 | | 0.01 | 0.28 | | | | | |
| K1 | | | | | | | | | | |
| N0 | 433 | 196 | 0.11 | 10.5 | 6.2 | 4.3 | 0 | 6.2 | 9.5 | 15.7 |
| N100 | 732 | 295 | 0.19 | 18.2 | 10.2 | 7.7 | 7.6 | 2.9 | 8.7 | 19.2 |
| SED | 43.6 | 14.9 | | 1.34 | 1.38 | 0.34 | | | | |
| K2 | | | | | | | | | | |
| N0 | 325 | 128 | 0.11 | 7.7 | 3.5 | 2.8 | 0 | 4.9 | 13.9 | 18.8 |
| N100 | 388 | 132 | 0.12 | 8.7 | 4.0 | 2.9 | 1.0 | 4.8 | 22.0 | 34.1 |
| SED | 25.1 | 11.4 | | 0.34 | 0.34 | 0.88 | | | | |

SED = standard error of difference; * = measurement not available.

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$N_{dfa}$ is the difference between $N_{pl}$ in beans and wheat (reference crop)
$N_{dpl}$ is the daily plant N uptake rate (g N $m^{-2}$ $day^{-1}$); $N_{pl}$ at the end of season divided by crop duration.
$N_f$ is the difference $N_{pl}$ in fertilized and non-fertilized treatments.
$N_l$ is the labile soil N ($N_{pl}$ + $N_{min}$ - $N_{dfa}$)
$N_s$ is calculated from equation 7.5.

# Chapter 8

## Water use and water use efficiency

### 8.1 Introduction

This chapter describes the soil water measurements and their analysis, the objective of which is to investigate in the different environments the extent to which crop management practices influenced the soil water balance, and the consequences for water use efficiency. First, the results of the root growth measurements are presented, as this information is used later when attempting to partition water losses between evaporation and drainage. Later sections discuss the measurements of consumptive water use (from measured changes in profile water content), and the use of a variety of techniques for partitioning overall water losses between drainage, transpiration and direct evaporation from the soil surface

### 8.2 Root Growth

Crop water uptake is influenced by the size of the root system and its ability to take up and transport water. Root size was determined from the root length density (see section 3.5.4) in the three experiments. The total root length density (RLD) in the top 75 cm was 4133, 6041, 4648 m $m^{-3}$ at Sonning, K1 and K2. Treatments did not have a significant effect on total RLD. Therefore pooled RLD and percentage distribution at varying depths for the three experiments were presented in figure 8.9. Approximately 80% of the total root system was found within the top 45 cm and this pattern was similar in all three experiments (figure 8.1).

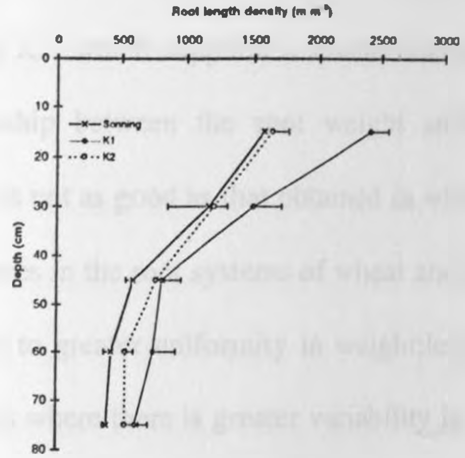


Figure 8.1a. Root length density (m m$^{-3}$) at Sonning, K1 and K2 experiments (pooled data for all treatments). Bars represent standard error of means.

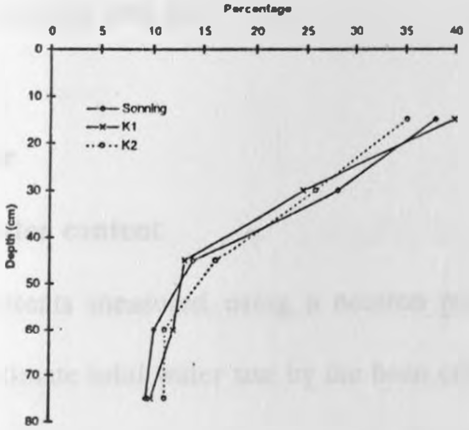


Figure 8.1b. Percentage root length density disribution with depth at Sonning, K1 and K2 experiments.

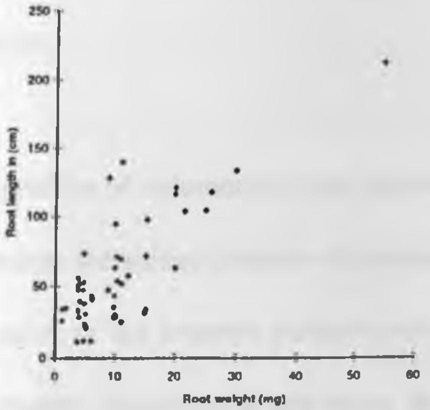


Figure 8.1c. The relationship between root length (cm) and root weight (mg) in the K2 experiment.

From cumulative ET data, the implications of these results was that at Sonning a large LAI (highest LAI = 6) was supplied by a root system whose length was similar to the root system in K2, which supplied a smaller canopy (LAI = 2). There was a weak linear relationship between the root weight and root length (figure 8.1c). The relationship was not as good as that obtained in wheat (Gregory *et al.*,1978) probably due to differences in the root systems of wheat and beans. The fibrous root system of wheat is likely to greater uniformity in weight:length relationship than the tap root system of beans where there is greater variability in root diameter. Assuming that the linear relationship between weight and length was similar in all three experiments, then there was a higher proportion of dry matter allocated to the root system in K2 compared to Sonning and K2.

## 8.3 Soil Water

### 8.3.1 Soil water content

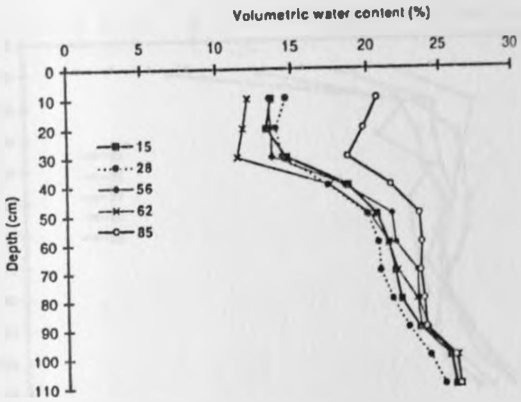
Soil water contents measured using a neutron probe at Sonning and in K1 were analyzed to estimate total water use by the bean crops. Measurements were made on 11 days at Sonning and on 9 days in K1. Soil water contents were measured gravimetrically on 4 occasions to 75 cm depth in K2 because of non-availability of a neutron probe.

At Sonning, profiles of volumetric water content in selected treatments on 5 dates are shown to illustrate the salient features of the season (figure 8.2). The treatments shown are representative of the extreme rainfed treatments. In both treatments there tended to be a progressive depletion of soil water through the growing season to 100 cm depth. Any change in water content during rain-free periods was assumed to be due to evaporation from the soil surface and water uptake by roots. At Sonning, the longest dry periods were 0-28 DAP and 50-66 DAP.

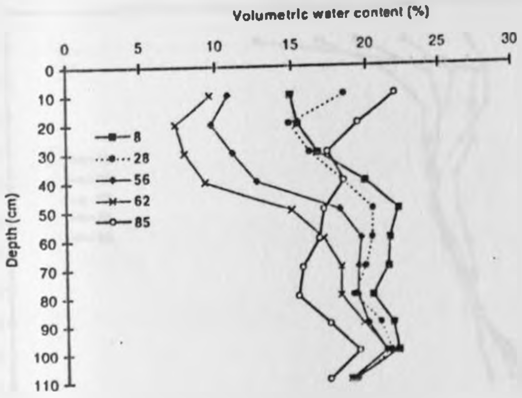
Water was lost primarily from the upper 50 cm of the profile, and losses during the first month were greater in the N100D2 treatment compared with the N0D1 treatment, reflecting the greater uptake of water by roots generated by the larger canopy in the fertilised, densely planted stand. The pattern of water loss below 50 cm was similar in cropped and bare soil treatments, and was evident as early as 15-23 DAP. Given that roots would not have penetrated to 50 cm by this time, there was undoubtedly a significant drainage component in the soil water balance, at least during the early part of the growing season.

Examples of soil water depletion patterns in K1 are shown in Figure 8.3. Any treatment effects on water content profiles are difficult to see because the unusually high and frequent rainfall caused the water content profiles to be remarkably stable. The only rainfree periods between adjacent probing dates were 26-40 DAP, 65-79 DAP and 81-95 DAP. Loss of water during these periods was evident to 90 cm depth, but water contents below 100 cm consistently increased during the growing season indicating that drainage was occurring throughout.

a: bare soil



b: N0D1, rainfed treatment



c: N100D2, rainfed treatment

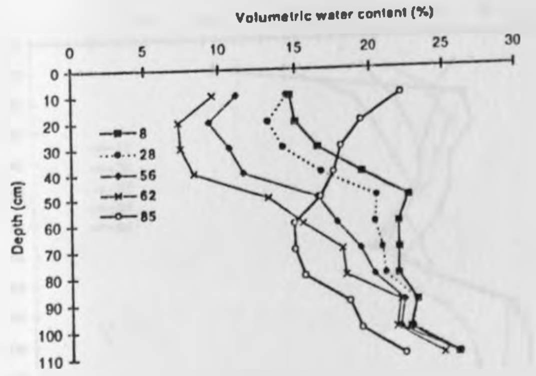
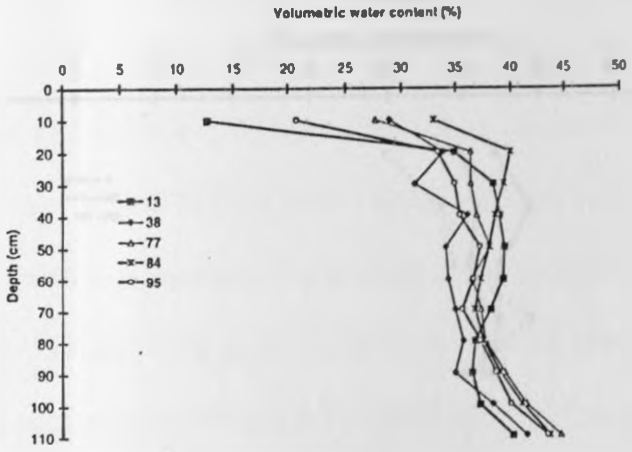
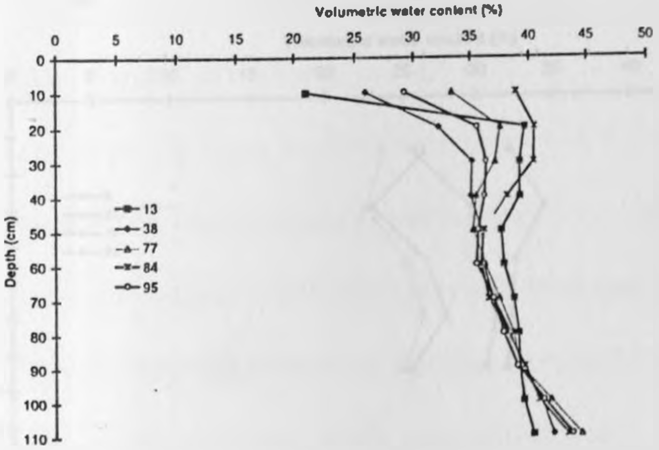


Figure 8.2. Volumetric water content (%) with depth in a bare soil treatment and in the N0D1 and N100D2 treatments at different times (DAP) indicated in the legend at Sonning.

a: Bare soil treatment



b: N0D1, rainfed treatment



c: N100D2, rainfed treatment

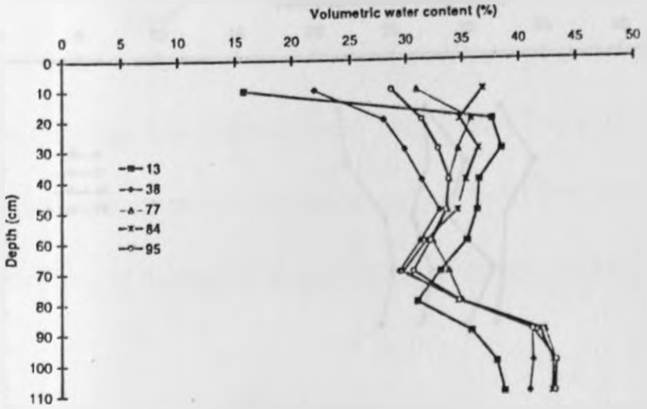
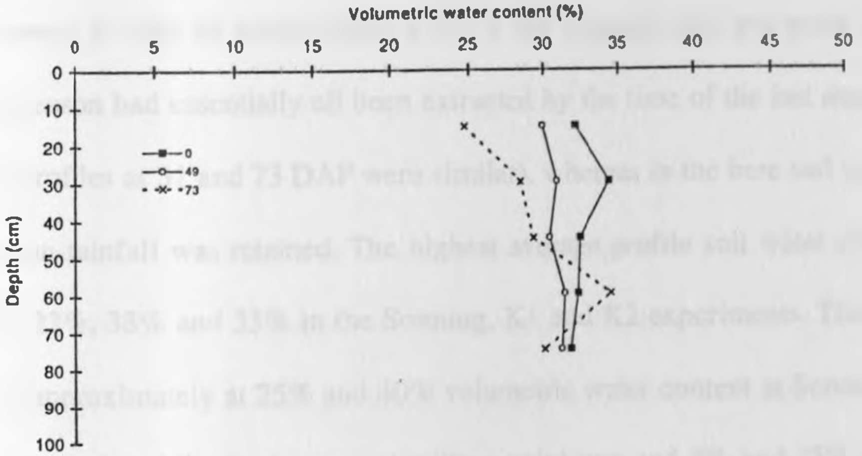
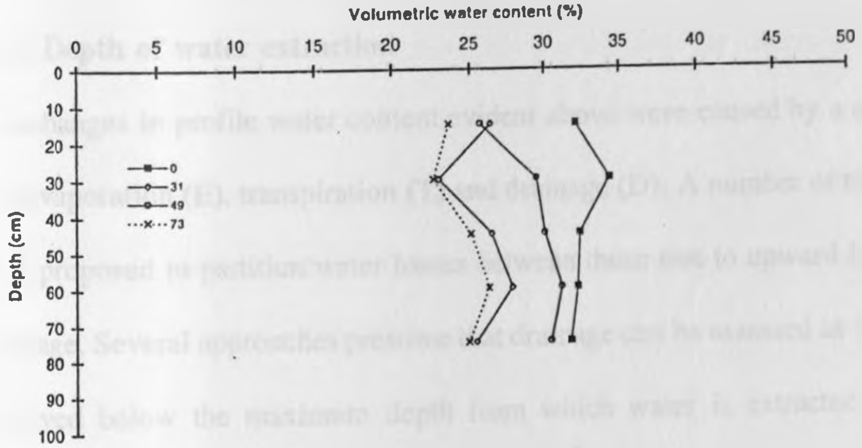


Figure 8.3. Changes in soil volumetric water content (%) with depth in bare, N0D1 and N100D2, rainfed treatments at different times (DAP) in the K1 experiment. The numbers in the legend are DAP when measurements were made.

a: Bare soil



b: N0D1



c: N100D2

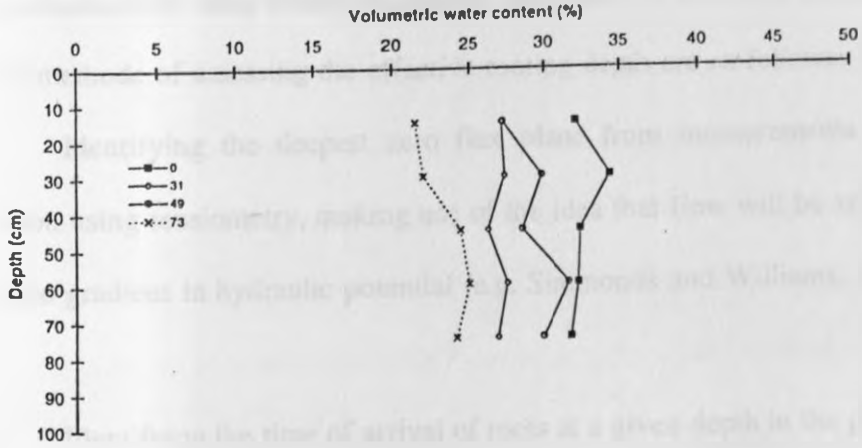


Figure 8.4. Volumetric water content (%) in bare soil, N0D1 and N100D2 rainfed treatments in the K2 experiment at 0, 31, 49 and 73 DAP.

In the very much drier K2 season there was drying to the maximum depth of measurement (75 cm) during the first 31 days after planting followed by net rewetting between 31 and 49 DAP (figure 8.4). In the cropped soil, the water that infiltrated midseason had essentially all been extracted by the time of the last measurement (i.e. the profiles at 31 and 73 DAP were similar), whereas in the bare soil some of the mid season rainfall was retained. The highest average profile soil water content obtained was 23%, 38% and 33% in the Sonning, K1 and K2 experiments. The field capacity was approximately at 25% and 40% volumetric water content at Sonning and Kabete respectively while the permanent wilting point was and 8% and 25% (figure 3.7).

### 8.3.2 Depth of water extraction

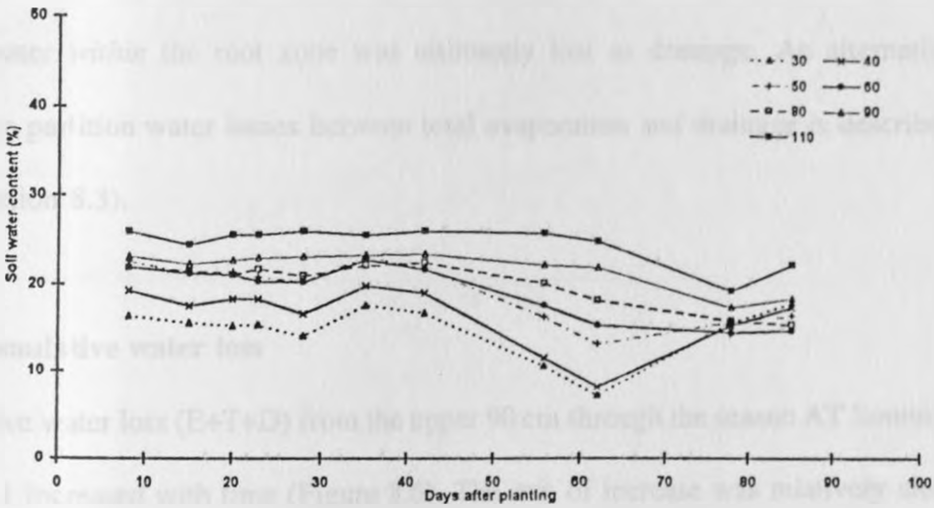
The changes in profile water content evident above were caused by a combination of soil evaporation (E), transpiration (T) and drainage (D). A number of techniques have been proposed to partition water losses between those due to upward flow (E+T) and drainage. Several approaches presume that drainage can be assessed as water depletion observed below the maximum depth from which water is extracted by roots. For example, McGowan and Williams (1980) defined an effective rooting depth as the maximum depth from which measurable quantities of water are extracted by roots. Two methods of assessing the effective rooting depth are as follows:

a) Identifying the deepest zero flux plane from measurements of soil water suction using tensiometry, making use of the idea that flow will be zero where there is zero gradient in hydraulic potential (e.g. Simmonds and Williams, 1989);

b) Identifying the time of arrival of roots at a given depth in the profile from the observed inflection point in the rate of loss of water from the depth in question (McGowan and Williams, 1989). The presumption is that slow rates of water loss initially will be due to downward flow, whereas any subsequent acceleration in the rate of drying indicates water uptake by roots.

An attempt to estimate the effective rooting depth was made using approach 'b'. Figure 8.5 shows examples of the time courses of water content at selected depths. At Sonning (Figure 8.5a) the inflections in the time courses of water content at 30 to 80 cm depth imply the arrival of roots at these depths at some time between 40 and 60 DAP. Roots appeared to have arrived at 90 and 110 cm depth between 60 and 80 DAP. In K1 (Figure 8.5b) the picture was confused by the frequent rainfall causing fluctuations in water content at all depths. Although there appeared to be loss of water from all depths towards the end of the seasons, this was certain to include a drainage component because measurements showed that the water loss continued after the plants were harvested at 146 DAP.

In the absence of more reliable information, it was decided, rather arbitrarily, to assume that the maximum depth of water extraction was 90 cm, which is consistent with the observations described in section 8.2 that roots were recovered from the maximum depth of sampling (i.e. 75 cm). The sensitivity of the seasonal totals of water extraction to the choice of the lower boundary was assessed to get an indication of likely errors. It was found that in both Sonning and K1, changing the assumed maximum depth of water extraction from 90 to 100 cm depth resulted in a 10 mm a: Sonning, N100D2 rainfed treatment



b: K1, N100D2 rainfed treatment

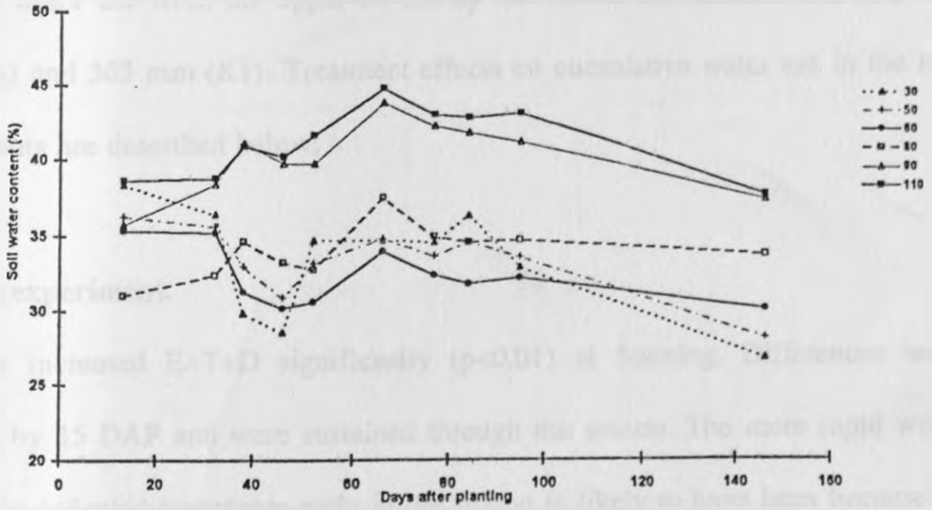


Figure 8.5. Changes in soil volumetric water content (%) with time for selected soil depths at Sonning and K1 experiments.

change in the cumulative seasonal water loss ascribed to total evaporation, which represented less than 5% of the overall cumulative water loss in the cropped plots. However, it is recognised that water losses calculated from changes in water content within the root zone are still uncertain, because it is both possible and likely that some of the water *within* the root zone was ultimately lost as drainage. An alternative attempt to partition water losses between total evaporation and drainage is described later (Section 8.3).

### 8.3.3 Cumulative water loss

Cumulative water loss (E+T+D) from the upper 90 cm through the season AT Sonning and in K1 increased with time (Figure 8.6). The rate of increase was relatively slow during the early stages when canopies were small, increased mid-season and tailed off towards physiological maturity of the crop. Average values (across all treatments) of the total water use from the upper 90 cm by the end of the season were 238 mm (Sonning) and 363 mm (K1). Treatment effects on cumulative water use in the two experiments are described below.

**Sonning experiment.**

Irrigation increased E+T+D significantly ($p<0.01$) at Sonning. Differences were apparent by 15 DAP and were sustained through the season. The more rapid water loss by the irrigated treatments early in the season is likely to have been because of more rapid soil evaporation. However, the mean daily rate of water loss from the irrigated treatments between 15 and 40 DAP was in excess of the potential evaporation rate, implying that irrigation must have generated a drainage loss. Later in the season

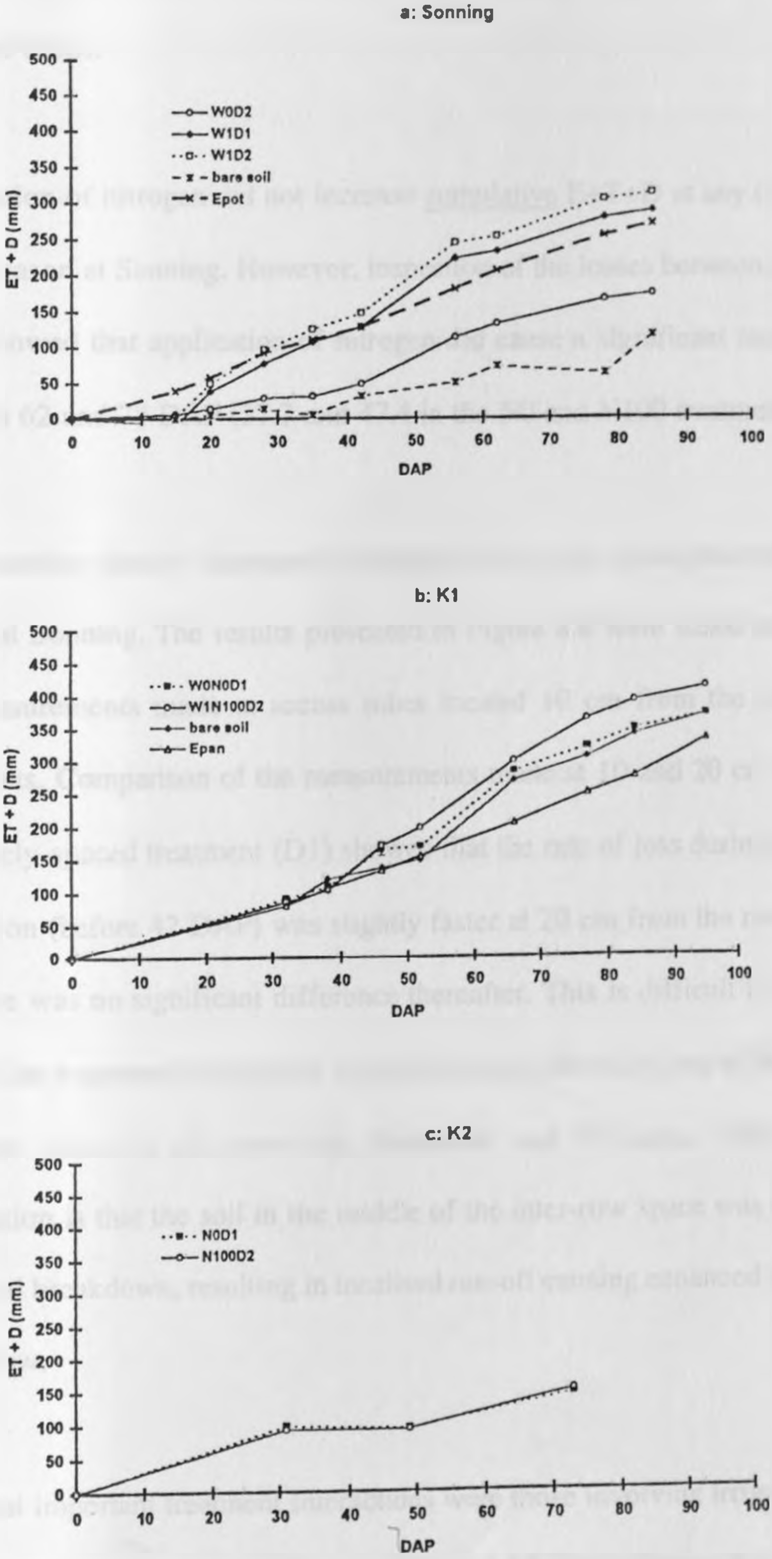


Figure 8.6. Seasonal cumulative ET+D and Epot (mm) at Sonning, K1 and K2 (rainfed treatments) experiments.

the mean daily losses from the irrigated treatments were similar to potential evaporation, and could have been sustained by the large leaf area indices in the irrigated crops.

Application of nitrogen did not increase cumulative E+T+D at any time in the course of the season at Sonning. However, inspection of the losses between adjacent probing dates showed that application of nitrogen did cause a significant increase in the loss between 62 and 78 DAP (37.7 and 47.4 in the N0 and N100 treatments respectively).

High planting density increased cumulative water use throughout the measurement period at Sonning. The results presented in Figure 8.6 were based on the analysis of the measurements made at access tubes located 10 cm from the row in all of the treatments. Comparison of the measurements made at 10 and 20 cm from the row in the widely-spaced treatment (D1) showed that the rate of loss during the early part of the season (before 42 DAP) was slightly faster at 20 cm from the row than at 10 cm, but there was no significant difference thereafter. This is difficult to explain because it would be expected that rates of extraction during the early part of the seasons would be faster closer to the row (e.g. Simmonds and Williams, 1989). One possible explanation is that the soil in the middle of the inter-row space was more exposed to structural breakdown, resulting in localised run-off causing enhanced infiltration closer to the row.

The most important treatment interactions were those involving irrigation (W x D and W x N), which were evident between 23 and 85 DAP (Figure 8.6a). A Nitrogen x density interaction was only noted between 42 and 62 DAP (Table 8.1), where application of nitrogen caused a significant reduction in water use in the low density treatment only, which is difficult to explain. However, the main effect apparent in Table 8.1 is the greater water use by the high density treatment, because of the greater water demand generated by the larger canopy.

Table 8.1 Effect of nitrogen and planting density on ET+D at Sonning.

| Nitrogen | ET+D (mm) | | | | | |
|---|---|---|---|---|---|---|
| | Density | | | | | |
| | D1 | | | D2 | | |
| | 42 | 56 | 62 | 42 | 56 | 62 |
| N0 | 95 | 169 | 186 | 100 | 179 | 196 |
| N100 | 82 | 162 | 174 | 98 | 180 | 191 |
| SED | 1.8 | 1.5 | 1.2 | | | |
| CV% | 2.2 | 1.3 | 0.7 | | | |

**K1 experiment.**

Irrigation increased total water use significantly ($p<0.05$) only at 95 DAP (E+T+D = 348 and 372 in the rainfed and irrigated treatment respectively). There were no apparent effects of either plant density or nitrogen application on the overall water loss. Though plant density had no 'main factor' effect apparent in an analysis of variance, Table 8.2 suggests that increasing density caused more water use in the rainfed treatments (as would be expected from the larger canopy) but less water use in the irrigated treatments (the irrigation x density interaction was significant at $p<0.05$).

Table 8.2 Effect of irrigation and planting density on ET+D in K1.

| Irrigation/DAP | ET+D (mm) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Density | | | | | | | | | |
| | D1 | | | | | D2 | | | | |
| DAP | 52 | 66 | 77 | 84 | 95 | 52 | 66 | 77 | 84 | 95 |
| W0 | 139 | 243 | 289 | 316 | 338 | 163 | 268 | 304 | 333 | 359 |
| W1 | 177 | 257 | 340 | 372 | 390 | 158 | 265 | 307 | 336 | 355 |
| SED | 9.6 | 11.7 | 9.01 | 10.6 | 7.5 | | | | | |
| CV% | 9.8 | 4.5 | 4.8 | 5.2 | 4.4 | | | | | |

There was also an apparent interaction between plant density and nitrogen, with nitrogen having a negative effect on water use in the low density crop, but no effect at the higher density (Table 8.3). These interactions with density are hard to explain, and seem somewhat improbable. One of the factors that might confound the interpretation of the plant density effects is the uncertainties associated with estimating representative averages in the widely spaced rows, where there are likely to be systematic variation in water dynamics with distance from the row.

Table 8.3 Effect of nitrogen and planting density on ET+D in K1.

| Nitrogen | ET+D (mm) | | | | | |
|---|---|---|---|---|---|---|
| | Density | | | | | |
| | D1 | | | D2 | | |
| | 77 | 84 | 95 | 77 | 84 | 95 |
| N0 | 334 | 362 | 381 | 308 | 335 | 359 |
| N100 | 296 | 325 | 347 | 304 | 335 | 354 |
| SED | 5.09 | 8.55 | 7.04 | | | |
| CV% | 2.5 | 3.3 | 4.7 | | | |

## 8.4 The soil water balance components

### 8.4.1 Partitioning between total evaporation (E+T) and drainage (D)

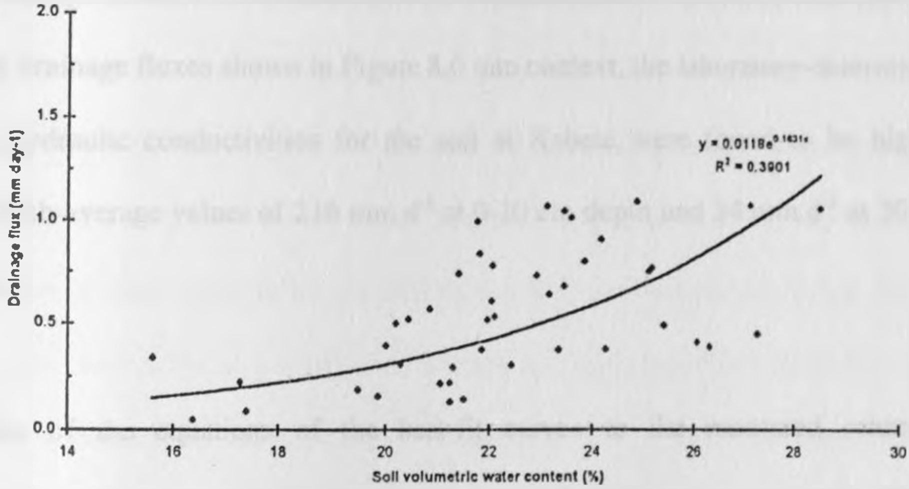
Inspection of the data from the bare soil plots indicates some of the difficulties in the partitioning between total evaporation and drainage. In the bare plots, total water use (E+D) over the seasons were 131 mm and 362 mm at Sonning and in K1 respectively. Water loss from the bare plots was similar to the cropped plots early in the season at

Sonning (Figure 8.6a), but deviated later once there was significant water uptake by roots. By contrast, the water loss from both bare and cropped soils in K1 was similar throughout the season (Figure 8.6b), because the profiles were close to field capacity much of the time, and water not used by the crop in the bare soil was lost instead through drainage. Hence partitioning between total evaporation and drainage, especially in K1, is difficult, but likely to be a factor that differs widely between treatments in which there were large differences in transpiration caused by differences in canopy size.

### 8.4.2 Drainage (D)

An attempt was made to estimate drainage fluxes using the data obtained in the bare soil plots. During the early parts of the seasons, it can be reasonably assumed that there was no drainage below the lowest depth of measurement, and that losses through evaporation are restricted to the upper 30 cm of the profile. Given the assumption of a zero flux plane at 30 cm depth based on observed patterns of water depletion in the bare soil (Figures 8.2a and 8.3a), then the drainage flux at a given depth below 30 cm could be assessed by summing changes in profile-layer water contents from the zero flux plane to the depth in question. This is essentially similar to the technique used by Klaij and Vachaud (1992) to relate the drainage flux at a given depth to the corresponding volumetric water content by analysis of the internal redistribution of water within a profile following rainfall. This analysis was carried out on data from 3 access tubes at Sonning and 2 at Kabete, the results of which are shown in Figure 8.7. The ranges of soil water contents prevailing at the time when the criteria required for the analysis were fulfilled were 16-29% at Sonning, and 34-46% at Kabete.

a: drainage flux (mm day$^{-1}$) from bare soil at Sonning



b: Drainage flux (mm day$^{-1}$) from bare soil in K1.

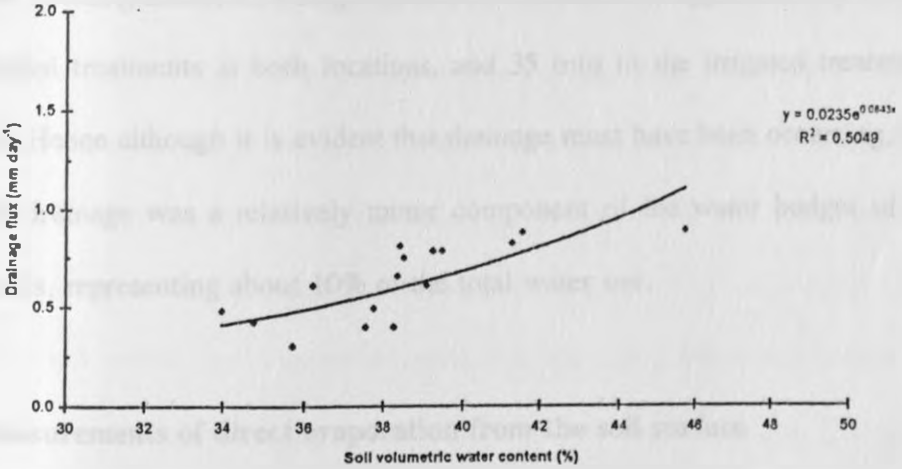


Figure 8.7. Estimated drainage flux (equivalent to unsaturated hydraulic conductivity) from the soil profile at Sonning and Kabete.

The analysis revealed that drainage fluxes were negligible (i.e. <0.4 mm $d^{-1}$ ) at volumetricwater contents below 20% at Sonning and 34% at Kabete. At higher water contents drainage fluxes tended to increase, but were extremely variable. Similar conclusions were reached by Pilbeam *et al.*(1995) and Klaij and Vachaud (1992) using similar analyses. Though best-fit curves were obtained (Figure 8.7), use of these to predict drainage fluxes from measured water contents should be treated with caution. To put the drainage fluxes shown in Figure 8.6 into context, the laboratory-determined saturated hydraulic conductivities for the soil at Kabete were found to be highly variable, with average values of 216 mm $d^{-1}$ at 0-10 cm depth and 34 mm $d^{-1}$ at 30-40 cm depth.

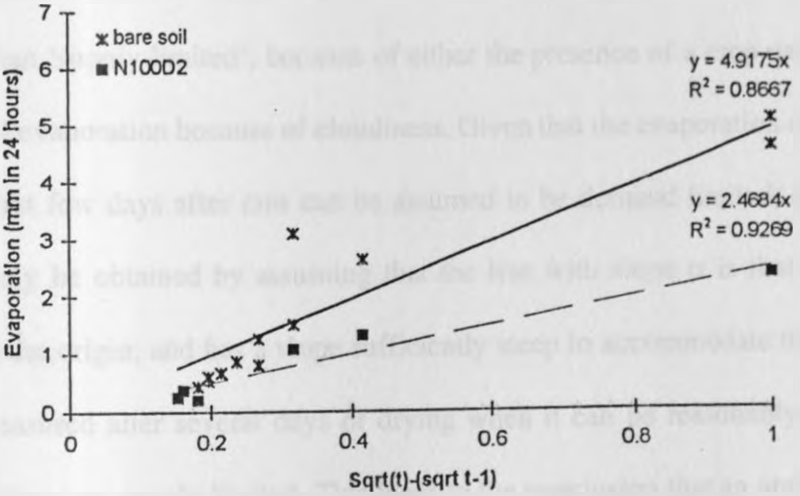
Application of the equations of the best-fit curves to the measured seasonal fluctuations in volumetric water content at the lowest depths of measurement in three experiments resulted in estimates of seasonal drainage totals of zero in K2, with drainage at Sonning and in K1 being limited to a maximum of approximately 30 mm in the rainfed treatments at both locations, and 35 mm in the irrigated treatments (table 8.8). Hence although it is evident that drainage must have been occurring, it is likely that drainage was a relatively minor component of the water budget of the cropped soils, representing about 10% of the total water use.

### 8.4.3 Measurements of direct evaporation from the soil surface

Direct evaporation from the soil surface was measured on a number of dates in all three experiments using microlysimetry. Following the rationale based on the expectation that the supply-limited evaporation rate would be inversely proportional to the square root of time, the daily evaporation rate data were plotted according to equation 2.8 to determine the value of $\alpha$ (Figure 8.8), which would be used as the basis for the subsequent estimation of the seasonal totals for direct evaporation from the soil surface. The resulting graphs show that good linear relations were not generally obtained. In particular, it was often noted that the amount of evaporation drainage then than would have been expected from the rates measured later on. The implication is that the rate of evaporation in many cases was not supply limited, but rather was limited by the evaporative demand. In the case of some of the bare soil measurements this may have been because the potential evaporation rate was less than the 'water supplying' capacity of the soil during the early stages of drying. In the cropped soils there is the additional complication that the evaporative demand at the soil surface is reduced by the presence of foliage intercepting radiation, reducing air mixing and humidifying the air adjacent to the soil surface.

At Sonning, there was generally a good straight line for the bare soil plots, with a value of $\alpha$ (4.9 mm $d^{-1}$) suggesting that the supply-limited evaporation rate during the first day would be 4.9 mm. The observation that this rate of evaporation was achieved during the first day after rain was fortuitous in the sense that the measurements happened to be made during a period of exceptionally high evaporative demand. In the cropped soil, where the evaporative demand at the soil surface was reduced, a much slower rate of evaporation from the soil (2.5 mm $d^{-1}$) was measured. Taking the bare soil curve as being representative of supply limited evaporation, the best estimate for $\alpha$ for the soil at Sonning was of the order of 4.9 mm $d^{-1}$ from a wet soil on a clear day.

a: Sonning



b: Kabete

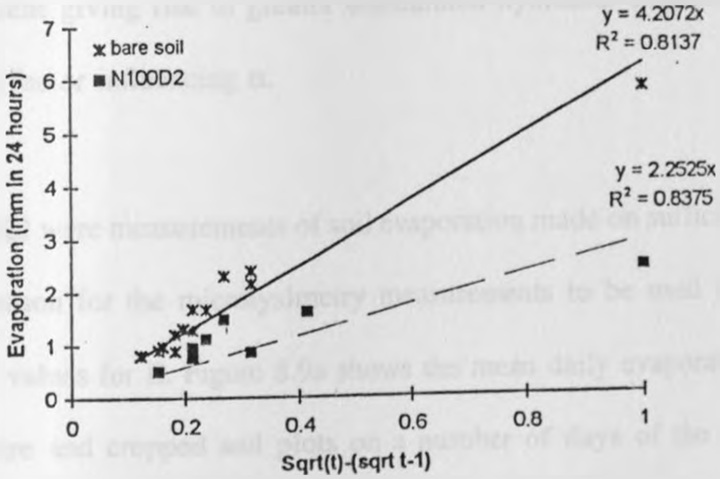


Figure 8.8. Evaporation from bare soil and soil beneath the crop canopy over time since the first day after rain in rainfed treatments.

The K1 and K2 experiments were carried out in the same field, so the data should be looked at collectively. Both data sets show that evaporation rates tended to be faster from bare soil than cropped soil, even several days after rainfall, and that evaporation rates during the first 3 days after rain showed no consistent pattern with time. These general observations imply that the rates of evaporation were often 'demand limited' rather than 'supply limited', because of either the presence of a crop canopy or a low potential evaporation because of cloudiness. Given that the evaporation rates measured in the first few days after rain can be assumed to be demand limited, estimates of $\alpha$ could only be obtained by assuming that the line with slope $\alpha$ is that which passes through the origin, and has a slope sufficiently steep to accommodate the evaporation rates measured after several days of drying when it can be reasonably assumed that evaporation was supply limited. This leads to the conclusion that an appropriate value of $\alpha$ for the Kabete soil is in the region of 5 to 7 mm $d^{-1}$. It is to be expected that the value of $\alpha$ for the Kabete soil would exceed that at Sonning, because of the higher clay content giving rise to greater unsaturated hydraulic conductivity, which is the principal factor influencing $\alpha$.

Only in K2 were measurements of soil evaporation made on sufficient number of days in the season for the microlysimetry measurements to be used to directly estimate seasonal values for E. Figure 8.9a shows the mean daily evaporation rates measured in the bare and cropped soil plots on a number of days of the season. These data suggest that it was on the first and second days after rainfall that there was a significant difference between the cropped and bare soils in evaporation rate. Figure 8.9b shows the data presented in Figure 8.9a as cumulative totals for the 31 days that evaporation was measured. It is NOT an estimate of seasonal evaporation, as it takes no account of evaporation on those days when evaporation was not measured. If it is reasonable to assume that the 31 days of measurement were a representative selection of days during the season, then the first conclusion to draw is that the seasonal loss of water through direct evaporation from the soil surface was reduced by around 20% by the presence of a crop, and that there was little effect of the density treatments on soil evaporation, despite their influence on leaf area index. The second conclusion is that the average daily rate for the 31 days of measurement was about 1.45 and 1.19 mm $d^{-1}$ for the bare soil and cropped soils respectively. These average values suggest cumulative totals for E of 106 and 87 mm by 73 DAP in the bare and cropped soils respectively.

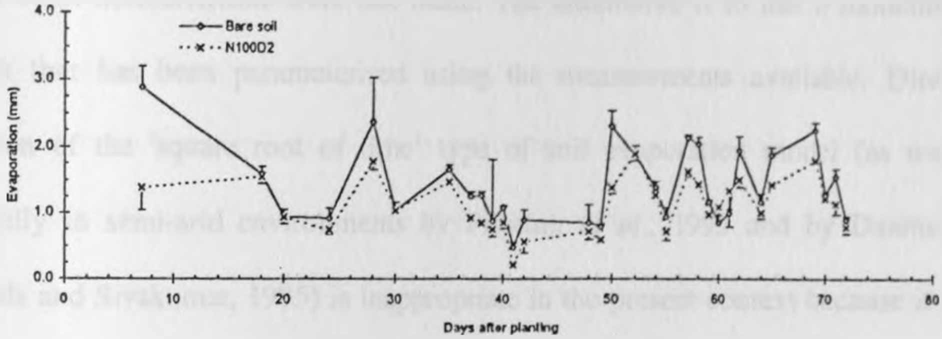


Figure 8.9a. Daily evaporation (mm) from bare soil and soil beneath the crop canopy in K2. Bars represent standard error of mean (n=5). Only part of the bar is shown in each case for clarity.

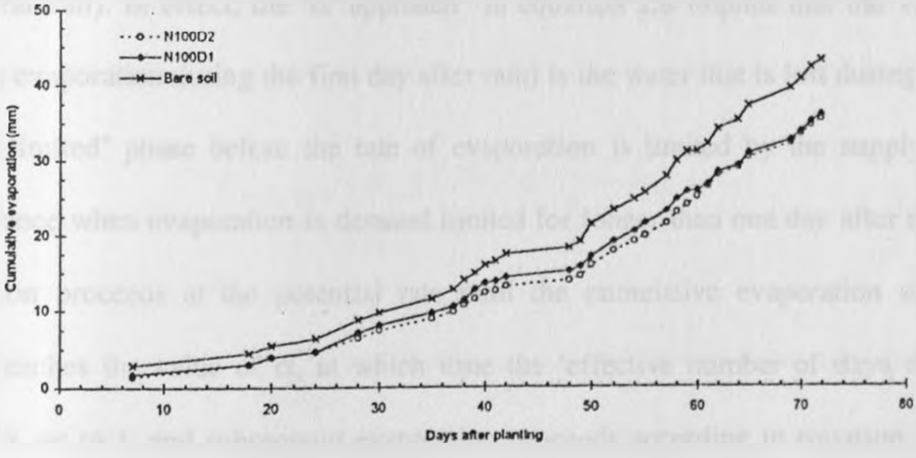


Figure 8.9b. Cumulative evaporation from bare soil and soil beneath crop canopy over the season in K2

### 8.4.4 Modelling direct evaporation from the soil surface.

There were problems in using measured soil evaporation rates on a few selected days to estimate seasonal totals in E, because of uncertainties about the rates of evaporation on days when measurements were not made. The alternative is to use a modelling approach that has been parameterised using the measurements available. Direct application of the 'square root of time' type of soil evaporation model (as used successfully in semi-arid environments by Pilbeam *et al.*, 1995 and by Daamen, Simmonds and Sivakumar, 1995) is inappropriate in the present context because it is not reasonable to assume that by the end of day 1 after rain that evaporation is strictly supply-limited. In such circumstances, the approach needs to be modified to take account of 'demand-limited' evaporation during the early stages of a drying cycle. The simplest approach is to presume that the rate of evaporation at any time is either 'demand limited' (and equal to the potential evaporation rate) or supply limited (and therefore proceeding at a rate that is controlled by the cumulative evaporation since the last rainfall). In effect, the '$\alpha$' approach in equation 2.8 implies that the value of $\alpha$ (the evaporation during the first day after rain) is the water that is lost during the 'demand-limited' phase before the rate of evaporation is limited by the supply of water. Hence when evaporation is demand limited for longer than one day after rain, evaporation proceeds at the potential rate until the cumulative evaporation since rainfall reaches the value of $\alpha$, at which time the 'effective number of days after rainfall' is set to 1, and subsequent evaporation proceeds according to equation 2.8. Further details of this rationale are given by Daamen, Simmonds and Sivakumar (1995).

When a crop is present, there is the complication that an appropriate value needs to be calculated for the potential evaporation rate that takes account of shading effects of the crop canopy. This has been done in the past by assuming that the climatically determined potential evaporation rate (e.g. calculated using the Penman-Monteith equation) is reduced proportionally to the fraction of incident radiation that reaches the soil surface (so that the potential evaporation rate from completely shaded soil is zero). The fraction of incident radiation penetrating to the soil surface can easily be estimated from the leaf area index using Beer's law, assuming the extinction coefficient is known (cf. Figure 6.7). However, Daamen, Simmonds and Sivakumar (1995) suggested a modification to this approach as they found that direct evaporation from the soil surface is less sensitive to shading than is implied by this approach. They reasoned that the radiation load is only one of two contributors to the potential evaporation rate, because the Penman-Monteith equation consists of the sum of a radiation term and an aerodynamic term, and that it is only the radiation term that is reduced directly by shading. They proposed that the potential rate of evaporation from the soil surface ($E_{pot,shaded}$) shaded by a canopy of leaf area index LAI is given by:

$$E_{pot,shaded} = E_{pot}\left(\frac{\exp(-K\,LAI) + W}{1 + W}\right) \qquad 8.1$$

Where W is the magnitude of the aerodynamic term in the Penman-Monteith equation expressed as a fraction of the radiation term. An analysis of the meteorological data for the three experiments showed that the average seasonal values of W were 0.5, 0.48 and 1.0 for Sonning, K1 and K2 respectively. The higher value for K2 was caused by the higher saturation deficit.

A second way in which a crop might affect evaporation from the soil surface is by the uptake of water by roots causing the soil close to the surface to dry, thereby causing the evaporation rate to decrease more rapidly during the 'supply limited' phase. Daamen *et al.*(1995) suggested a simple approach for taking account of this effect, which assumed that during the 'supply-limited' phase, the rate of water loss from the part of the profile being depleted by soil evaporation was enhanced by root water uptake, where the loss through root water uptake was assumed to be proportional to the loss through soil evaporation, with a coefficient of proportionality V. Hence the simple 'square root of time' relation between the rate of soil evaporation and time was modified according to:

$$t_{2,eq} = \left(\frac{\Sigma(1 + V)\, E_{s,2}}{\alpha}\right)^2 \qquad 8.2$$

where $t_{2,eq}$ is the equivalent number of days into second stage drying, $E_{s,2}$ is the loss due to direct evaporation from the soil surface, and V is the rate of water uptake by roots from the surface layer expressed as a fraction of the loss through direct evaporation from the soil surface. Daamen *et al.* (1995) suggested that a typical value of V for a crop with roots concentrated near the surface was 1, with most crops likely to have values falling between extremes of 0 and 2.

The analysis which follows makes use of the above relations in a simple 'demand-limited/supply-limited' model of direct evaporation from the soil surface which has as inputs daily values for rainfall, leaf area index and potential evaporation rate, and the extinction coefficient, W and V set as constants appropriate for the crop and climate in question. The model was based closely on the daily accounting procedure outlined by Pilbeam *et al.*, (1995b) in their 'supply-limited' model (ESCALC), but with the following modifications to account for periods early in the drying cycle when evaporation might be demand limited:

1. If the cumulative evaporation since the last rain is less than $\alpha$, then if the daily evaporative demand is less than $\alpha$, then cumulative evaporation will increase by the value of the daily evaporative demand, calculated using equation 8.1.

2. Following a rain event, the 'effective number of days after rainfall' will only be set to 1 on the day when the cumulative evaporation since the rain event reaches $\alpha$. This might take several days in cases where there is a low demand for direct evaporation from the soil surface.

3. Once cumulative evaporation since the last rain reaches $\alpha$, the 'effective number of days after rain' is set to 1, and evaporation enters the 'water limited stage' and evaporation from the soil surface is controlled by the square root of time relation, with coefficient $\alpha$ (equation 2.7).

4. When roots are also extracting water from the surface layer, the 'effective number of days after rain' will be increased according to equation 8.2, with the result that direct evaporation from the soil surface decreases more quickly with time than would be the case for a bare soil.

5. In the event of very small rainfall events causing only partial rewetting of the soil surface layer being dried through soil evaporation, the accounting procedure used

in ESCALC (Pilbeam *et al.*, 1995) is used to ensure that soil evaporation is only increased for the time that the water supplied in the rain event remains available. Once the small rain event has re-evaporated, the rate of sol evaporation returns to it's value immediately preceding the small rain event.

A model following these rules was set up on an EXCEL spreadsheet. To test the model, the following crop and climatic parameters were used, with W, K and α being based on experimental data presented earlier, and V being taken from Daamen *et al.*, (1995).

Table 8.4. Values of the parameters for the 'two-stage' soil evaporation model

| | Sonning | K1 | K2 |
|---|---|---|---|
| Extinction coefficient (K) | 0.5 | 0.7 | 0.5 |
| Aerodynamic term of P-M equation as a fraction of the radiation term (W) | 0.5 | 0.48 | 1.00 |
| alpha ($\alpha$) | 4.5 | 5 | 5 |
| Root water extraction from the surface layer as a fraction of the rate of direct evaporation from the soil surface (V) | 1 | 1 | 1 |

The first step was to examine the sensitivity of the estimated seasonal totals of direct evaporation from the soil surface in the Sonning and Kabete experiments to the choice of W and V. This was done by using the daily rainfall and leaf area index values for selected treatments which are likely to have a large contrast in soil evaporation (i.e. comparing bare soils with either unirrigated, unfertilised, low density crops, or irrigated, fertilised, high density crops). The results are presented in Table 8.5.

Table 8.5 shows that estimated seasonal losses through soil evaporation were strongly dependent on the value of W in situations where there was a large canopy and frequent rain events (so evaporation was often 'demand limited'), but little effect in the rainfed K2 treatment where shading by the canopy was relatively small and the soil surface was rarely rewetted. Though evaporation is sensitive to W, the value of W can be determined accurately from the meteorological data, and so this is not a source of great uncertainty. Evaporation losses were also sensitive to the value of V. In contrast to the sensitivity to W, the sensitivity was greatest in environments where ‘supply-limited’ evaporation was the dominant component of the seasonal loss (e.g. in the rainfed K2 and Sonning treatments).

Table 8.5. Seasonal values for direct evaporation from the soil surface (mm) for selected treatments, estimated using the 'two-stage' evaporation model, using different combinations of values for the W and V inputs. Numbers in bold indicate the values obtained using the best estimates of W and V for each crop/environment combination.

| W | V | K1 | | | K2 | | | | Sonning | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | bare, W0 | W0 N0 D1 | W0 N100D2 | bare W0 | W0 N0 D1 | W1 N100 D2 | bare W1 | bare W0 | W0 N0 D1 | W1 N100 D2 | bare W1 |
| 0 | 0 | 224 | 180 | 134 | 99 | 97 | 144 | 186 | 179 | 126 | 91 | 210 |
| .5 | 0 | | 197 | 174 | | 97 | 161 | | | 149 | 147 | |
| 1 | 0 | | 205 | 189 | | 98 | 168 | | | 158 | 169 | |
| 0 | 1 | | 164 | 127 | | 66 | 122 | | | 93 | 89 | |
| .5 | 1 | | 179 | 159 | | 68 | 137 | | | 111 | 135 | |
| 1 | 1 | | 186 | 172 | | 69 | 144 | | | 118 | 151 | |
| 0 | 2 | | 161 | 122 | | 61 | 110 | | | 79 | 85 | |
| .5 | 2 | | 175 | 155 | | 63 | 121 | | | 96 | 128 | |
| 1 | 2 | | 181 | 168 | | 64 | 127 | | | 100 | 145 | |
| RAIN | | 384 | 384 | 384 | 105 | 105 | 240 | 240 | 274 | 274 | 441 | 441 |
| 'best' values | | 224 | 179 | 159 | 99 | 69 | 144 | 186 | 179 | 111 | 135 | 210 |

Limited validation of the predictions in table 8.5 was possible. The 31 days of soil evaporation measurements in K2 suggested that the seasonal loss from the bare soil was 106 mm, compared with a prediction of 99 mm in table 8.5. These data also showed that the seasonal totals for the cropped treatments were reduced to 87 mm ( a 'saving' of 18%) compared with a prediction of 69 mm (a 'saving' of 30%). Though the two-stage model has predicted a greater reduction in soil evaporation due to the presence of a crop than was observed, it can be seen from table 8.5 that the estimated seasonal total for E is strongly dependent on the value of V. Indeed, if V is set to zero (implying that the roots are not 'competing' with direct evaporation for soil water, the presence of a crop leads to negligible saving of water through the effect of shading (i.e. E is reduced from 99 mm in bare soil to 98 mm from the cropped soil). Clearly, if an appropriate value of V between 0 and 1 were selected, then good agreement could be achieved between the predicted and measured effects of the influence of the crop on the reduction in E. The so-called 'best' value for V of 1 was that suggested by Daamen *et al.* (1995) as being appropriate for a cereal with good ground cover. Because V is influenced by the transpiration rate, it would be more appropriate to make V dependent on the fraction of incident radiation intercepted by foliage in order to simulate the smaller drying effect of water uptake that would be expected for crops with only partial ground cover. Hence the two-stage evaporation model described above was modified to make V dependent on leaf area index, by rewriting equation 8.2 as:

$$t_{2,eq} = \left(\frac{\Sigma(\ 1 + V_{max}\ [e^{-KLAI}])\ E_{s,2}}{\alpha}\right)^2 \qquad 8.3$$

where $V_{max}$ is the value of V for a crop with complete ground cover, which might reasonably be assumed to have a value of around 1.

Table 8.6 shows the results of the revised simulations, taking account of the effect of changing crop size on the root extraction term, assuming $V_{max}=1$.

Table 8.6 Seasonal values for direct evaporation from the soil surface (mm) for selected treatments, estimated using the revised 'two-stage' evaporation model with a leaf area index dependent root extraction term. Numbers in brackets indicate best estimates from direct measurements using microlysimetry.

| Treatments | Sonning | K1 | K2 |
|---|---|---|---|
| rainfed bare soil | 179 | 224 | 99 (106) |
| W0N0D1 | 134 | 192 | 86 (87) |
| W0N100D2 | | 171 | |
| W1N100D2 | 138 | | 148 |
| irrigated bare soil | 210 | | 186 |

To further validate the predictions on table 8.6, a comparison was made between the direct measurements of soil evaporation on the days of microlysimetry and the predictions made using the two-stage model. Table 8.7 summarises the results by comparing the total evaporation for all the microlysimetry days with the corresponding totals obtained using the model.

Table 8.7 Comparison of the total soil evaporation from the days when microlysimetry was done, with the corresponding value predicted by the model

| Treatments | Sonning | K1 | K2 |
|---|---|---|---|
| **Cropped soil** | | | |
| Measured | 4.6 | 9 | 44 |
| Simulated | 7.5 | 16 | 40 |
| Number of days | 7 | 10 | 31 |
| **Bare Soil** | | | |
| Measured | 14 | 17 | 35 |
| Simulated | 16 | 18 | 35 |
| Number of days | 8 | 10 | 31 |

In the bare soil treatments the agreement was good at all sites, giving confidence in the model predictions. In the cropped treatments the agreement was less good, with the model tending to overestimate soil evaporation in the K1 and Sonning experiments. A likely explanation of the overestimation at these sites is that the effect of the canopy on reducing the rate of evaporation during the 'demand limited' phase was underestimated using equation 8.1. The assumption behind equation 8.1 was that it is only by reducing radiation penetration to the soil surface that the canopy reduces evaporation, whereas the canopy will also have other effects such as reducing the windspeed and humidifying the air which will tend to reduce evaporation. These effects are not accounted for in the model. It follows that the predicted seasonal values of E for the crops grown in Sonning and K1 are likely to be overestimated. In K2, the 'demand limited' phase contributed only a small part of the seasonal total for E, and agreement between measured and predicted values was much better.

### 8.4.5 The Water Balance

With the proviso that the predicted E from cropped soils is likely to be an underestimate at Sonning and in K1, the upper part of Table 8.8 presents the best estimates resulting from the analyses in sections 8.4.2 to 8.4.4 for the water balance components for selected treatments in each of the experiments. The 'rain' row includes any irrigation. The E+T+D row shows the total seasonal water use from analysis of profile water contents. The E row shows the estimates of E from the two stage evaporation model in it's most refined form with the ground-cover dependent values of V. The drainage row shows the estimates of drainage from the drainage flux/water content relationship.

Transpiration was estimated by difference. In all cases, transpiration is less than half of E+T+D. Because it is being estimated as a relatively small difference between relatively large numbers which have some uncertainty, the result is likely to have a large error, and should be treated with caution. Even so, it can be concluded that in all cases transpiration was, at best, comparable to direct evaporation from the soil surface, and was in many cases very much less.

Table 8.8. The seasonal water balance components (in mm) of selected treatments.

| | Site/treatment | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Sonning | | | K1 | | | K2 | |
| | Bare | W0N0D1 | W1N100D2 | Bare | W0N0D1 | W1N100D2 | Bare | W0N0D1 |
| **WATER BALANCE** | | | | | | | | |
| Rain | 164 | 164 | 331 | 384 | 384 | 444 | 105 | 105 |
| E+T+D | 125 | 172 | 320 | 365 | 370 | 412 | 124 | 146 |
| E | 146 | 138 | 115 | 224 | 192 | 171 | 99 | 86 |
| D | 44 | 20 | 34 | 44 | 31 | 36 | 0 | 0 |
| T | -65 | 14 | 171 | 97 | 147 | 205 | 25 | 60 |
| **TOTAL DRY MATTER IN RELATION TO TRANSPIRATION** | | | | | | | | |
| TDM (g m-2) | 0 | 260 | 802 | 0 | 415 | 743 | 0 | 324 |
| SD (kPa) | 0.2 | 0.2 | 0.2 | 0.7 | 0.7 | 0.7 | 1 | 1 |
| TDM/T (g/kg) | | 18.6 | 4.7 | | 2.8 | 3.6 | | 5.4 |
| TDM*SD/T(g kPa kg) | | 3.9 | 1.0 | | 3.9 | 5.0 | | 5.5 |
| "Expected T" | 0 | 65 | 101 | 0 | 133 | 234 | 0 | 175 |

The calculation of "expected T" is based on the assumption that TDM*SD/T is 3 g kPa/ kg

The calculation of "expected T" is based on the assumption that TDM*SD/T is 3 g kPa/ kg

An attempt to check on the estimates of transpiration was made by comparing estimated of transpiration with the amounts of total dry matter produced (lower part of table 8.8). The amount of dry matter produced per unit of water transpired is expected to vary inversely with the saturation deficit of the air, and so be least in K2 and most at Sonning, as was observed. Many studies have shown that water use efficiencies (expressed as dry matter produced per unit of transpiration, normalised by the saturation deficit) tend to fairly conservative. For example, Pilbeam *et al.*, (1995b) referred to a range of studies by others which showed that for C3 plants the water use efficiency expressed in this form were close to 3 g kPa/kg, although their results for beans grown in a range of contrasting environments within Kenya were closer to 1.8 g kPa/kg. They attributed the slightly lower values than have been observed for C3 cereals to nitrogen fixation causing the beans to be less efficient. The estimates of TDM*SD/T in table 8.8 range from 1.0 to 5.5. Hence the bean crops studied are remarkably efficient by comparison with other C3 species, or there has been a systematic underestimate of transpiration. The latter is the more likely, as it has already been established that E has probably been overestimated by the two-stage evaporation model, especially when a crop is present.

In an attempt to assess the magnitude of the error in the transpiration estimate, the last row in table 8.8 shows the values for T that would have been required to produce the recorded dry matters at final harvest, assuming a normalised transpiration efficiency of 3 g kPa/kg. It is seen that the discrepancies between the two estimates of transpiration are erratic. Of particular note is that the estimates of T from the water balance in K1 for the two contrasting crops were not very different, whereas the large differences in dry matter production imply that the larger crop should have had 75% more transpiration than the smaller one. This discrepancy suggests that the large crop had more of an effect in reducing E (hence increasing T) than was predicted by the soil evaporation model, as was noted earlier. The other notable discrepancy is the large amounts of transpiration that would have been required in K2 to produce the observed amounts of dry matter, assuming the normalised water use efficiency of 3 g kPa/kg. These values of T are either close, or even exceed, the total water use estimated from the changes in profile water content (i.e. E+T+D), which is improbable. The implication is that the water use efficiency for the K2 crop was rather greater than the 'typical' value for a C3 crop. Why this should be is uncertain. It accords with the earlier observation that the K2 crops were also unusually efficient with respect to light use efficiency. One possibility is that the soil water stress resulted in most photosynthesis taking place at times of day when the evaporative demand was relatively low, with the result that the water use efficiency would be increased because of the lower saturation deficit at the time that leaves were taking up $CO_2$.

## 8.5. Conclusions

Despite the uncertainties in the water balance component estimates, a number of conclusions can be drawn with respect to the influence of the crop (and of crop management) on water use efficiency.

First, in each of the seasons it is likely that soil evaporation was a major component of the water budget. Though there are uncertainties in the transpiration:soil evaporation partitioning, it is likely that in most of the treatments soil evaporation was comparable to, or greater than, transpiration. A similar conclusion was reached by Pilbeam *et al.*, (1995b) which showed for maize, bean and maize-bean intercrops grown in a number of contrasting seasons in Kenya that the proportion of total evaporation attributed to transpiration was as little as 15% in seasons with 150 mm rainfall, rising to 40% for seasons with 400-500 mm rainfall.

Second, there appeared to be only a limited extent to which intensifying crop production through use of fertilisers and increasing plant density could influence the transpiration:soil evaporation partitioning. The microlysimetry showed that, on average, measured rates of evaporation from the soil surface beneath a crop were only 20% slower than from bare soil. Similar conclusions were reached using the 'two-stage' evaporation model in which it was assumed that the presence of a crop reduced 'energy-limited' evaporation through reduction in the radiation term of the Penman-Monteith equation, and reduced 'supply-limited' evaporation through soil drying via water uptake from surface layers by roots. However, the simple 'two-stage' model used appeared to underestimate the effect of dense foliage on 'demand limited' evaporation. Once again, the limited effect of crop management on soil evaporation is in agreement with the results of Pilbeam *et al.*, (1995b) that very different crop management had only small effects on direct evaporation from the soil surface.

Third, the application of the 'two-stage' evaporation model to the analysis of the K2 data showed the importance of water uptake by roots causing a reduction in soil evaporation in seasons where most water is lost through 'supply-limited' evaporation.

# Chapter 9

# General discussion and conclusions

## 9.1 Introduction

Large differences in total dry matter and seed yields between sites in the three experiments were observed. This was apparent even between the well irrigated, well fertilized treatments of the K1 and Sonning experiments. The generally lower yields in the K2 experiment were undoubtedly attributable largely to the shortage of water, as even the irrigated treatments had a theoretical soil moisture deficit of 117 mm (table 3.4). A key question is **"why were the yields generally higher at Sonning than K1, despite the climate being broadly similar, and nitrogen and water being nominally well supplied?"**

The theoretical frame work to analyze the relationship between dry matter production and radiation interception is provided by a variant of equation 2.8 (Charles-Edwards, 1982):

$$Y_s = HI * \varepsilon_s \, (\Sigma S_i * f') \qquad 9.1$$

Where: $Y_s$ is seed yield (g m$^{-2}$); HI is harvest index; $\varepsilon_s$ is the ratio of dry matter to intercepted radiation (conversion efficiency, g MJ$^{-1}$); $\Sigma S_i$ is the cumulative total of intercepted radiation (MJ m$^{-2}$); $S_i$ is the amount of radiation intercepted on day i and f' is the fraction of incident radiation intercepted.

Table 9.1 shows some of the parameters in equation 9.1 together with other summary data to enable comparison of the means of treatments at the three experiments.

Mwezi Moja beans showed great variability in total dry matter in the three experiments, but a strong conservatism in the HI (table 9.1) which was not apparently affected by the very different environments, implying that HI was genetically determined or the environmental constraints were not severe enough to alter dry matter partitioning patterns. Hence differences in seed yield were directly attributable to the differences in dry matter production per plant.

The differences in TDM among the three experiments was either due to differences in PAR interception or conversion efficiency ($\varepsilon_s$). $\varepsilon_s$ was highest in the K2 experiment and lowest at Sonning (table 9.1). There was 22.5% difference in $\varepsilon_s$ between Sonning and K2 and only 3.2% difference between K1 and Sonning. Biological nitrogen fixation (BNF) might have been expected to influence $\varepsilon_s$. BNF requires an energy input that is derived from photosynthetic products which might otherwise have contributed to total dry matter. It was observed that there were no nodules at Sonning whereas healthy pink nodules were present at Kabete. The N balances at Kabete indicated BNF of the order of 28 to 77 kg N ha$^{-1}$ over the season. Estimates of the amount of carbohydrate required to fuel fixation of N are highly variable, and suggested values range between 1.4 and 8 g carbon g$^{-1}$ N fixed (Atkins, 1984). Hence 28 to 77 kg N ha$^{-1}$ would represent 39 kg C and 616 kg C ha$^{-1}$ which represents approximately 132 to 905 kg TDM ha$^{-1}$ (assuming 40% of bean tissue is carbon: M. Wood, personal communication). The mean cost for BNF would be 519 kg TDM ha$^{-1}$

and seed loss of 230 kg ha$^{-1}$ (i.e. approximately 10% of the average seed obtained in the K1 experiment). Despite this, there were observed to be no differences in $\varepsilon_s$ between K1 and Sonning. One possible reason for the lack of effect of fixation on $\varepsilon_s$ is that increased BNF created a stronger sink for carbohydrates, and thereby stimulated photosynthesis.

A second possible reason for the apparent lack of effect of BNF on $\varepsilon_s$ is that there were other factors influencing $\varepsilon_s$. There were differences in leaf N concentration (table 9.1). Muchow and Davis (1988) reported reduction in $\varepsilon_s$ when leaf N concentration were low. There is evidence that there is a threshold N leaf concentration that must be exceeded before photosynthesis is reduced (White and Izquierdo, 1991), and this threshold is usually much lower (1.9% N) than the foliar N concentration observed in these experiments.

The differences in bean yield between sites can hardly be explained by either differences in HI or in $\varepsilon_s$, leaving the amounts of PAR intercepted in the season as the primary reason for the differences between sites in yield. Sonning had a higher maximum f' (caused by higher LAI), and had also a larger canopy duration (figure 9.1 and table 9.1). There are a number of plausible hypotheses to explain site differences in LAI and leaf area duration (LAD).

## 9.2 Hypotheses

### Weather factors

i) Higher saturation vapour pressure deficit at Kabete reduced the rate of leaf expansion.

ii) Long days during vegetative phase of the crop at Sonning increased canopy photosynthetic rate resulting in faster canopy expansion. There was a temperature x photoperiod interaction that resulted in lengthening of canopy duration at Sonning.

iii) Sonning had relatively cool temperatures after maximum LAI which possibly slowed canopy senescence (i.e. increased LAD).

### Soil factors

The amount of total plant N taken up by unfertilized crop in a season (plant N yield) is a good indicator of the inherent available soil N.

iv) Soil N supply was 4.6 g $m^{-2}$ higher at Sonning than K1 , hence soil N supply was greater at Sonning than K1 (section 7.4.4). Both experiments were well watered (tables 3.2 and 3.3). The differences in LAI and LAD were possibly due to:

  a) losses through leaching in K1 reduced soil N supply for plant use

  b) more readily available mineral N at Sonning as residual effect of heavy fertilizer use

  c) timing of fertilizer application

High saturation vapour pressure deficits reduce the rate of leaf expansion rate (Squire, 1990). The higher saturation vapour pressure deficit may have reduced canopy expansion, hence reducing f' at Kabete compared to Sonning.

The fractional PAR intercepted (f') and LAI in the course of the season was highest at Sonning and least in the K2 experiment (figure 9.1a and b).The similarities in LAI and f' at 200 °C days in the three experiments is indicative of temperature being the major factor controlling LAI and f' early in the season. Divergence later in the season indicates that factors other than temperature influenced f'. It is probable that there was N limitation due to loss through leaching in the K1 experiment and water shortage in the K2 experiment.

There may have been a temperature x photoperiod effect on f' at Sonning. This interaction on crop development was difficult to separate. The average day length during vegetative growth was 16 hours at Sonning and 12 hours at Kabete. The thermal duration to flowering was comparable in the three experiments despite that flowering was delayed by 12 days at Sonning compared to K2. Long days and high temperatures early in the season at Sonning may have increased daily photosynthetic rate and LAI development in the vegetative phase while lower temperature during the reproductive phase could have prolonged canopy duration. The larger LAI at Sonning supported the formation of more pods plant$^{-1}$ and/or more seeds pod$^{-1}$. Long leaf area duration in the reproductive phase favoured prolonged seed filling at Sonning, resulting in higher hundred-seed weight. Most of the difference in seed yield between the Sonning and K1 is explained by differences in the number of seeds plant$^{-1}$.

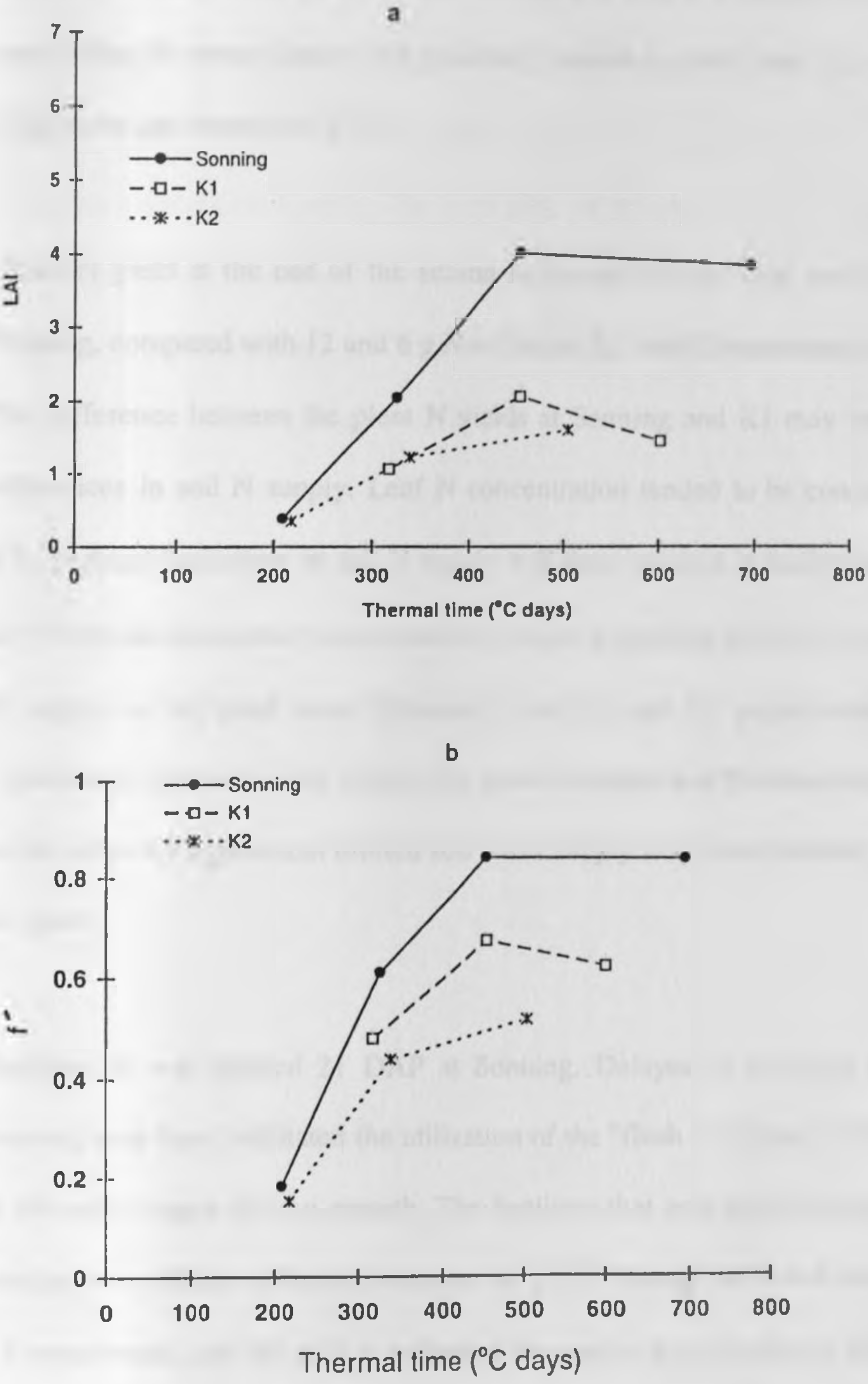


**Figure 9.1. Change of mean a: LAI and b: fractional PAR interception with thermal time (°C days) at the Sonning, K1 and K2 experiments.**

Seed yield difference between K1 and K2 are accounted for by differences in seed weight (56%) and number of seeds plant$^{-1}$ (31%; table 9.1). Laing *et al.*, (1984) reported similar results for cv. Porillo Sintetica at CIAT, Colombia. The duration of seed filling is more closely and positively related to yield than the rate of filling (Izquierdo and Hoesfield, 1983).

Plant N yield at the end of the season in the unfertilized crop was 16 g N m$^{-2}$ at Sonning, compared with 12 and 6 g N m$^{-2}$ in the K1 and K2 experiments respectively. The difference between the plant N yields at Sonning and K1 may be attributed to differences in soil N supply. Leaf N concentration tended to be conservative (table 9.1); perhaps limitations in soil N supply at Kabete resulted in earlier leaf senescence as N from old leaves was translocated to younger expanding leaves. Limitations of soil N supply to the plant were different in the K1 and K2 experiments. In the K1 experiment, high soil water supply may have increased soil N losses through leaching while in the K2 experiment limited soil water supply may have reduced N availability for plant.

Fertilizer N was applied 21 DAP at Sonning. Delayed N fertilizer application at Sonning may have facilitated the utilization of the "flush N" (Birch, 1960) at Sonning in the early stages of crop growth. The fertilizer that was applied three weeks after planting was utilized efficiently because the plant demand for N had increased. In the K1 experiment, rain fell after a prolonged dry period and possibly a large amount of N was mineralised early in the season. Application of fertilizer N at planting resulted in N fertilizer loss through leaching because soil N supply was high but plant N demand was low. At Sonning, there is generally heavy use of fertilizer than at Kabete. It is possible that residual soil N contributed to high available soil N.

Another possible reason for differences in LAI and LAD in the three experiments might include differences in soil phosphate supply (not measured). Heavy basal phosphate application rates at the beginning of the season at Sonning may have contributed to high available phosphate for plant uptake. It is probable that high residual P levels in the soil may have contributed to increased delayed leaf senescence thus increasing LAD (Grabau *et al.*, 1986).

Table 9.1 Summary of factors and yield parameters contributing to differences in dry matter production in the three experiments. The values represent average data of all the treatments in each experiment.

| Parameter | Experiment | | |
|---|---|---|---|
| | Sonning | K1 | K2 |
| Crop Duration (days) | 114 | 95 | 73 |
| TDM (g m$^{-2}$) | 752 | 582 | 397 |
| Seed yield (g m$^{-2}$) | 332 | 246 | 130 |
| Hundred seedwt (g) | 40 | 38.7 | 29.9 |
| Seeds plant$^{-1}$ | 30.5 | 20.5 | 15.7 |
| HI | 0.43 | 0.43 | 0.43 |
| Maximum LAI at flowering | 4 | 2 | 1.2 |
| LAD - Vegetative (days) | 61 | 22 | 13 |
| Reproductive (days) | 111 | 27 | 16 |
| Days to 50% flowering (DAE) | 40 | 32 | 28 |
| Thermal duration to 50% flower (°C days) | 384 | 405 | 382 |
| Crop coefficient (g kPa kg) | 2.5 | 4.5 | 5.5 |
| Maximum fractional incident radiation intercepted | 0.84 | 0.65 | 0.5 |
| Radiation conversion efficiency - $\varepsilon_s$ (g MJ$^{-1}$) | 0.62 | 0.64 | 0.76 |
| Mean daily incident total Solar radiation (MJ day$^{-1}$) | 14.4 | 16.9 | 18.8 |
| Mean daily temp. (°C) | 18.3 | 17.8 | 18.5 |
| Mean seasonal SD (kea) | 0.2 | 0.7 | 1.0 |
| Leaf N concentration at the end of vegetative phase (%) | 3.4 | 3.8 | 3.8 |
| Seed N concentration | 3.8 | 3.3 | 2.8 |

The LAD in table 9.1 is defined as:

$$LAD = \frac{(L_2 - L_1)\,(T_2 - T_1)}{2} \qquad 9.2$$

Where $L_1$ and $L_2$ are LAI at times 1 and 2

$T_1$ and $T_2$ are time (days) when LAI was measured

On the whole, the average seed yield obtained at Sonning was higher (3320 kg $ha^{-1}$) than those reported in temperate bean producing areas (1700 kg $ha^{-1}$; Agricultural Statistics, 1994). Seed yields at Kabete in both the K1 and K2 seasons were higher (2460 and 1300 kg $ha^{-1}$ respectively) than national average yields in Kenya (500 kg $ha^{-1}$; Jaetzold and Schmidt, 1983). However the yields obtained at Kabete are comparable to those obtained by Kimani *et al.*, (in press).

### 9.3 General discussion and conclusions

There appeared to be only a limited extent to which intensifying crop production through use of fertiliser nitrogen and increasing plant density could influence the transpiration:soil evaporation partitioning contrary to the original hypothesis. The microlysimetry studies showed that, on average, measured rates of evaporation from the soil surface beneath a crop were only 20% slower than from bare soil. Similar conclusions were reached using the 'two-stage' evaporation model. This value may be even lower in a crop field surrounded by bare soil due to the oasis effect. The oasis effect in the three experiments was minimal because the bean crops were surrounded by cropped fields. The limited effect of crop management on soil evaporation is in agreement with other results that different crop management practices had only small effects on direct evaporation from the soil surface (Pilbeam *et al.*, 1995b; Yunusa *et al.*, 1993b). Where irrigation is practised, application of large quantities of water that will meet evaporation demand and leave some water crop growth will be beneficial. Use of irrigation methods that minimise evaporative loss (i.e. subsurface irrigation) would increase the efficiency of water use for crop production. Availability of soil water particularly during the seed filling phase would be crucial to minimize leaf abscision. Soil management strategies that would increase stored soil water (i.e decreasing run-off losses) and matching planting density with soil water supply to save water for seed filling stage would prolong the grain filling period.

Total plant nitrogen uptake and utilisation for seed production depended on plant growth rate, soil water and fertilizer nitrogen supply. Low crop growth rates due to limited soil water supply resulted in reduced percentage fertilizer nitrogen recovery in the crop. Probably more fertilizer would be recovered in the crop if fertilizer was applied later in the season, when the plants were bigger and soil mineral nitrogen supply would have been utilized by the crop, rather than at sowing time. The quantity of plant nitrogen derived from biological nitrogen fixation depended on availability of *Rhizobium* in the soil and on plant demand for N. Irrigation did not increase biological nitrogen fixation in the experiments because either rhizobium was absent or the applied water was lost through evaporation.

In conclusion, the key to bean production improvement is through establishment of a substantial LAI that is durable through the reproductive phase. This be may achieved through adequate nitrogen supply and "effective" irrigation to increase leaf area duration. Remobilization of N from leaf tissue to the seed results in reduction in physiological activity which is deleterious to sustained high rates of seed growth (Sinclair and De Wit, 1976). Adequate nitrogen supply for seed development from either fertilizer N application, biological nitrogen fixation or uptake from soil mineral N in necessary during the seed filling stage. This may be achieved through maintaining BNF supply through the reproductive phase or split fertilizer N application. The following are possible management strategies that may improve leaf area development:

* Delaying fertilizer application for at least 2 weeks after planting to would allow crop establishment and utilization of inherent soil mineral N that is mineralised after the rains. This would minimise leaching losses before crop is establishment. N fertilizer can be applied as split application towards the end of the vegetative phase to provide the plant N during the reproductive phase.

* Where irrigation is not feasible, some soil water conservation methods that increase availability of stored soil water during the reproductive phase would be beneficial. These might include methods that reduce runoff losses i.e. terracing, planting in furrows and micro-catchments that encourage run-on within a field.

* High planting density may be used as a way of increasing LAI when water and nitrogen are not in limited supply. The choice of planting densities may require a system of predicting rainfall at the beginning of the season before planting.
* Leaf area can be maintained through protection measures against pest

herbivory and disease damage.

## 9.4 Recommendations for future work

The following are suggested areas of future research based on the findings from this work.

1. Establishment of split N application for beans programs to match bean nitrogen demand with crop growth rate so as to maximise fertilizer use efficiency.
2. There are large quantities of soil mineral N in the Kabete soil (over 500 kg ha$^{-1}$ to 75 cm depth). This indicates that there are possibilities of leaching $NO_3^-$ ions to the ground water. An understanding of seasonal N dynamics (using $^{15}N$) will facilitate understanding the partitioning of soil N between crop production and losses.
3. Improvement of water use through canopy size manipulation seems to have limited success. A combination of methods of reducing evaporation and selection of cultivars with differing rooting characteristics (to increase the amount and improve use of stored soil water for crop production) may improve WUE.
4. Establishing irrigation schedule that would be effective.
5. There is an need to establish the base temperature for leaf development in *Phaseolus vulgaris*.
6. The biophysical effect of nitrogen of leaf expansion under ample water supply needs verification.

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# APPENDICES

Appendix 1

Table 1. Analysis of variance for the effects of irrigation, nitrogen and planting density on TDM (g m$^{-2}$) at 114 DAP.

| Source of variation | d.f. | s.s. | m.s. | v.r. | F probability. |
|---|---|---|---|---|---|
| reps stratum | 2 | 47168 | 23584. | 1.12 | |
| main plot effect | | | | | |
| Irrigation (W) | 1 | 34381 | 34381 | | |
| reps.main stratum (Error a) | 2 | 42291 | 21146 | 1.83 | |
| Subplot effect | | | | | |
| Nitrogen (N) | 1 | 203154 | 203154 | 17.5 | 0.014 |
| Irrigation x nitrogen | 1 | 58701 | 58701 | 5.08 | 0.087 |
| Residual (error b) | 4 | 46239 | 11560 | 0.91 | |
| Sub-subplot effect | | | | | |
| Density (D) | 1 | 452310 | 452310 | 35.62 | <.001 |
| W x D | 1 | 185596 | 185596 | 14.62 | 0.005 |
| N x D | 1 | 45470 | 45470 | 3.58 | 0.095 |
| W x N x D | 1 | 12105 | 12105 | 0.95 | 0.357 |
| Residual (error c) | 8 | 101587 | 12698 | | |
| Total | 23 | 1229003 | | | |

This is a typical ANOVA output to evaluate the effect of treatments on the different parameters measured in the three experiments. The assessment of the main effect of irrigation the measured parameters was confounded with replication because irrigation was not randomised. The interaction between irrigation, fertilizer N and planting density was assessed (table 1). The effect of planting density was assessed with the most accuracy; the d.f of the error term of the sub-subplot level (planting density level)was highest and hence had the greatest precision to evaluate treatment effect.

Table 2 The distribution of $NH_4^+$-N, $NO_3^-$-N and total mineral N in different layers in the top 75 cm of the soil profile in the K1 and K2 experiments.

| Experiment | Start | | | End | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Bare soil | | | N0 | | | N100 | | |
| | $NO_3^-$ | $NH_4$ | Total | $NH_4^+$ | $NO_3^-$ | Total | $NH_4^+$ | $NO_3^-$ | Total | $NH_4^+$ | $NO_3^-$ | Total |
| | g $m^{-2}$ | | | | | | | | | | | |
| K1 | | | | | | | | | | | | |
| Depth (cm) | | | | | | | | | | | | |
| 0-15 | 3.6 | 6.4 | 10.0 | 5.0 | 11.7 | 16.7 | 4.4 | 8.1 | 12.5 | 6.5 | 14.1 | 20.6 |
| 15-30 | 7.0 | 7.1 | 14.1 | 4.9 | 9.9 | 14.9 | 5.5 | 7.3 | 12.8 | 7.3 | 8.3 | 15.6 |
| 30-45 | 5.8 | 7.3 | 13.1 | 9.2 | 13.5 | 22.8 | 5.1 | 5.2 | 10.3 | 6.7 | 5.7 | 12.4 |
| 45-60 | 4.4 | 5.3 | 9.7 | 5.9 | 20.1 | 25.9 | 4.9 | 6.7 | 11.5 | 5.4 | 5.6 | 11.1 |
| 60-75 | 4.4 | 6.4 | 10.8 | 6.0 | 17.1 | 23.1 | 7.1 | 9.9 | 17.0 | 4.6 | 5.1 | 9.7 |
| Total | 25.2 | 32.5 | 57.7 | 31.0 | 72.4 | 103.4 | 27.0 | 37.2 | 64.2 | 30.5 | 38.8 | 69.4 |
| K2 | | | | | | | | | | | | |
| 0-15 | 5.5 | 10.5 | 16.0 | 16.3 | 5.7 | 22.1 | 9.5 | 9.7 | 19.3 | 9.0 | 17.7 | 26.7 |
| 15-30 | 12.9 | 7.3 | 20.2 | 8.1 | 4.8 | 12.9 | 9.9 | 7.5 | 17.4 | 8.6 | 9.8 | 18.3 |
| 30-45 | 3.2 | 3.0 | 6.2 | 14.7 | 4.5 | 19.2 | 9.2 | 4.2 | 13.4 | 9.2 | 7.0 | 16.2 |
| 45-60 | 4.9 | 2.1 | 7.0 | 12.0 | 4.9 | 16.9 | 6.1 | 3.7 | 9.8 | 7.3 | 5.4 | 12.7 |
| 60-75 | 3.1 | 2.9 | 6.0 | 10.8 | 6.4 | 17.2 | 8.6 | 3.1 | 11.7 | 5.9 | 3.3 | 9.3 |
| Total | 29.6 | 25.8 | 55.4 | 62.0 | 26.3 | 88.3 | 43.4 | 28.2 | 71.6 | 40.0 | 43.3 | 83.2 |

# APPENDIX II

# LIST OF ABBREVIATIONS

| | |
|---|---|
| $\alpha$ | Alpha |
| ABA | Abscicic acid |
| ARE | Apparent fertilizer N recovery efficiency |
| CGR | Crop growth rate |
| $C_p$ | specific heat of the air |
| cv | coefficient of variation |
| D | Drainage |
| D1 | low planting density treatment |
| D2 | High planting density |
| DAP | Days after planting |
| De | plant density |
| $\varepsilon_s$ | radiation conversion efficiency |
| ea | Actual vapour pressure |
| EAST | East African Standard Time |
| $E_{pan}$ | Pan evaporation |
| $E_{pot}$ | Potential evaporation |
| $E_{pot}$ | Potential evaporation |
| $E_{pot,shaded}$ | Potential rate of evaporation from the soil surface shaded by a canopy |
| es | Saturated vapour pressure |
| $E_s$ | Evaporation from bare soil |
| ET | Evapotranspiration |
| $E_{s,2}$ | Water loss due to direct evaporation from the soil surface (stage 2 evaporation) |
| $\rho_a$ | Density of the air at constant pressure |
| $\gamma$ | Psychrometric constant |
| $\Delta$ | Slope of the saturation vapour pressure versus temperature |
| D | drainage |
| d | zero plane displacement |
| u | wind speed at height z |
| RWC | Relative water content |
| $\psi\pi$ | Solute potential |
| F | Quantity of fertilizer applied |
| g | Grams |
| HAP | hours after planting |
| kg | Kilograms |
| K | Light extinction coefficient |
| k | Crop coefficient |
| K2 | Kabete experiment 2 |
| KI | Kabete experiment 1 |
| kPa | Kilo pascals |

| | |
|---|---|
| LAI | Leaf area index |
| $LA_{discs}$ | Leaf disc area |
| $LA_{total}$ | total leaf area |
| $Lwt_{disc}$ | Weight of leaf disc |
| $Lwt_{total}$ | total plant leaf weight |
| m | meters |
| MJ | Mega Joules |
| MPa | Mega pascals |
| N | Nitrogen |
| N0 | No nitrogen fertilizer treatment |
| N100 | Fertilized treatment |
| $N_{dfa}$ | Nitrogen derived from biological fixation |
| $N_f$ | plant N derived from fertilizer |
| $N_{end}$ | soil mineral N at the end of the crop growing season |
| $N_{min}$ | soil mineral N |
| $N_{start}$ | soil mineral N at beginning of the crop growing season |
| $N_{pl}$ | total plant N (g $m^{-2}$) |
| $N_{plant}$ | Plant N concentration |
| $N_s$ | plant N derived from soil |
| $N_{sc}$ | Neutron count in soil |
| NUE | Nitrogen use efficiency |
| $N_{min}$ & $N_{imm}$ | Total soil-N mineralised and immobilised in the season respectively |
| $N_{sf}$ | soil-N derived from fertilizer (fertilizer N unrecovered by the crop). |
| $N_{dpl}$ | Plant daily N uptake |
| $N_l$ | Labile soil N |
| $\Delta N_{min}$ | change in soil mineral N between end and beginning of the season |
| $N_w$ | Neutron count in water |
| P | precipitation (rainfall and irrigation) |
| PAR | Photosynthetically active radiation |
| $r_a$ | Aerodynamic resistance |
| $r_c$ | Bulk stomatal resistance. |
| $R_{off}$ | Run off |
| $R_n$ | Net radiation flux density |
| RH | Relative humidity |
| RWC | Relative water content* |
| $\Sigma$ | Summation sign |
| $\Delta S$ | Change in storage |
| S | Daily incident radiation |
| SD | Saturation vapour pressure deficit (kPa) |
| SE | Standard error |
| SED | Standard error of mean differences |
| $S_i$ | amount of radiation intercepted by foliage |
| SLA | Specific leaf area |

| | |
|---|---|
| $S_y$ | seed yield |
| SDmin,max | mean of the minimum and maximum saturation deficits |
| SDmin | minimum saturation deficit |
| SDmax | maximum saturation deficit |
| SD0900 | Saturation deficits at 0900 hours |
| SD1500 | Saturation deficits at 1500 hours |
| SD0900,1500 | mean saturation deficit of S0900 and S1500 |
| SD0600-1800 | mean of the hourly saturation deficit during the daylight hours, from 0600 to 1800 |
| SD0000-2400 | mean hourly saturation deficit over the whole day |
| $SD_{diurnal}$ | Seasonal diurnal saturation deficit |
| T0900 & T1500 | Temperatures measured at 0900 and 1500 hours respectively |
| T | Transpiration |
| t | Time (days after rain). |
| $TDM_f$ | Total dry matter yield in a fertilized crop |
| $TDM_{fo}$ | Total dry matter yield in an unfertilized crop |
| TDM | Total dry matter |
| O.M | Soil oraganic matter |
| $\chi_s$ | Vapour concentration at saturation |
| $S_i$ | $S_i$ is the amount of radiation intercepted on day i |
| TTDAP | Thermal time calculated from daily mean temperature since day zero days after planting |
| TTHAP | Thermal time calculated from mean hourly temperature since day zero days after planting |
| TTHAPc | Thermal time calculated from mean hourly temperature since day zero days after planting corected for temperatures lower than $T_b$ |
| $T_b$ | base temperature |
| $\phi$ | Thermal time (°C days) |
| $Ti$ | Mean daily temperature |
| $t_{2,eq}$ | Equivalent number of days into second stage drying |
| °C | Degrees centigrade |
| $\psi$ | Leaf water potential |
| $\theta$ | Volumetric water content |
| Tmean | daily mean temperature |
| $T_{max}$ | daily maximum temperature |
| $T_{min}$ | daily minimum temperature |
| $U_f$ & $U_{fo}$ | Amounts of nutrient uptake up by the fertilized and unfertilized crop respectively |
| V | The rate of water uptake by roots from the surface layer expressed as a fraction of the loss through direct evaporation from the soil surface. |
| $V_{max}$ | value of V for a crop with complete ground cover |
| W0 | Rainfed treatment |
| W1 | Irrigated treatment |

| | |
|---|---|
| WUE | Water use efficiency |
| Y | Total dry matter (g $m^{-2}$) |
| $Y_o$ | minimum individual plant dry matter required for seed yield |
| z | Height at which wind speed is measured |
| $z_o$ | roughness length |