Quantifying Components of the Energy Balance of a Maize and Bean Intercrop

By

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DECLARATION

I declare that the thesis hereby submitted by me for the Master of Science in Agrometeorology degree at the University of the Free State is my own independent work and has not previously been submitted by me to another University / Faculty. I further cede copyright of the thesis in favour of the University of the Free State.

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LIST OF SYMBOLS AND ABBREVIATIONS

BREB	Bowen ratio-energy balance
°Cd	Degree-days
c_{pa}	Specific heat at constant pressure (kJ kg^{-1} $°C^{-1}$)
CN	Curve Number (unitless)
dt	Change in time (d)
dw	Change in mass between two harvests (g/plant)
D	Deep water drainage below the rooting zone (mm)
DAP	Day after planting (d)
DOY	Day of the year (d)
Dr	Root zone depletion (mm)
e_a	Average hourly ambient vapour pressure (kPa)
$e^{o}(T_{hr})$	Saturation vapour pressure(kPa)
E	Amount of water evaporated from the soil surface (mm)
ET	Evapotranspiration (mm)
ETc	Evapotranspiration from crop surface(mm)
ETo	Potential evapotranspiration (mm)
f_1	Ratio of ground covered by maize
f_2	Ratio of ground covered by bean
G	Soil heat flux density (MJ m^{-2})
GDD	Growing degree days
h_1	Height of maize crop (m)
h_2	Height of bean crop (m)
H	Sensible heat flux (MJ m^{-2})
I	Irrigation amount (mm)
I_a	Initial abstractions (unitless)
Kc	Crop coefficient (unitless)
K_h	Eddy diffusivity of heat (unitless)

Ks	Soil water stress factor
K_v	Eddy diffusivity of water vapour (unitless)
L_d	Incoming long-wave radiation (W m^{-2})
L_u	Emitted short-wave radiation (W m^{-2})
p	Atmospheric pressure (kPa)
RAW	Readily available soil water
Rf	Rainfall (mm)
Rf_{day}	Rainfall received within a given day (mm)
RGR	Relative growth rate ($gg^{-1}d^{-1}$)
R_{off}	Runoff (mm)
R_n	Net radiant flux density (W m^{-2})
S	Retention parameter (mm)
S_t	Incoming short-wave radiation (W m^{-2})
TAW	Total available water (mm)
T	Water uptake by plant roots (mm)
$\bar{T}_a$	Daily mean air temperature (°C)
T_{base}	Base temperature (°C)
T_{hr}	Mean hourly temperature (°C)
T_{min}	Minimum temperature (°C)
T_{max}	Maximum temperature (°C)
T_{opt}	Optimum temperature for growth (°C)
u_2	Average hourly wind speed (m s^{-1})
W	Initial dry mass (g/plant)
αSt	Reflected short-wave radiation (W m^{-2})
β	Bowen ratio (ratio)
∂e	Change in vapour pressure(kPa)
∂T	Change in air temperature (°C)
∂z	Distance between the two measurement levels (m)

Δ	Slope of saturation vapour pressure curve(kPa °C^{-1})
Δt	Time interval between consecutive days of measurement (d)
ΔW	Change in soil water content of the root zone(mm)
ε	Ratio molecular weight of water vapour/dry air (ratio)
γ	Psychrometric constant (kPa °C^{-1})
λ	Latent heat of vaporization (kJ kg^{-1})
λE	Latent heat flux density (W m^{-2})
θ_w	Volumetric soil water (mm)
ρ_a	Mean air density (kg m^{-3})

ABSTRACT

QUANTIFYING COMPONENTS OF THE ENERGY BALANCE OF A MAIZE AND BEAN INTERCROP

By

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Quantification of the energy balance components is useful to enable analysis of irrigation scheduling and water use efficiencies in addition to calibration and validation of crop models. An experiment was conducted at Bainsvlei, Bloemfontein during the rainy season (January to April) of 2003 to quantify the energy balance components and determine the phenology of maize and bean crops within the intercropping system.

The Bowen ratio energy balance method was used to quantify the components of the energy balance. Net radiant flux (R_n), soil heat flux (G), wet and dry bulb temperature and other meteorological variables were measured. The energy balance components were estimated from day of year (DOY) 47 to 79 and classified based on the height of instrument in four datasets as follows:- from DOY 47 to 58, 59 to 69, 70 to 79 and 90 to 100. During the last period (90 to 100 DOY) measurements were made over bare soil, as the crop was harvested following a hailstorm. Data collected on Cloudy days and where β approached -1 were excluded from the analysis. It was found that the latent heat flux was low throughout the crop growing season. This was mainly due to soil water stress, rather than energy availability. More than 57% of the energy was utilized in generating sensible heat flux rather than for evapotranspiration. Average net radiation inputs were 1.60±0.31 MJ m^{-2}, 1.69±0.15 MJ m^{-2}, 1.19±0.57 MJ m^{-2} and 1.20±0.20 MJ m^{-2}respectively, for the datasets as classified above. The average latent heat fluxes as a fraction of the net radiation during these times were $0.30R_n$, $0.37R_n$, $0.41R_n$ and $0.65R_n$. The average sensible heat fluxes as a fraction of the net radiation were $0.56R_n$, $0.50R_n$, $0.48R_n$ and $0.22R_n$ for datasets as mentioned above respectively. The soil heat flux was on average 13.2% of net radiation throughout the time of measurement. Comparison of ET calculated from Bowen ratio and FAO Penman-Monteith equation showed significant difference for the hourly values. However, there was no significant difference at the daily time scale. This suggests that the methods might be complimentary for estimating ET for a long period of time, using the range of a day or more.

The phenology of maize and bean was monitored during the vegetative period. It was found that the maize accumulated 90 °Cd from planting to emergency, 408 °Cd from emergency to tassel initiation and 258 °Cd from tassel initiation to silking. Beans accumulated 513 °Cd to complete the vegetative stage and 243 °Cd from R1 (50% of plants have at least one flower at any node) to R4 (50% of plants have pods with seeds at beginning of pod filling stage). The maize exhibits a delay in its development even if the required growing degree-days were accumulated due to the severe water stress. However the development of the bean was not affected by the competition involved in the intercropping system both for water and light.

UITTREKSEL

KWANTIFIKASIE VAN DIE KOMPONENTE VAN DIE ENERGIEBALANS VAN 'n MIELIE-BOON TUSSENGEWAS

Deur

SOLOMON AFEWORKI GEBREKRISTOS

MSc in Landbouweerkunde by die Universiteit van die Vrystaat

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Kwantifikasie van die energiebalanskomponente is bruikbaar om analise van besproeiingskedulering en watergebruiksdoeltreffendheid, sowel as kalibrasie en validasie van gewasmodelle uit te voer. 'n Eksperiment is te Bainsvlei, Bloemfontein gedurende die reënseisoen (Januarie tot April 2003) uitgevoer om die energiebalanskomponente te kwantifiseer en om die fenologie van mielie en boongewasse binne die tussengewassisteem te bepaal.

Die Bowen verhouding energiebalansmetode is gebruik om die komponente van die energiebalans te kwantifiseer. Nettostralingsvloed (R_n), grondhittevloed (G), droë en natbol temperatuur en ander meteorologiese veranderlikes is gemeet. Die energiebalans komponente is bereken vanaf dag van jaar (DOY) 47 tot 79 en geklassifiseer volgens hoogte van instrument in vier datastelle: van DOY 47 tot 58, 59 tot 69, 70 tot 79 en 90 tot 100. Gedurende die laaste periode (90 tot 100 DOY) is lesings op kaal grond geneem omrede die gewas na 'n haelstorm geoes is. Data versamel op bewolkte dae, waar β -1 nader, is nie by die analise ingesluit nie. Daar is gevind dat die latente hittevloed regdeur die gewas groeiseisoen laag is. Die het plaasgevind hoofsaaklik as gevolg van grondwaterstres, eerder as energie beskikbaarheid. Meer as 57 % van die energie is

gebruik om aanvoelbare hittevloed, eerder as vir evapotranspirasie te genereer. Gemiddelde nettostra-lingsinsette is 1.60±0.31 MJ m^{-2}, 1.69±0.15 MJ m^{-2}, 1.19±0.57 MJ m^{-2} en 1.20±0.20 MJ m^{-2} respek-tiewelik vir die datastelle soos hierbo geklassifiseer. Die gemiddelde latente hittevloed as 'n fraksie van nettostraling gedurende hierdie tye was 0.30R_n, 0.37R_n, 0.41R_n en 0.65R_n. Die gemiddelde aanvoelbare hittevloed as 'n fraksie van die nettostraling is 0.56R_n, 0.50R_n, 0.48R_n en 0.22R_n vir datastelle voorheen genoem. Die grond-hittevloed regdeur die totale tydperk van lesingopnames, is gemiddeld 13.2 % van die nettostraling. Vergelyking van ET bereken vanaf Bowen verhouding en FAO Penman-Monteith vergelyking, het noemenswaardige verskille vir uurlikse waardes gedemonstreer. Daar is nietemin geen noemensw-aardige verskil op die daaglikse tydskaal gewaar nie. Die voorstel wat hieruit spruit is dat die metodes komplimentêr van aard vir ET oor 'n lang tyderk mag wees, indien 'n reeks van 'n dag of meer gebruik word.

Die fenologie van beide mielies en bone is gedurende die vegetatiewe fase gemonitor. Daar is gevind dat mielies 90 °Cd vanaf plant tot opkoms, 408 °Cd vanaf opkoms tot pluimverskyning, 258 °Cd vanaf pluimsverskyning tot baardverskyning geakkumuleer is. Bone het 513 °Cd geakkumuleer om die vegetatiewe fase te voltooi en 243 °Cd vanaf R1 (50 % plante het ten minste een blom by enige knoop) tot R4 (50 % plante het peule met sade by die begin van die peulvullingstadium). Die mielies vertoon 'n agterstand in ontwikkeling as gevolg van ernstige water-stres, al is die vereiste groeigradedae geakkumuleer. Nietemin is die ontwikkeling van bone in die tussengewas-sisteem nie deur kompetisie vir beide water en lig beinvloed nie.

CHAPTER ONE

INTRODUCTION

In developing countries rainfed agriculture on about 80% of the arable land accounts for 60% of the food production. Only about 20% of the arable land in developing countries is irrigated, but it produces 40% of all food production. It is projected that the world population will grow from 6 billion to 8.3 billion by the year 2030, hence an additional 2 billion people need to be fed in the next 30 years. Food and Agricultural Organization (FAO) projects that world food production needs to increase by 60% to feed the growing world population. Optimal crop water use under both rainfed and irrigated agriculture will play a key role in ensuring food security (FAO, 2000).

Farmers in the developing world have been growing two or more crops together on the same piece of land for many centuries (Austin and Marais, 1987). Research on intercropping has started to provide an understanding of why farmers use such mixtures, and to help improve productivity in ways relevant to specific practices (Wallace, 1985). Associated cropping of maize (*Zea mays L.*) and beans (*Phaseolus vulgaris* L.) is one of the most common cropping systems used by small-scale farmers in sub-Saharan Africa.

It is estimated that 80% of beans and 60% of maize in Latin America is produced by small-scale farmers, mostly in associated cropping (Francis, Flor and Proger, 1978). The usual explanation offered for the advantage of using such a system is that the cereal and legumes species make partial, complementary use of resources in time or space, thus utilizing resources more efficiently. In tropical and subtropical regions the cereal component is usually maize, sorghum or millet and to a lesser extent rice. The legume is usually cowpea, groundnut, soybean, chickpea, beans or pigeonpea (Ofori and Stern, 1987).

Energy flux density available at the earth's surface is mainly sensible (resulting from temperature changes with no phase change of water) or latent (results from phase change of water usually from liquid to vapour with no temperature change). Plant growth is dependent on photosynthesis. While the plant exchanges gases with the air for photosynthesis, some water evaporates. Water is taken up from the soil by plant roots to replace this water. The water leaving the plant is called transpiration. In addition to this, some water also evaporates from the soil surface that is called evaporation. The combination of the two processes is called evapotranspiration (Trimmer and Hansen, 1994).

People are attempting to alter the balance between these energy terms that is latent and sensible heat fluxes. Bowen (1926) realized the significance of the terms and considered the ratio of sensible heat to latent heat to be important for partitioning the energy balance into its various components. The partitioning of available radiation into sensible and latent heat flux density is strongly influenced by changes in vegetation characteristics (Rosset, Riedo, Grub, Geissmann, and Fuhrer, 1997). Thus, in the intercropping situation the components of the energy balance are not expected to be the same as in the case of a homogeneous canopy surface. Owing to the advantages that intercropping has over a sole crop system it is important to quantify the components of the energy balance in an intercropping system. This can be used in crop growth modeling, estimating water use by plants and calculating water use efficiency.

Heat unit systems such as Growing Degree Days (GDD), Thermal time and Crop Heat Units (CHU) have been used to quantify the effect of temperature on crop phenology. Accurate simulation of phenology is important because virtually all growth processes such as leaf photosynthesis and dry matter accumulation are influenced by the stage of development. Thus duration of the life cycle is an important factor influencing total crop dry matter accumulation and grain yield (Hodges, 1991).

Thus, as air temperature has a great influence on plant phenological stages it is important to determine its effect on intercropping. This can be used in crop growth models, which can assist farm managers in operational decisions so that the most critical stages of growth occur during periods of favourable weather (Hodges, 1991).

The objectives of the study are:

- To quantify the components of the energy balance in a Maize/Bean intercrop system.
- To determine the response of maize and bean phenology to air temperature due to the difference in canopy structure encountered in intercropping.

CHAPTER TWO

LITERATURE REVIEW

2.1 Advantages of Intercropping

Intercropping is the traditional form of agriculture in many developing countries, especially those with tropical climates (Austin and Marais, 1987). The main consideration for mixing crops together is to reduce the risk of crop failure. The farmer reasons that if two or more crops are grown at the same time, at least one will survive to provide a successful harvest. But there are other reasons also. Frequently one can find short-duration and long-duration crops in the mixtures. This helps spread labour needs more evenly. Food crops are usually mixed with cash crops to help ensure both subsistance and a source of disposable income. Cereals and legumes are often mixed, probably more for dietary reasons than for any beneficial effect that the nitrogen-fixing powers of the legumes convey to the associated cereal crop or to a subsequent one (Francis, Prager and Tejada, 1982).

Research on intercropping started to provide an understanding of why the farmer uses such mixtures, and to help improve his productivity in ways relevant to his practice. It has now been shown that inter-cropping may have several advantages over sole cropping (Sarkar and Shit, 1992). Observations from past research indicate that intercrops produce higher yield than when the component crops are grown as sole crops. It has been mentioned that this is due to the more efficient utilization of environmental resources (Willey and Osiru, 1972). Thus intercrop appears to make better use of the natural resources of radiation, land and water. (Mukhala, 1998; Tsubo, 2000; Connelly, Goma and Rahim, 2001; Ogindo, 2003).

Cereal/legume intercrops are preferred in many different parts of the tropics and maize is grown in association with pigeon pea (Sivakumar and Virmani, 1980), maize and cowpea (Wahua, Babalolo and Akenova, 1981; Watiki, Fukai, Banda and Keating, 1993), or maize and beans (Ayisi and Poswall, 1997; Siame, Willey and Morse, 1997) or maize and groundnuts (Liphadzi, Thomas and Hammes, 1997). The persistence of intercropping over the years has been due to its stability and resilience under variable growing conditions (Trenbath, 1999; Francis, *et al.*, 1978; Willey, 1979). Recent research has shown that intercropping can produce higher yields than its component sole system. Several mechanisms make this cropping system attractive, among which, is the important aspect of better utilization of environmental resources. The advantage associated with this superior use of resources has been well explored in the last two to three decades (Willey, 1979; Francis, Ofori and Stern, 1987; Willey, 1990; Fukai, 1993).

Willey (1990) in his review of resource use by multi-cropping systems attributed the yield advantage of intercrops to temporal and spatial complementarily in the use of resources. Beets (1982) observed that multiple cropping allowed for better utilization of atmospheric and soil environmental factors.

2.2 Energy Balance

Evaporation of water requires relatively large amounts of energy, which can be provided either in the form of sensible heat or radiant energy (Allen, Pereira, Raes, and Smith, 1998). Therefore, the evapotranspiration process is governed by energy exchange at the vegetation surface and is limited by the amount of energy available. Because of this limitation, as stated by Arya (1988) it is possible to predict the evapotranspiration rate by applying the principle of energy conservation. Over time, the energy arriving at the surface must equal the energy leaving the surface during the same time interval. All fluxes of energy should be considered when deriving an energy balance equation. According to the energy balance equation, the energy of net radiation, R_n, is dissipated by three processes such that:-

$$R_n = G + \lambda E + H \qquad 2.1$$

Where R_n is the net radiant flux density, H is the sensible heat flux density, λE the latent heat flux density and G is soil heat flux density by conduction. The soil heat flux density is small (a few percent of R_n) under a dense cover of vegetation but can be large on an hourly basis for bare soil, though the net value of G over 24 hours is negligible. The various terms can be either positive or negative. Positive R_n supplies energy to the surface and positive G, λE and H remove energy from the surface. The storage term is usually considered to be negligible. Change in G, whether positive or negative are reflected in changes in soil temperature. When G is positive, soil temperature rises. In Equation 2.1 only one-dimensional heat transfer is considered and the net rate at which energy is being transferred horizontally, by advection from outside of system in equilibrium, is ignored.

The equation is restricted to the four components: R_n, λE, H and G. Other energy terms, such as heat stored or released in the plant, or the energy used in metabolic activities, are not considered as they accounts for only a small fraction of the daily net radiation and can be considered negligible on daily basis when compared with the other four major components (Stewart, 1984; Thom, 1975; Wesson, Lai and Karenkatul, 2001; Preston-Whyte and Tyson, 1988).

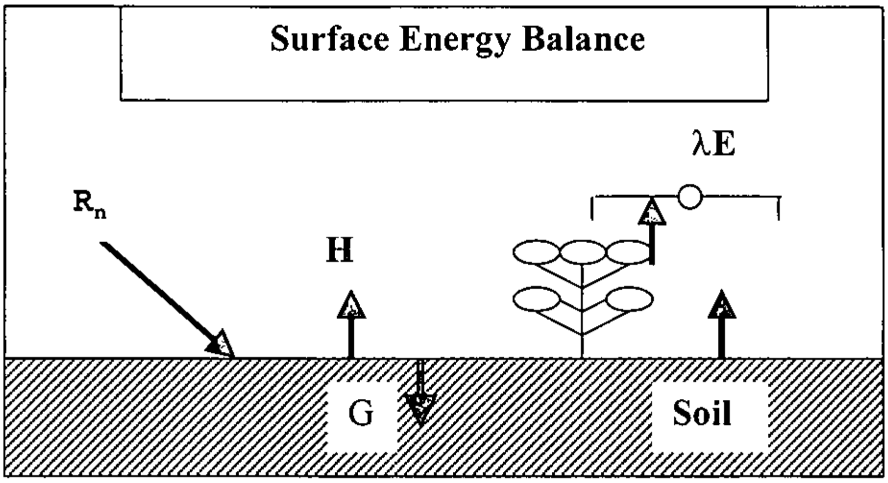


Fig. 2.1. Schematic representation of the surface energy balance components considering vertical fluxes only

After the input of energy, the most important factor governing the rate of evaporation is the efficiency of removal of water vapour from the surface. For a given wind speed and air vapour pressure gradient, the rate of removal of water vapour depends on the atmospheric turbulence induced by the wind blowing over the surface. Over relatively smooth bare soil the turbulence will be low, whilst over rough forests it will be much greater; for agricultural crops, the turbulence will be between these extremes (Stewart, 1984).

The latent heat flux density (λE) represents the evapotranspiration fraction of the energy balance can be derived from the energy balance equation if all other components are known. Net radiation (R_n) and soil heat flux density (G) can be measured or estimated from climatic and soil properties (Zapata and Martinez-Cob, 2002). Measurements of the sensible heat flux density (H) are however complex and cannot be easily monitored. H requires accurate measurement of temperature gradients above the surface. Arya (1988) demonstrated that the growth of vegetation over a flat surface introduces several complications into the energy balance and these are:

First, the ground surface is no longer the most appropriate level at which to conduct for the surface energy balance, because the radiative, sensible and latent heat flux densities are all especially variable within the vegetative canopy. The energy budget of the whole canopy layer will be more appropriate to consider. For this, measurements of R_n, H, and λE are needed at the top of the canopy (preferably, well above the top of the plants or trees where horizontal variations of fluxes may be neglected but measurement is still within the boundary layer). Figure 2.2 demonstrates the general trend of energy balance components above a well watered transpired surface on a sunny day.

Second, the rate of energy storage consists of two parts, namely, the rate of physical heat storage and the rate of biochemical heat storage as a result of photosynthesis and carbon dioxide exchange. The latter may not be important on a time scale of a few minutes or hours to a day, commonly used in micrometeorology. However, the rate of heat storage by a vegetative canopy is not easy to measure or calculate (Arya, 1988).

Third, the latent heat exchange occurs not only due to evaporation at the crop and soil surface, but to a large extent due to transpiration from the plant leaves. The collective term for evaporation from the soil surface and transpiration is called evapotranspiration (Arya, 1988).

The energy balance that is an important factor and key component in the energy and water use efficiency, need to be studied in an intercropping system. Quantification of crop evapotranspiration is required to make analysis of irrigation scheduling and efficiencies. Besides it helps to calibrate and validate crop growth models.

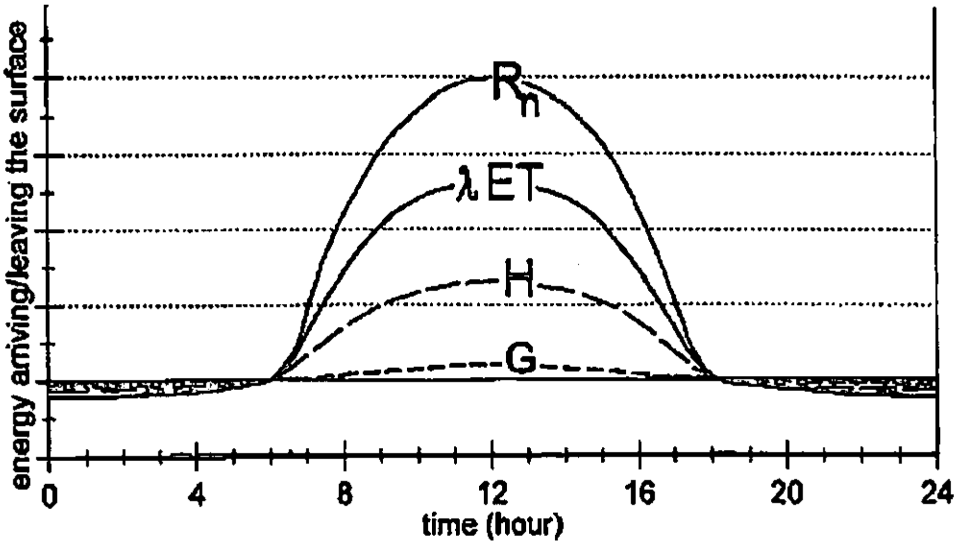


Fig. 2.2. Schematic presentation of the diurnal variation of the components of the energy balance above a well watered transpiring surface on a cloudless day (Allen, *et al.*, 1998)

In a field experiment quoted by Allen *et al.* (1998) derived the latent heat flux density (λE), representing the evapotranspiration fraction, from the energy balance equation. Soil heat flux density (G) and net radiation (R_n) were estimated from climatic parameters.

There are various methods of directly measuring evapotranspiration using micrometeorological measurements. The common theme among all micrometeorological methods is that measurements of meteorological variables are made within the boundary layer the land surface to determine fluxes of energy (Allen *et al.*, 1998).

Another method of estimating evapotranspiration is the mass transfer method. This approach considers the vertical movement of small parcels of air (eddies) above a large homogeneous surface. The eddies transport material (water vapour) and energy (heat) and momentum from and/or towards the evaporating surface. By assuming steady state conditions and that the eddy transfer coefficients for water vapour are proportional to those for heat and momentum, the evapotranspiration rate can be computed from the vertical gradients of air temperature and water vapour via the Bowen ratio. Other direct measurement methods use gradients of wind speed and water vapour. These methods and other methods such as eddy covariance, require short time interval for measurements of vapour pressure, and air temperature or wind speed at different levels above the surface. Therefore, their application is restricted to highly sophisticated research situations (Allen *et al.*, 1998).

Savage, Everson, and Metelerkamp (1997) pointed out that energy flux density transfer at the earth's surface is mainly sensible heat H (resulting from temperature change with no phase change of water) or latent heat (resulting from phase change of water usually from liquid to vapour with no temperature change). Bowen (1926) realized the significance of the terms and considered the ratio of sensible heat to latent heat to be important for partitioning the energy into various components. This ratio is commonly known as the Bowen ratio β, and forms the basis of the method that is used to calculate sensible and latent heat energy flux from surface.

The Bowen ratio-energy balance (BREB) method estimates latent heat flux density from a surface using measurements of air temperature and humidity gradients, net radiation, and soil heat flux density. The assumptions made usually in Bowen ratio calculations are that the surface has to be homogeneous and there must also be adequate fetch (Fritschen and Simpson, 1989). It is an indirect method, compared to methods such as eddy covariance, which directly measures turbulent fluxes, or weighing lysimeters, which measure the mass change of an isolated soil volume with plants growing in it. Its advantages include straight-forward, simple measurements; it requires no information about the aerodynamic characteristics of the surface of interest; it can integrate latent heat flux density over large areas; it can estimate fluxes on fine time scales (less than an hour); and it can provide continuous measurements. The accuracy of the measurements are sensitive to the resolution of the sensors and whether the biases of the instrumentation that measure gradients and energy balance terms are correct, (except R_n); the possibility of discontinuous data when Bowen ratio approaches -1, and the requirement of adequate fetch to ensure adherence to the assumptions for the method to hold true (Todd, Evett and Howell, 2000).

The partitioning of available energy (R_n-G) between sensible (H) and latent (λE) heat flux density is usually obtained by the Bowen ratio energy balance method (Tanner, Greene and Bingham, 1987). The Bowen ratio is given by:

$$\beta = \frac{H}{\lambda E} \qquad 2.2$$

The Bowen ratio, β, is used with the energy balance equation to yield the following expressions for λE and H:

$$\lambda E = \frac{R_n - G}{1+\beta} \qquad 2.3$$

$$H = \frac{\beta}{1+\beta}(R_n - G) \qquad 2.4$$

where R_n is the net radiation and G is soil conduction flux.

Over an averaging period, t, (20-60 minutes) empirical relationships between fluxes and vertical gradients can be formulated as:

$$H = -\rho_a c_{pa} K_h \frac{\partial T}{\partial z} \qquad 2.5$$

$$\lambda E = -\frac{\rho_a c_{pa}}{\gamma} K_v \frac{\partial e}{\partial z} \qquad 2.6$$

where ∂T and ∂e are the temperature and vapour pressure difference between the two measurement levels, $\gamma = c_{pa}p/\varepsilon\lambda$ is the psychrometric constant, c_{pa} (1.01 kJ kg^{-1} $°C^{-1}$) is

the specific heat of air at constant pressure, p is the atmospheric pressure (kPa), ρ_a is the mean air density, ε the ratio between the molecular weights of water vapour and air (0.622), and λ is the latent heat of vapourization ($kJkg^{-1}$), K_h the eddy diffusivity of heat, K_v the eddy diffusivity of water vapour. The convention used for the signs of the energy fluxes is R_n positive towards surface and G positive when it is conducted downward from the surface. Sensible and latent heat flux densities are positive upward, in a direction opposite to that of the gradients (eq. 2.5 and 2.6). For a temperature gradient $(\partial T/\partial z) < 0$, the sensible heat flux density H is positive;

and for a vapour pressure gradient $(\partial e/\partial z) < 0$, the latent heat flux density λE is positive.

The mean daily G value is often one or more orders of magnitude lower than R_n. However, over short periods, it can be quite large and show large variations since it involves the thermal properties of the soil that vary largely with water content. When precipitation or irrigation has occurred, the soil heat flux density pattern can be distorted considerably due to heat transfer with the soil water movement (Rosenberg, Blad and Verma, 1983).

The accuracy of the method can be assessed by comparing the calculated fluxes with an independent measurement of evapotranspiration such as that supplied by a lysimeters or eddy covariance instrument (Perez, Castellvi, Ibanez, and Rosell, 1999). Unfortunately, these other sophisticated methods are not often available.

In a field experiment of an energy balance of permanent pastures at different altitudes, it was found that the values of β obtained during the night (from 18:00 to 09:00) were to be rejected, according to the criteria defined by Ohmura (1982). This criterion stated that if β approaches to -1 the calculated fluxes would not possess numerical meaning. Therefore, the data should be excluded from evaluation. They also pointed out that the maximum β was associated with the driest conditions. High wind speeds reduced aerodynamic resistance and allowed sensible heat to be transferred from the warmer boundary layer to the cooler canopy. The advection of sensible heat toward the canopy (H, dropped to -150 Wm^{-2}) led to λE of 300 Wm^{-2}, which exceeds R_n by 100%.

Blad and Rosenberg (1974) observed underestimation of latent heat flux density of alfalfa by the Bowen ratio energy balance method compared to lysimeters under conditions of sensible heat advection. Subsequently Verma, Rosenberg and Blad (1978) and Motha, Verma and Rosenberg (1979) showed that the exchange coefficient for heat was greater than that for water vapour during sensible heat advection.

The definition of Rosenberg *et al.* (1983) was used, where advection is the "transport of energy or mass in the horizontal plane in the downwind direction". Sensible heat advection was not directly measured, but was inferred when the ratio of Bowen ratio latent heat flux density to available energy (R_n-G) was greater than 1, and when sensible heat was consumed rather than generated by the maize/bean intercrop field.

2.2.1 Fetch requirement

Savage *et al.* (1997) pointed out that fetch is the distance of traverse across a uniformly rough surface. A maize crop for instance may be regarded as a typical rough surface. If evapotranspiration is to be measured above a maize crop, due consideration must be given to the fetch. Adequate fetch would ensure that the actual evapotranspiration from the maize is being measured and not the evapotranspiration from the areas adjacent to the maize field. Thus, adequate fetch ensures that the two measurement levels for temperature and humidity are within the adjusted surface boundary layer. Some of the assumptions on which the BREB method relies are one dimensional transport of energy and location of sensors, which measure gradients, within the equilibrium sub-layer where fluxes are assumed to be constant with height (Fritschen and Simpson, 1989). These assumptions can be met if adequate upwind fetch is available. A fetch to height - above surface ratio of 100:1 is often considered a rule of thumb (Rosenberg, *et al*, 1983; Allen, Smith, Pereira and Perrier, 1994), although in contrast a ratio as low as 20:1 was considered sufficient when the Bowen ratio was small and positive (Heilman, Brittin and Neale, 1989).

2.3 Penman-Monteith Evapotranspiration Calculation Method

The FAO (Allen *et al.*, 1998) has presented an updated procedure for computing reference surface and crop evapotranspiration from meteorological data and a crop coefficient. According to this updated method the evapotranspiration rate from a reference crop surface, not short of water, is called the reference crop evapotranspiration (ETo). This reference surface is a hypothetical grass reference crop with specific characteristics. The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices (Allen *et al.*, 1998). Thus, a crop coefficient, Kc, was introduced to include the effect of the crop on evapotranspiration. The primary characteristics that distinguish the crop from reference grass are crop height, albedo and canopy resistance. Consequently, different crops will have different Kc coefficients. The changing characteristics of the crop through the growing season also affect the Kc coefficient. Different methods of calculating evapotranspiration have been employed. However due to many shortcomings and its validity for a wide range of locations and climates, FAO Penman-Monteith method is recommended as the sole standard method. For hourly calculation it is given by (Allen *et al.*, 1998):

$$ETo = \frac{0.408\,\Delta(R_n - G) + \gamma \dfrac{37}{T_{hr} + 273} u_2 (e^o(T_{hr}) - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \qquad 2.7$$

Where ETo is reference evapotranspiration (mm), R_n is net radiation at the grass surface ($MJm^{-2}\ h^{-1}$), G is soil heat flux density ($MJm^{-2}\ h^{-1}$), T_{hr} is mean hourly air temperature (°C), Δ is slope of saturation vapour pressure curve at T_{hr} (kPa $°C^{-1}$), γ is psychrometric constant (kPa° C^{-1}), e^o (T_{hr}) is saturation vapour pressure at air temperature T_{hr} (kPa), e_a is average hourly ambient vapour pressure (kPa) and u_2 average hourly wind speed ($m\ s^{-1}$). The concept of the reference evapotranspiration was introduced to study the evaporative demand of the atmosphere independently of crop type, crop development and management practices (Allen *et al.*, 1998).

2.4 Soil Water Balance

Et can also be determined by measuring the various components of the soil water balance. This method consists of assessing the incoming and outgoing water flux of the crop root zone over a given time period. Irrigation (I) and rainfall (Rf) add water to the root zone. Part of Rf and I might be lost by surface runoff and by deep percolation. Water might also be transported upward due to capillary rise from a shallow water table toward the root zone. Soil evaporation and crop transpiration deplete water from the root-zone. If all the fluxes other than evapotranspiration can be assessed, the evapotranspiration can be deduced from the water balance of soil water content over the time period. The soil water balance method can usually only provide evapotranspiration estimates over long time periods of the order of a week or ten-day periods (Allen *et al.*, 1998). The root zone can be represented by means of a container in which the water content may fluctuate. To express the water content as root zone depletion is useful. It makes the adding and subtracting of losses and gains straightforward as the various parameters of the soil water budget are usually expressed in terms of water depth. Rainfall, irrigation and capillary rise of groundwater towards the root zone increase the available soil water in the root zone. Soil surface evaporation, crop transpiration and percolation losses remove water from the root zone and increase the depletion. The water balance equation for a specific area of land can be given as (Bennie & Hensley, 2001):

$$(E+T) = Rf + I \pm R_{off} \pm D \pm \Delta W \qquad 2.8$$

where Rf is rainfall between two consecutive measurements (mm), I is applied irrigation (mm), E is amount of water evaporated from the soil surface between two consecutive measurements (mm), T is water uptake by plant roots which for practical purposes is equal to the transpiration loss through evaporation from the plant canopy (mm), R_{off} is runoff (-) from, or run-on (+) onto the soil surface between two consecutive measurements (mm), D is deep water drainage below the rooting zone or beyond the deepest roots (-) or upward water flux into the root zone (+) (mm) and ΔW is change in soil water content of the root zone between two consecutive measurements (mm).

Using equation 2.8 the evapotranspiration between two consecutive soil water measurements can be calculated, when all the other components have been measured. The soil water content can be measured using a neutron probe, which is common technique for measuring the soil water content of the soil profile.

2.5 Phenology

Phenology is defined as a branch of science dealing with the relations between climate and periodic biological phenomena (Jones, White, Boote, Hoogenboom and Porter, 2000). Stated another way, phenology is the study of the response of living organisms to seasonal and climatic changes in the environment in which they live. Seasonal changes include variations in the duration of sunlight, precipitation, temperature and other life-controlling factors (Hodges, 1991; Wallace and Enriqueze, 1980).

It is of importance to distinguish between growth and development. Growth means an increase in size of the plant in terms of size, volume or mass. Whereas development is characterized by the differentiation of cells into specialized cells to form various tissues, organs and organisms (Stewart and Dwyer, 1986). In maize, for instance, reproductive development starts at the transition of the growing point from vegetative to reproductive development at tassel initiation. Tassel initiation occurs between the 4- to 10-leaf tip stages, depending on the cultivars. There are three more or less distinct phases of rate of dry matter accumulation: (i) a period of exponential dry matter accumulation during a plant's early growth, (ii) a period of more or less linear dry matter accumulation, and (iii) a period of declining dry matter accumulation (leaf senescence). These phases of growth, however, are not associated with phases of phenological development. Phenology can be described qualitatively in terms of morphological phases and sub-phases of the life cycle. Duration of the life cycle from planting to physiological maturity, and the sub-phases, vary among genotypes of different relative maturity length (Yan and Wallace, 1998).

Temperature affects many plant processes including nutrient uptake, water absorption, photosynthesis, respiration, and translocation of photosynthesis. As a result temperature is considered the most important environmental factor governing plant development (Barebecel and Eftimescu, 1972; Coelho and Dale, 1980). An understanding of the way plant react to different temperatures is of considerable importance in developing varieties for a specific thermal environment. Leaf growth characteristics provide meaningful parameters for the study of temperature-plant development relationships and the effect of temperature on leaf growth has been documented for a number of crop species (Thiagarajah and Hunt, 1982). Milthorpe (1959) showed that the rate of cucumber leaf expansion increased between 12 and 24°C, and that the rate of production of new leaves also increased with temperature.

The linearity of the growth rate/temperature relation for leaf extension in millet, up to an optimum temperature of about 30°C, when water is not limiting, is consistent with the finding for other cereals (Ong, 1983). Since rates of plant development are governed by temperature and water status, changes in these variables as a result of intercropping could account for the differences in allocation of dry matter (Ong, 1984; Harris, Natarajan and Willey, 1987).

Aldrich and Leng (1972) and Hodges (1991) stated that commonly monitored phenological events for maize are:

- Emergence date
- End of juvenile phase
- Tassel initiation
- Silking
- Beginning of effective filling period of grain
- Effective filling period of grain
- End of effective filling period of grain
- Physiological maturity

As it is presented by Jones, White, Boote, Hoogenboom and Porter (2000), commonly monitored phenological events for beans are (V is vegetative, R is Reproductive):

- VE when 50 % of plants have some part visible
- V1 when 50 % of plants have completely unrolled leaf at first node above the unfoliate node
- V2 when 50 % of plants with 2 leaves above the unfoliate on the main stem
- V (n) when 50 % of plants with n leaves above the unfoliate on the main stem
- R0 when floral induction occurs
- R1 when 50 % of plants have at least one flower at any node on the plant
- R2 when 50 % of plants have at least one pod formed and ready to grow
- R3 when 50 % of plants have at least one fully expanded pod
- R4 when 50 % of plants have pods with seeds beginning to grow
- R5 is when 50 % of plants have at least one pod containing a full-sized green seed
- R6 when 50 % of plants first have at least one pod that is yellowing or physiological maturity.

2.5.1 Degree-day concepts

Temperature controls the developmental rate of many organisms. Plants require a certain amount of heat to develop from one point in their life cycles to another. This measure of accumulated heat is known as physiological time. Theoretically, physiological time provides a common reference for the development of organisms. Physiological time is often expressed and calculated in units called degree-days (°Cd), (Yan and Wallace, 1998).

Upper and lower developmental threshold temperatures have been determined for some organisms through controlled temperature laboratory and field experiments. The lower developmental threshold for a plant is the temperature below which development stops. The upper developmental threshold is the temperature above which the rate of growth or development begins to decrease or stop (Stewart, Lianne and Carrigan, 1998; Yan and Hunt, 1999).

The calculation of thermal time is based on the linear relationship between time and temperature between T_{base} and T_{opt}, although it can be easily modified to take into account temperature above T_{opt} (Garcia-Huidobro, Monteith and Sugre, 1982).

The total amount of heat required, between the lower and upper thresholds, for a plant to develop from one point to another in its life cycle is calculated as a thermal time with units of degree-days (°Cd). Degree-days are the accumulated product of time and temperature between the developmental thresholds for each day.

McMaster and Wilhelm (1997) noted that there are two types of implementations for calculating accumulated thermal time. The first method is where $[(T_{max} + T_{min})/2] < T_{base}$, then $[(T_{max} + T_{min})/2] = T_{base}$. This method seems to be the most widely used methods for calculating thermal time, particularly in growth simulation models (e.g., Davidson and Campbell, 1983; Kirby, 1995). The second method implemented was where if $T_{max} < T_{base}$, then $T_{max} = T_{base}$, and if $T_{min} < T_{base}$, then $T_{min} = T_{base}$. This is the most commonly used method in calculating thermal time for maize, but is used for other crops as well (e.g. Baker and Gallagher, 1983; Swanson and Wilhelm, 1996). Occasionally a combination of the two methods is used (Baker and Gallagher, 1983).

The most simple useful definition of thermal time (GDD) is

$$GDD=\sum_{i=1}^{n}(\bar{T}_a-T_{base})\times\Delta t \qquad 2.9$$

Where $\bar{T}_a$ is mean daily air temperature, T_{base} is the base temperature at which development stops, Δt is the time interval between consecutive days of measurements and n is the number of days of temperature observations used in the summation. The calculation of $\bar{T}_a$ is usually performed by taking an average of the daily maximum and minimum temperatures.

The above mentioned calculation of thermal time is appropriate for predicting plant development (Hanks and Ritchie, 1991). Stewart *et al.* (1998) grouped different locations into four groups based on thermal time requirement in a field experiment of maize hybrids based on a general thermal index. One of the methods used to evaluate the general thermal index was a coefficient of variation (CV). The reliability of the thermal index is determined by its consistency across years and locations but not across hybrid, since the index is to be used to characterize the thermal requirements of individual hybrids (Table 2.1)

Table 2.1. Characterization of four hybrid groups of maize numbered from highest to lowest relative maturity ratings (after Stewart *et al.*, 1998)

Hybrid Group	Time period (years)	locations (code)	Mean thermal time * --------$GDD_{30,\ 10}$-------- Vegetative	Reproductive
1	5	146	748	669
2	5	115	710	631
3	5	69	651	588
4	13	109	595	525

* Growing degree days with threshold limits of 30 °C as T_{opt} and 10 °C as T_{base}

For the vegetative period the response function used for the four hybrids grown was the sigmoid curve similar to those measured by Ellis, Summerfield, Edmeades and Roberts (1992) on maize hybrids under controlled environmental conditions.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Field experimentation

3.1.1 Experimental layout, treatment and climate

A. General Information

A field experiment was conducted during the rainy season of 2003 at the experimental station of the Department of Soil, Crop and Climate Sciences, at the University of the Free State. It is situated 12 km north of the University main campus (Latitude 29°01′ S, Longitude 26°08′ E, Altitude of 1372 m above sea level). The size of the plot comprising the Maize/Bean intercropping was 120 m x 85 m. It was not replicated due to fetch requirements.

The long-term average monthly maximum temperatures of Bloemfontien airport (see table 3.1) are in the range of 16.8 °C to 30.8°C while average monthly minimum temperatures varied between -1.9 °C and 15.3 °C (SA Weather Service, 1961-1990). The annual rainfall of the experimental area is in the range of 350 to 600mm year^{-1}. Eighty percent of the rainfall occurs between November and April during the summer growing months.

Average hourly weather data during the growing season of 2003 collected at the site is also presented in table 3.2 for months January to April. During these months mean hourly temperature ranges from 35.3 °C to 4.8 °C, relative humidity ranges from 94.9% to 7.7%, maximum solar radiation was 4.47 MJ m^{-2} h^{-1} and the total rainfall received from January to April was 274.7 mm.

Table 3.1 Long-term (1961-1990) mean monthly weather data from Bloemfontein Airport, South Africa (latitude 29°06′ S, longitude 26° 18′E, altitude 1351 m above sea level)

Item	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Mean**
Tmax (°C)	30.8	28.8	26.9	23.1	20.1	16.8	17.4	20.0	24.0	26.1	28.1	30.1	**24.4**
Tmin (°C)	15.3	14.7	19.7	7.7	2.5	-1.5	-1.9	0.5	5.2	9.1	11.7	13.8	**8.1**
Tmean (°C)	23.0	21.8	12.4	15.4	11.3	7.7	7.7	10.3	14.6	17.6	19.9	22.0	**15.3**
Rainfall (mm)	81.4	99.9	74.2	56.3	14.0	12.6	8.9	14.1	21.7	46.7	61.2	61.1	**-**
ETo (mm)	298.2	229.2	186.4	185.2	112.9	76.9	124.9	145.1	180	224	253	290.9	**192.3**
Aridity Index	0.27	0.44	0.40	0.30	0.16	0.16	0.07	0.10	0.12	0.21	0.24	0.21	**0.22**

Table 3.2 Mean hourly weather data for each month during the growing period estimated with an automatic weather station situated at the experimental site (U_2 is wind speed at 2-meter height, RH is relative humidity, Rs is solar radiation and Rf is rainfall)

Month	Temp. °C Max	Temp. °C Min	RH % Max	RH % Min	u_2 ms^{-1} Mean	Rs Wm^{-2} Mean	Rs Wm^{-2} Max	Monthly Rf mm Total
January	31.7	16.2	92.8	7.7	2.03	354.3	1244	73.7
February	29.9	16.7	94.7	10.7	1.65	270.8	1218	63.1
March	28.9	13.4	94.9	9.0	1.70	275.7	1116	131.4
April	26.5	12.4	92.6	13.1	1.59	212.5	1004	6.5

The long-term mean rainfall during the months of January to April was 311.8mm, which was 37 mm higher than the rainfall received during the same months in 2003.

A maize cultivar SNK2147 and a dry bean cultivar Eienskappe-PAN 127 were planted in the experiment. Weather data were collected throughout the growing season from an automatic weather station situated at the experimental site.

The crops were sown on the 15 January 2003. Prior to sowing date a germination test was performed to ensure the viability of germination before planting. Seedbed preparation was done early in the season. The seeds were sown with two rows of bean in-between the maize plants, which was planted with space of 140 cm apart, where as the inter-row distance between the bean plants was 40cm. The distances from either side to the maize were not equal, but they were 30cm and 70cm (Figure 3.1 and Figure 3.2) due to the practical aspects of the tractor wheels and planter alignment.

A commercial fertilizer, which was 150 kgha^{-1} of (NPK 4:2:1) was applied at 150Kg ha^{-1}. Regular weeding was carried out by hand, or hand hoe, keeping the plots virtually weed free throughout the growing season. Access tubes were installed in order to take readings for soil water using the neutron probe. Unfortunately the hailstorm that occurred on 20th march 2003 damaged the crops before crop maturity. The crops were cut on 29th march 2003.

←---------1.40m -------→←-----------1.40m-------------→

M B B M B B M

M B B M B B M

M B B M B B M

M B B M B B M

M B B M B B M

←0.3m→←0.4m-→←---0.7m--→←-0.3m-→←-0.4m-→←---0.7 m--→

Fig. 3.1. Field crop arrangement of an intercropping of maize and beans with inter-row distance of 1.40m for maize and 0.40m for beans, where M = maize and B = beans

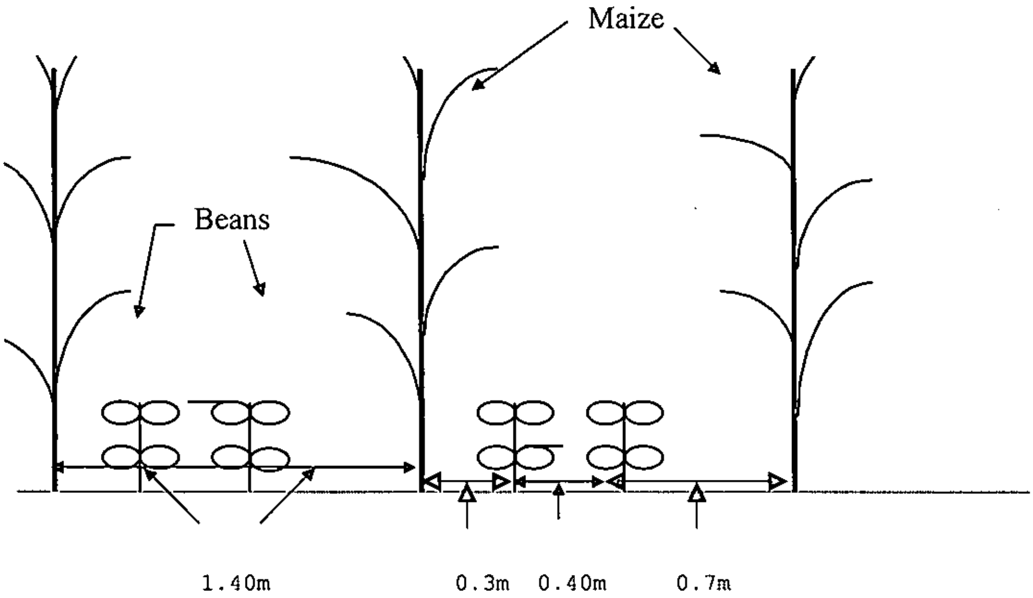


Fig. 3.2. Field crop arrangement of an intercropping of maize and beans with inter-row distance of 1.40m for maize and 0.40m for beans

B. Micrometeorological measurements

The necessary meteorological measurements, such as net radiation (using Q7.1 net radiometer), dry bulb temperature (thermocouples) and wet bulb temperature (thermistors), were measured at two levels, the first level was just above the maize canopy, and the second level was one meter above the first level. Measurements of air temperature, wet bulb temperature, net radiation and soil heat flux density were made at regular intervals of 10 minute, and recorded with a Campbell Scientific CR10X data logger. The stored data were subsequently transferred to a PC for analysis. Energy balance components were then quantified during certain stages of the growing period.

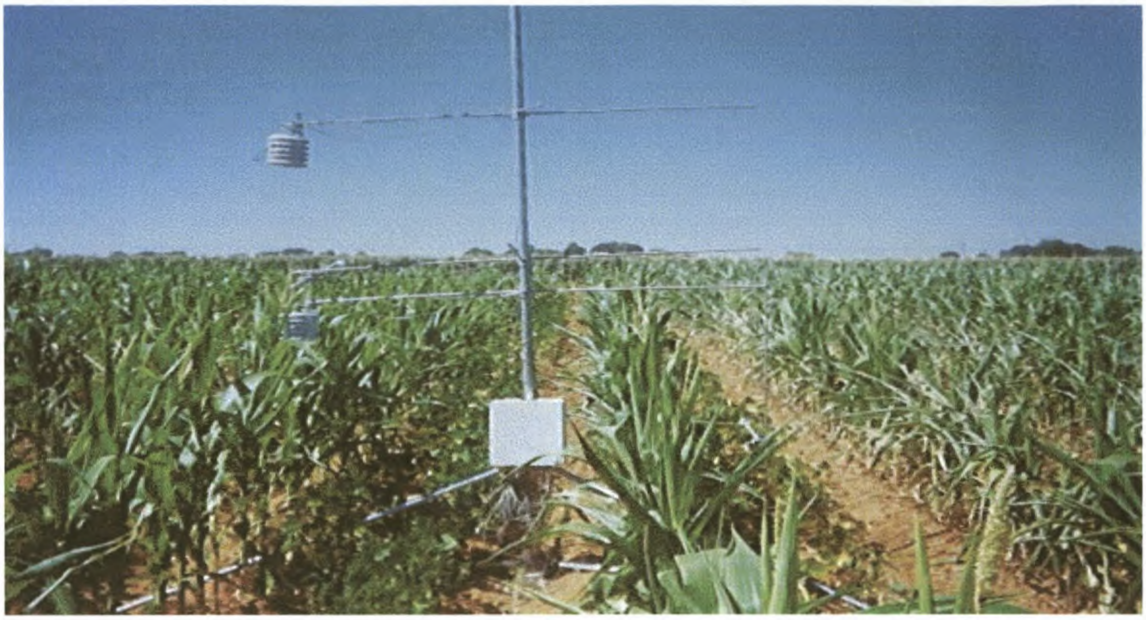


Fig. 3.3 Placement of micrometeorological instruments above Maize-bean intercropping at the Bainsvlei soil science experimental site (6 weeks after planting during the 2003 season)

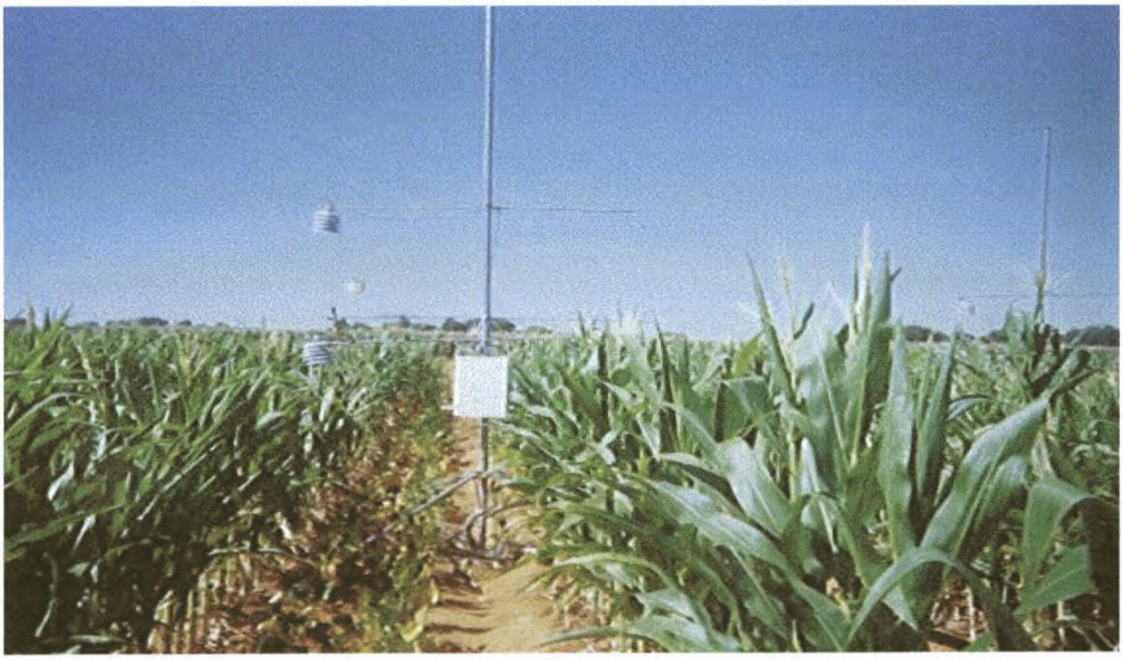


Fig. 3.4 Placement of micrometeorological instruments above Maize-bean intercropping at the Bainsvlei soil science experimental site (8 weeks after sowing during the 2003 season)

C. Phenology

Different plant developmental phases were also monitored during the specific period of the growing season. This was done to monitor the response of crop development to air temperature. Thermal time was calculated during the growing period to describe the heat energy received by the crop over a given time period.

3.1.2 Agronomic information

The experiment was carried out on a sandy loam soil Bainsvlei Amalia, which represents a good dryland soil in South Africa (Soil Classification Working Group, 1991). The general physical properties of the soil are summarized in Table 3.3.

Table 3.3. Particle size distribution and bulk density of the soil profile at the experimental site (Ibrahim, 2003)

Depth (mm)	Sand (%)				S (%)	C (%)	Texture	Bulk density gcm^{-3}
	Co	M	F	T				
0-200	0.4	6.8	63.8	91	4	5	Sand	1.64±0.05
200-400	0.4	7.7	78.9	87	2	11	Loamy sand	1.72±0.07
400-600	0.3	5.5	70.2	74	6	20	Sandy loam	1.62±0.04
600-800	0.4	5.5	72.1	76	6	18	Sandy loam	1.58±0.05
800-1000	0.2	4.8	73.0	76	4	20	Sandy loam	1.64±0.06
1000-1200	0.3	4.8	73.9	78	4	18	Sandy loam	1.67±0.08
1200-1400	0.3	5.4	71.3	76	4	20	Sandy loam	1.68±0.08
1400-1600	0.2	2.8	73.0	76	4	20	Sandy loam	1.71±0.04

Co=Coarse M=Medium F=Fine T=Total sand % S=Silt C=Clay

3.2 Measurement of Solar Radiation

3.2.1 Net radiation

Net radiation was measured during the growing period starting from day of year 47 to 100 using the REBS Q7.1 Net radiometer, which has sensitivity to wavelengths from 0.25 to 60 μm. The net radiation was measured just above the maize canopy. Net radiation above a stand of vegetation, (R_n), as defined by Ross (1975), as the algebraic sum of incoming short-wave and long-wave radiation less the reflected short-wave and long-wave radiation emitted by the stand and R_n can be calculated as follows:-

$$R_n = S_t - \alpha S_t + L_d - L_u \qquad 3.1$$

Where R_n - net radiant flux density
S_t - incoming short-wave radiation
αS_t - reflected short-wave radiation
L_d - incoming long-wave radiation
L_u - emitted long-wave radiation

3.3 Measurement of the Soil Heat Flux Density

Soil heat flux density was measured from day of year (DOY) 47 to 100 using the soil heat flux density plate. The soil heat flux density plate uses a thermopile to measure temperature gradients across the plate. The heat flux density plate was placed horizontally at a depth of 8cm below the surface to measure the soil heat flux density in the surface layer of the soil.

The soil heat flux density at the surface is normally calculated by adding the measured flux at a fixed depth, to the energy stored in the layer above the heat flux density plates. The specific heat of the soil and the change in soil temperature, over the output interval are required to calculate the stored energy.

The calculation of soil heat flux density requires site specific inputs for the bulk density, mass or volume basis soil water content, and the specific heat of the dry soil bulk density and mass basis soil water can be found by sampling (Klute, 1986).

In a field experiment Hanks and Ashcroft (1980) measured the volumetric soil water content to determine heat capacity of soil, by the CS615 water content reflectometer. A value of $840 JKg^{-1}K^{-1}$ for the heat capacity of dry soil was found to be reasonable value for most mineral soils.
In this experiment calibration of soil heat flux density plate was not done due to some technical difficulties. Instead existing calibration coefficients were used from previous experiment in which 35.6 mV is equal to 1 Wm^{-2} i.e. $Y = 35.6 \times X$. where Y is the soil heat flux density in Wm^{-2} and X is the soil heat flux density plate reading in mV (Kuschke, 1998).

3.4 Calibration of Thermocouples and Thermistors

Thermocouples and thermistors, which were used to measure dry and wet bulb temperature in this experiment, were calibrated in a temperature controlled water bath. One end of the sensor lead was connected to a CR10X Campbell

Scientific Inc. datalogger and the other end was put in a water bath that was set to a known temperature. For every change in temperature of the water an adequate time was given to stabilize and equilibrate the water thoroughly to the desired temperature. The readings were taken for the temperatures starting from 0°C to 50°C at 5°C increments. The voltage readings were recorded every 1 minute for 20 minutes at each temperature interval. The readings recorded by the datalogger were then downloaded using a laptop computer and transferred into a spreadsheet. Finally the readings and their corresponded temperatures were made into a calibration regression line to get the calibration coefficient. The coefficients obtained from the regression were used in the programme to calculate temperatures.

The Bowen ratio technique requires measurements of air temperature and water vapour pressure at two vertical points (separated by a distance of 1 m) above the canopy.
The wet bulb and dry bulb temperature measurement could be easily affected particularly by solar radiation. Therefore the measurement was typically done within a shield but at the same time allowing for adequate ventilation.

3.5 Crop Evaporation (ETc) Calculassions

Hourly evapotranspiration was calculated using the FAO updated procedure for computing reference (ETo) and crop evapotranspiration from meteorological data and crop coefficient (Allen *et al.*, 1998). The ETo obtained using this method incorporates only the effects of the climatic conditions. This can be represented as an index of atmospheric demand. Therefore ETo represents the atmospheric evaporative demand only, whereas Kc varies predominantly with the specific crop characteristics and only to a limited extent with climatic factors. Thus as it is noted by Allen *et al.*, (1998) this enables the transfer of standard values for Kc between locations and between climates.

Kc values for different growing stages were calculated by integrating the Kc values of each individual crop, taken from existing values, and their ratio of ground cover of each crop.
The calculation was done using the following formula (Allen *et al.*, 1998):

$$Kc_{field} = \frac{f_1h_1Kc_1 + f_2h_2Kc_2}{f_1h_1 + f_2h_2} \qquad 3.2$$

Where h_1 height of maize
h_2 height of bean
f_1 ratio of ground covered by maize
f_2 ratio of ground covered by bean
Kc_1 Crop coefficient value for maize
Kc_2 Crop coefficient value for bean

In addition to Kc a stress factor, Ks, was included in the ETc calculation. Nevertheless due to the water stress condition during the growing period a soil water stress coefficient (Ks) was calculated from the soil water measurement to correct the ETo. To determine the field capacity and wilting point, certain assumptions were made. Firstly the soil water content measured just after rainfall was considered as field capacity and secondly the soil water content measured when the plants started wilting is considered as wilting point.

The following formula was used to calculate the stress factor, Ks (Allen, *et al.*, 1998):-

$$Ks = \frac{TAW - Dr}{TAW - RAW} \qquad 3.3$$

Where Ks is stress factor, Dr is root zone depletion (mm), *TAW* is total available soil water in the root zone (mm) and *RAW* is readily available water.

Readily available soil water (*RAW*) was calculated using the following equation:

$$RAW = pTAW \qquad 3.4$$

Where p is average fraction of total available soil water (*TAW*) that can be depleted from the root zone before water stress occurs (0-1).

Due to the fact that the p value depends on the crop type, a value was taken from the table presented by Allen *et al.* (1998). In this study a value of 0.55 was used to calculate *RAW* for the maize-bean intercrop.

3.6 Measuring Plant Variables

3.6.1 Dry matter production

Shoot (or above-ground) biomass was measured by cutting the plants at ground level. Plant samples were harvested at 7-day intervals from day of year 49 to 79. Eight maize plants were harvested at each sampling and eight bean plants were harvested from each row of beans with different spacing. Dry matter production was determined for both the maize and bean plants. The samples from both crops were oven-dried at 80°C for a period of 4 days and the dry mass then recorded.

3.6.2 Plant developmental stages

Plant developmental stages were monitored during the growing period. Bean development stages were determined by counting the number of nodes on the main stem beginning at the unifoliate leaf node (V1) during the vegetative stages. As in the case of reproductive stages the pod and seed characters were also described in addition to nodes.

Maize development stages such as emergency date, tassel initiation (by destructive method), and silking were also recorded. Plant development stages were monitored up to day of year 79. On this day the crops were damaged by a hail storm.

3.7 Components of the Water Balance Equation

3.7.1 Change in soil water content

Soil water content was monitored every 6 to 8 days from day of year 41 to 91 during the growing season using a neutron probe (Campbell Pacific Nuclear (CPN), model 530). Twelve access tubes were installed in the field. These were three tubes in the intra-rows and three tubes in inter-rows. Each set was then duplicated in the field. The soils at the experimental site where deep and hence, access tubes were installed to a depth of 1.8 m below the soil surface. Measurements were taken at six levels: 0 to 300 mm, 300 to 600 mm and 600 to 900 mm, 900 to 1200 mm, 1200 to 1500 mm, 1500 to 1800 mm. The average amount of soil water used by the crops was determined by taking the arithmetic mean of the twelve tubes in the plot. This method was appropriate as the roots of both maize and beans were intertwined.

Although readings were taken up to a depth of 1800 mm, due consideration was only given down to a depth of 1500 mm, as there was significant water extraction only up to this level. In field research, water use has commonly been defined as the evapotranspiration component of a water balance. Input of water to the root zone is composed of two terms, Rainfall (Rf) and Irrigation (I) although no irrigation was applied to this field. Output of water from the root zone is composed of three terms, surface runoff (R_{off}); evapotranspiration (ET), which is the sum of evaporation from the soil surface and transpiration from leaves of plants; and deep drainage (D). Their relation is expressed by the water balance equation:

$$\Delta W = Rf + I \pm D - R_{off} - ET \qquad 3.5$$

Where ΔW is the change in the amount of soil water in the root zone.

The experimental site has a relatively flat surface and well-drained soils. Thus runoff was assumed to be negligible. The exception was during one heavy torrential rainfall event where runoff was evident. Consequently there was a need to estimate the runoff during this event.

The curve number method (Soil Conservation Service, 1972), also known as the hydrologic soil cover complex method, is a versatile and widely used procedure for runoff estimation. This method includes several important properties of the surface namely the soil's permeability, land use and antecedent soil water conditions, which are taken into consideration. In this study, the runoff from the SCS (Soil Conservation Services) Curve Number model was used to estimate the runoff. This model classifies soils in three groups: soils that have got high, medium and slow infiltration. Thus based on the soil's permeability and land use, the curve number was selected from a table to estimate the runoff.

The SCS curve number equation is (SCS, 1972):

$$\frac{(Rf_{day} - 0.2S)^2}{(Rf_{day} - 0.8S)} \qquad 3.6$$

where Rf_{day} is the rainfall depth for the day (mm), S is the retention parameter (mm). Curve number (CN) for the soil. The initial abstractions, I_a, is commonly approximated as 0.2S. The retention parameter is defined as:

$$S = 25.4 \times \left(\frac{1000}{CN} - 10\right) \qquad 3.7$$

3.7.2 Neutron probe calibration

The neutron probe measuring equipment calibration was done to convert data collected into actual soil water contents. Different opinions exist as to whether neutron probe measuring equipment should be calibrated in the laboratory or in the field. What is clear though is that each soil type requires its own calibration curve (Holmes, 1966). Calibration of the neutron probe (CPN) measuring equipment was carried out by comparing CPN count ratios to volumetric soil water content determined by gravimetric method.

Conversion of gravimetric soil water content to volumetric soil water content (mm), required determination of bulk densities at the experimental site soil at different depths, which can be achieved by the clod method (Blake & Hartge, 1986). In this study a bulk density of 1.67 gcm^{-3} was used to calculate the volumetric soil water over the whole soil profile (Ibrahim, 2003; Ogindo, 2003).

Eventually the CPN count ratio was plotted against the volumetric soil water (Fig 3.3) and the calibration coefficients were calculated *via* linear regression.

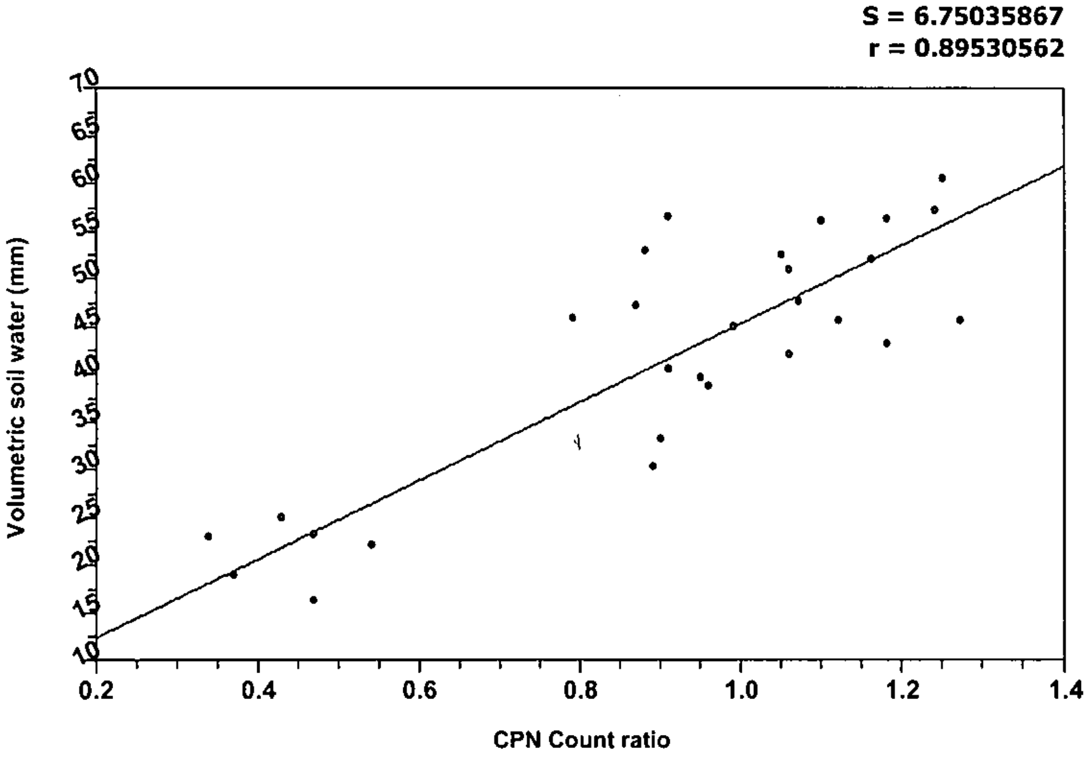


Figure 3.5 Calibration of the neutron probe carried out by comparing readings obtained by the probe with simultaneous volumetric soil water content, θ_w, (%) determined by gravimetric method

The linear fit is given by: $\theta_w = a + bx$

Where: a is the intercept

x is the count ratio

b is the slope (regression coefficient)

r^2 is the coefficient of determination.

Coefficients:

$a = 5.97 \quad b = 39.42 \quad r^2 = 0.73$

Regression Equation: $\theta_w = 5.97 + 39.42*\text{CPN count ratio}$

3.8. Bowen Ratio Energy Balance Calculations

According to the energy balance equation, the energy of net radiation, R_n, is partition by three processes such that:-

$$R_n = G + \lambda E + H \tag{3.8}$$

where R_n is the net radiation, H is the sensible heat flux density, G is heat flux density by conduction and λE the latent heat flux density. The storage term will be considered as negligible.

The partition of energy between sensible (H) and latent (λE) heat flux density is obtained by the Bowen ratio energy balance method (Tanner *et al.*, 1987). The Bowen ratio was calculated using equations 2.2, 2.3, 2.4, 2.5 and 2.6 mentioned in chapter two.

3.9 Statistical Analysis

Latent heat flux density obtained from the updated procedure presented by FAO (Allen *et al.*, 1998) for computing crop evapotranspiration and from Bowen ratio technique were compared using univariate, regressing, and mean difference statistics given by Willmott (1982 & 1984).

The root mean square difference, RMSD, was calculated by

$$\text{RMSD} = [\, n^{-1} \sum_{i=1}^{n} (Pi - Oi\,)^2 \,]^{1/2} \qquad 3.9$$

Where n is the number of hourly observations, and Pi and Oi are hourly observations of the two estimated variables being compared. The RMSD is a conservative absolute difference measurement because it is more sensitive to extreme differences (Willmott, 1984) and can be considered a high estimate of the actual average difference (Willmott, 1982). The RMSD expressed as a percentage of the two observations was used as a measure of relative difference. The index of agreement (IA) is a relative difference measure calculated with:

$$\text{IA} = 1 - \left[\frac{\sum_{i=1}^{n} (Pi - Oi\,)^2}{\sum_{i=1}^{n} (\, |Pi - \overline{O}\,| + |Oi - \overline{O}\,|\,)^2} \right] \qquad 3.10$$

where $\bar{O}$ is the mean of variable O, which is Bowen ratio ET in this study. Perfect agreement between P and O would be expressed by IA = 1 (Willmott, 1984).

CHAPTER FOUR

PHENOLOGY OF MAIZE-BEAN INTERCROP AND GROWTH ANALYSIS FOR ABOVE-GROUND BIOMASS

4.1 Introduction

Temperature controls the rate of development of plants. Plants require a certain amount of heat to develop from one stage in their life cycle to another. Theoretically, physiological time provides a common reference for the development of an organism. Physiological time is often expressed and calculated in heat units called degree days (°Cd), (Yan and Wallace, 1998).

Temperature affects many plant processes including nutrient uptake, water absorption, photosynthesis, respiration, and translocation of photosynthetic products. Development rate can be modified by several factors, such as photoperiod, soil water, solar radiation and fertility, but it is primarily affected by temperature (Baron, Shykewich and Hamilton, 1975; Cross and Zuber, 1972). As a result temperature is considered the most important environmental factor governing plant development (Barebecel and Eftimescu, 1972; Coelho and Dale, 1980). Thus determining plant phenology can be helpful in evaluation and validation of crop growth models. This in turn can assist farm managers in growing crops so that the most critical stages of growth occur during periods of favorable weather conditions (Hodges, 1991).

4.2. Maize Phenology

The accumulated growing degree-days (GDD) and days taken to complete specific development stages maize is presented in table 4.1. Duration of maize from planting to emergency was recorded as 7 days, 33 days from emergency to tassel initiation and 21 days from tassel initiation to silking. Although the measurement of net radiation was started on day of year (DOY) 47 the average net radiation from the day of measurement to tassel initiation was 1.60±0.31 MJ m^{-2}. The average net radiation during the period from tassel initiation to silking was 1.44±0.72 MJ m^{-2}.

The GDD accumulated during these development stages were 90 °Cd, 408 °Cd, and 258 °Cd respectively. The mean daily GDD for maize was 12.85±1.09 $^{\circ}Cdday^{-1}$, 12.37±1.36 $^{\circ}Cdday^{-1}$ and 12.33±1.38 $^{\circ}Cdday^{-1}$ respectively. In summing up the aforementioned results, 61 days was required to reach silking from sowing and the total GDD accumulated during this period was 757 °Cd. This result was close to those growing degree-days calculated by Stewart *et al.*, (1998) for four hybrid groups of maize. They found that in their study 748 °Cd, 710 °Cd, 651 °Cd and 595 °Cd for the different maturity groups of maize. A South African seed company (Pannar Seed Company, 2002) found that 690°Cd was required from planting to silking for the same variety as used in this study. The result found in this study was higher than the value calculated by Pannar. This shows that there was a delay in the development of the maize to complete the stages from planting to silking. Therefore there could have been some other factors affecting its development rather than temperature. The main factor that could be mentioned here was the inadequate soil water during the vegetative period.

Table 4.1 Days required for maize (cultivar SNK2147) to complete specific development stages and GDD accumulated during 2003 growing season

Stages	**Duration (days)**	**$GDD_{30,10}$**	**Cumulative GDD (from plating)**
Planting-Emergence	7	90	90
Emergency-Tassel initiation	33	408	498
Tassel initiation-Silking	21	258	757

4.3. Bean Phenology

The accumulated growing degree-days (GDD) and days taken to complete specific development stages of bean are presented in table 4.2. The time taken for the beans to complete the vegetative stages (VE-V6) was 42 days and the accumulated GDD was 513°Cd. Days taken to reach R4 (50% of plants have pods with seeds at beginning of pod filling stage) from R1 (50% of plants have at least one flower at any node) were recorded as 18 days and the accumulated GDD was 243 °Cd during that specific period. As it is mentioned above the measurement of net radiation was started late. However, the average net radiation during the period from R1 to reach R4 was 1.44±0.72 MJ m^{-2}.

The total number of days taken to reach R4 from planting were 61 days and the total accumulated GDD was 757 °Cd during the time of measurement. High Plains Regional Climate Center (2003) tried to classify various maturity groups of dry bean and found that 729.5°Cd, 775.56°Cd and 822.11°Cd for short, medium and long maturity groups respectively. These growing degree-days were accumulated from planting to R4. The growing degree-days accumulated to reach R4 in this study was close to the above figures between a short and medium variety. Therefore the bean probably was not being affected by the shading of maize or water stress.

Table 4.2 Days required for beans to complete specific development stages and growing degree-days accumulated during that period

Stages	DAP	Days	$GDD_{30,10}$	Mean daily °Cdd^{-1}	Cumulative °Cd (from planting)
VE	7	7	90	12.86±1.09	90
V1	12	5	46	9.23±0.76	136
V2	21	9	120	13.34±0.79	256
V3	30	9	121	13.46±1.43	377
V4	34	4	48	12.13±0.48	425
V5	37	3	29	9.86±1.48	455
V6	42	5	58	11.69±1.19	513
R1	47	4	64	12.95±0.60	578
R2	51	4	49	12.42±1.01	628
R3	56	5	68	13.71±0.46	696
R4	61	5	60	12.18±0.85	757

4.4 Growth Analysis for Above-ground Biomass Production

Primary production among plant communities results in accumulation of biomass with time, and the accumulation normally follows a sigmoid pattern (Gardner, Pearce and Mitchell, 1985). The primary data obtained from biomass accumulation was analyzed for its efficiencies in producing new material. This measure of efficiency is called relative growth rate normally abbreviated by the letters RGR.

Mean RGR is calculated from measurements taken at consecutive harvest dates t_1 and t_2, where dt = t_1-t_2. The relationship for calculation of RGR is derived from the standard compound interest equation (Blackman, 1919). Gardner *et al.* (1985) used the equation 4.1 to calculate instantaneous RGR: -

$$RGR = \frac{1}{W} \times \frac{dW}{dt} \quad [gg^{-1}d^{-1}] \qquad 4.1$$

where W is the initial dry mass, dW is the change in mass between two harvests while dt is the change in time.

The growth of total above-ground dry matter over time during the season was measured. Figure 4.1 shows the progress of dry matter accumulation during the vegetative period. The highest dry matter accumulation was found on DAP 54 at which time the leaf area index was 2.9. Thereafter probably due to severe soil water depletion the dry matter accumulation of maize declined. The bean with wider spacing showed slightly higher biomass accumulation than the bean with narrow spacing. This result could be due to less competition for soil water and radiation in the case of bean with wider spacing. However, statistically there was no significant difference at 95% P value. The RGR of maize and bean (with different spacing) is illustrated in Fig. 4.2. The result shows that the relative growth of maize was higher during the early stage in DAP 40. This was corresponding to the exponential growth phase (see Fig. 4.3). Figure 4.3 shows the pattern of maize growth over the growing period the data were also fitted to Richards growth model. The above-ground dray matter accumulation of maize is best fitted to the Richardson growth model and the r-value was 0.99. The function and its coefficients are also presented with the figure. This curve resulted from differential rates of growth. The relative growth rate of beans (with narrow space and wider space) was highest on DAP 55. The beans with narrow space showed higher RGR. The growth pattern of beans (with wider and narrow spacing) over the growing period is presented in Fig 4.4. The data for beans were also fitted to Richards growth model. The above-ground dray matter accumulation of bean was not best fitted to the Richardson growth model and the r-value was 0.71. The function and its coefficients are presented with the figure.

An attempt was also made to correlate the dry matter accumulation to the thermal time (see Fig. 6.5). It was found that 71.7 gm^{-2}, 178.4 gm^{-2}, 293.0 gm^{-2}, 540.0 gm^{-2} and 594.68 gm^{-2} at 425 °Cd, 490 °Cd, 578 °Cd, 683 °Cd and 757 °Cd respectively. Similarly the average bean dry matter accumulation for both spacing was 32.7 gm^{-2}, 46.5 gm^{-2}, 67.0 gm^{-2}, 212.8 gm^{-2} and 113.8 gm^{-2} at the corresponding thermal time mentioned above. These might help to predict the biomass production of maize and bean at certain growing degree-days calculated from temperature data.

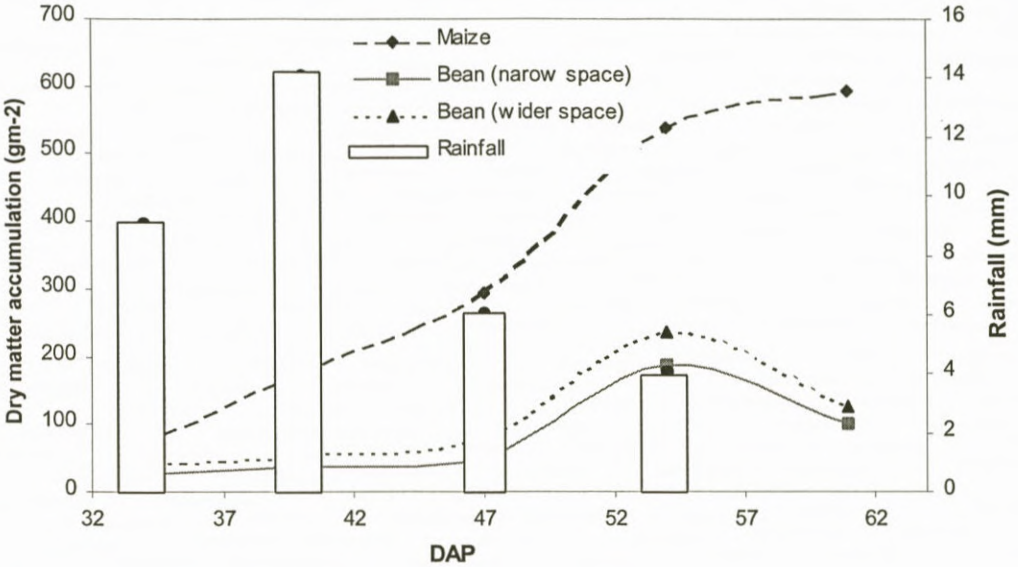


Fig. 4.1 Above-ground dry matter accumulation for maize and bean (with different spacing) and rainfall distribution during the season 2003

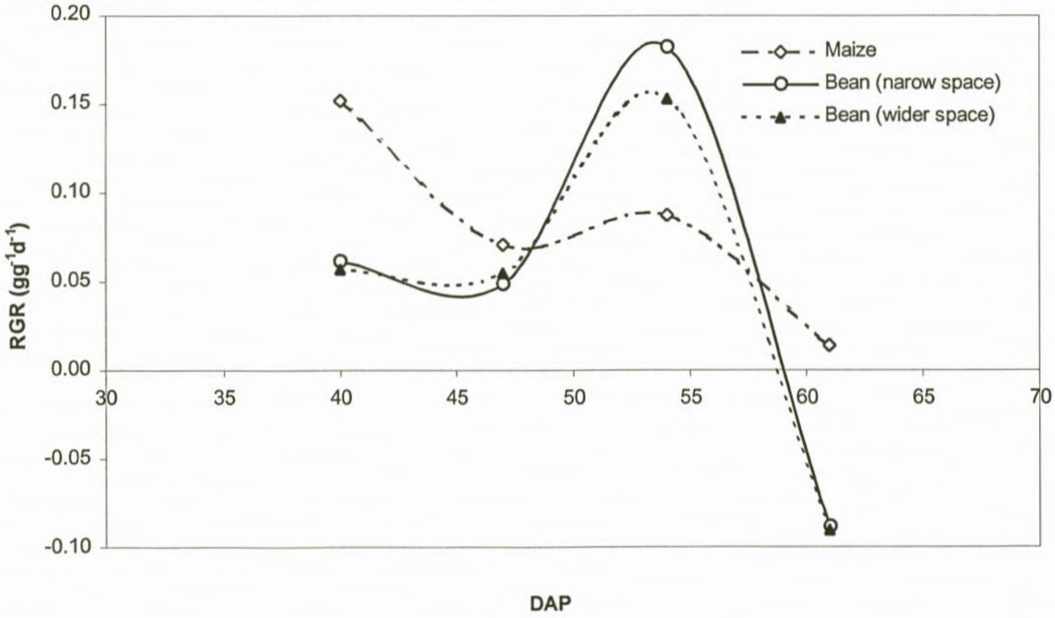


Fig. 4.2 Relative growth rates for crops based on actual above ground dry matter accumulation measurement

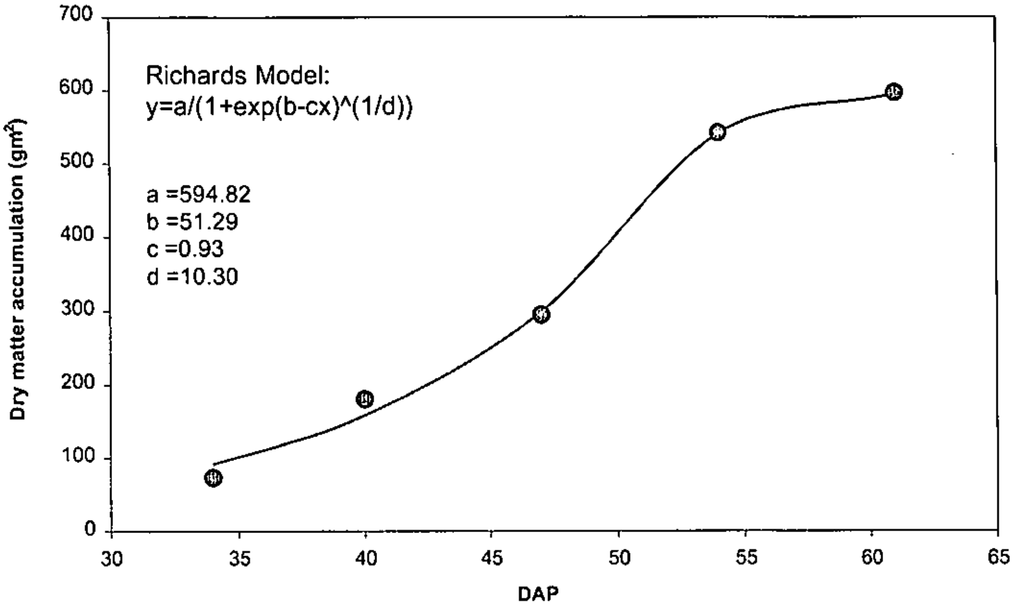


Fig. 4.3 Maize dry matter accumulation during the growing season with Richards model curve fitted line (r^2=0.99)

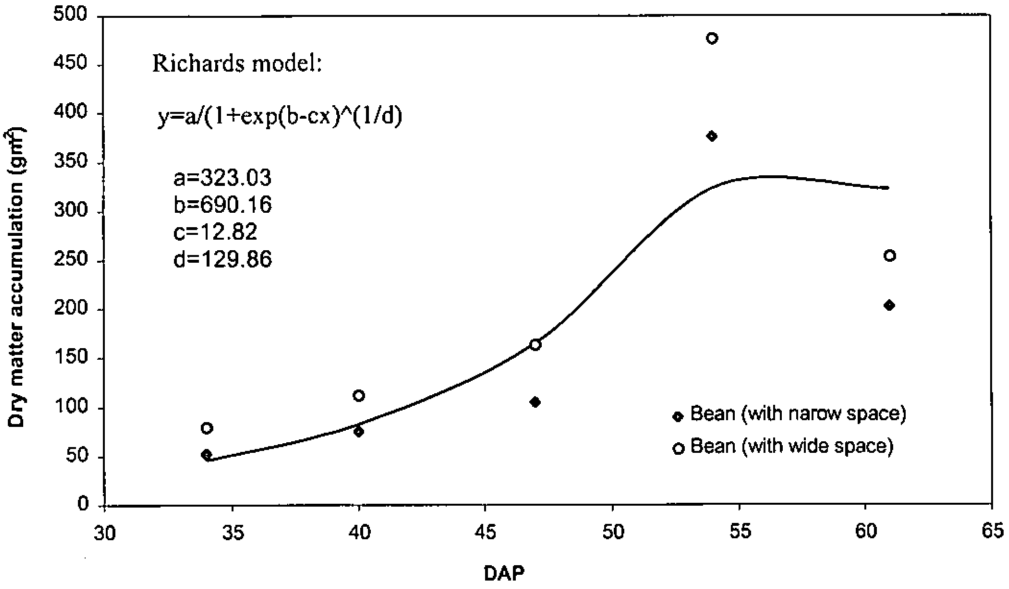


Fig. 4.4 Dry matter accumulation of bean with narrow and wider spaces during the growing season with Richards model curve fitted line (r^2=0.71), the above equation explains the growth rate of both data sets

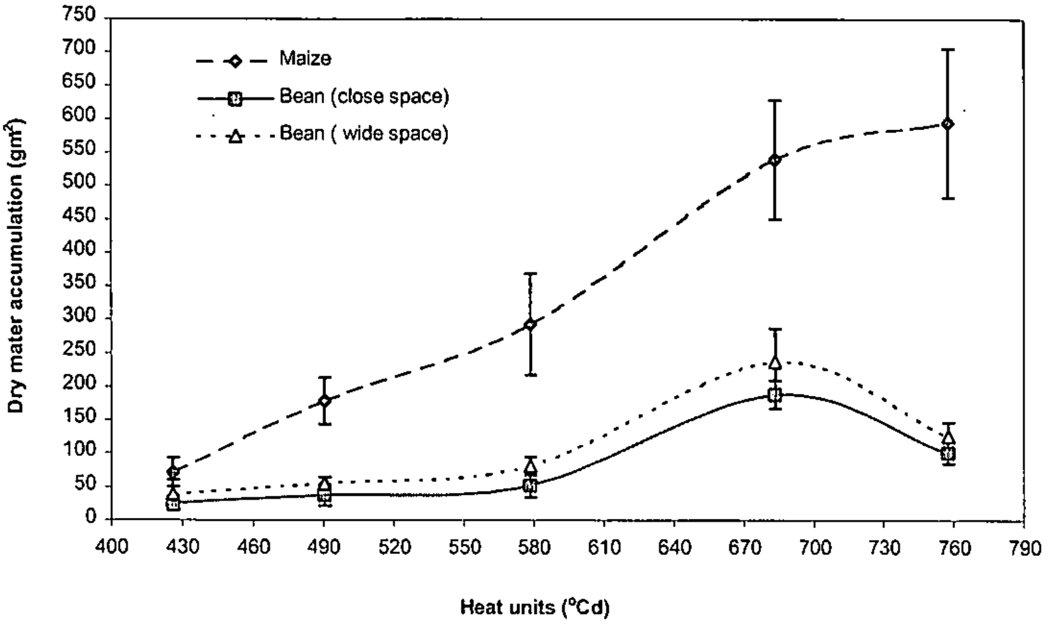


Fig. 4.5 Above-ground dry matter accumulation for maize and bean (with different spacing) versus growing degree-days

CHAPTER FIVE

COMPONENTS OF THE ENERGY BALANCE IN MAIZE-BEAN INTERCROP AND FROM BARE SOIL

5.1 Introduction

The Bowen ratio energy balance (BREB) technique is a micrometeorological method used to estimate latent heat flux density because of its simplicity, robustness, and relatively low cost (Todd *et al.*, 2000). The BREB method estimates latent heat (λE) and sensible heat (H) flux from a surface using measurements of humidity and air temperature gradients, net radiant (R_n) and soil heat (G) flux (Fritschen and Simpson, 1989). The BREB technique is an indirect method, compared to methods such as eddy covariance, which directly measure turbulent fluxes, or weighing lysimeters, which measure the mass of evaporation from an isolated soil volume with plants growing in it. This technique is based on the requirement of a relatively large amount of energy for evapotranspiration to occur, for instance 2.45 $MJm^{-2}d^{-1}$ of energy is required to evaporate 1 mmd^{-1} of water from a surface (Allen *et al.*, 1998).

It has some disadvantages, such as sensitivity to biases of instruments which measure the gradients and energy balance terms; the possibility of discontinuous data sets when the Bowen ratio approaches -1, and the requirement of adequate fetch to ensure adherence to the assumptions of the method (Todd, Klocke and Arkebauer *et al.*, 1996). Evapotranspiration is governed by energy exchange at the vegetative surface.

Thus it is possible to predict evapotranspiration rate by applying the principle of energy conservation (Arya, 1988). The Bowen ratio-energy balance method has been used to quantify water use (Malek, Bingham and McCurdy, 1990), calculate crop coefficients (Malek and Bingham, 1993), investigate plant-water relations (Grant and Meinzer, 1991; Malek, Bingham and McCurdy, 1992) and evaluate crop water use models (Farahani and Bausch, 1995; Todd *et al.*, 1996).

5.2. Components of the Energy Balance on Maize-bean Intercrop

The components of the energy balance over a maize and bean intercropped field, during specific different growth stages i.e. from DOY 47 to 78, are presented in Table 5.1, Table 5.2 and Table 5.3.

The daytime energy balance components are classified here based on the height of sensors during measurement. This is due to the fact that the sensors at different heights could experience different wind speeds. The height of the sensors was at 0.8 m, 1.05 m and 1.40 m during the different time periods. As they are shown in the tables below, the daytime components of energy balance are presented as follows: the first time period was from DOY 47-58, the second time period from DOY 59-69 and the third time period from DOY 70-79. The fourth time period was observations taken above the bare soil from DOY 90 to 100. Some of the cloudy days and those days with β approaching -1, that did not meet the quality criteria defined by Ohmura (1982), were rejected.

Selections of the diurnal variation shown by daytime (8:00-18:00) hourly energy balance components from maize/bean intercrop are presented in Fig. 5.1 (DOY 49,51,52,and 53) and Fig. 5.2 (DOY 61,64,69,and 70).

The net radiation and soil heat flux density presented in the tables below are measured values, whereas the latent and sensible heat flux density are calculated from the Bowen ratio equations.

Table 5.1 Daytime (8:00-18:00) energy balance components for a maize/bean intercrop, net radiation (R_n) and soil heat (G) flux are measured values while latent heat (λE) and sensible heat (H) fluxes are calculated from Bowen ratio energy balance method (The height of the lower level of sensors was at 0.80 m) for the period 16 to 27 February 2003

DOY	R_n (MJ m^{-2})	G (MJ m^{-2})	H (MJ m^{-2})	λE (MJ m^{-2})
47	17.25	2.26	9.86	5.11
48	11.79	1.54	7.87	2.36
49	14.96	1.94	8.40	4.59
51	16.46	2.16	7.90	6.39
52	19.38	2.54	10.75	6.08
53	20.00	2.64	10.78	6.57
57	11.40	1.49	6.56	3.34
58	17.35	2.28	10.36	4.70

Table 5.2 Daytime (8:00-18:00) energy balance components for a maize/bean intercrop, net radiation (R_n) and soil heat (G) flux are measured values while latent heat (λE) and sensible heat (H) fluxes are calculated from Bowen ratio energy balance method (The height of the lower level of sensors was at 1.05 m) for the period 28 February to 10 March 2003

DOY	R_n (MJ m^{-2})	G (MJ m^{-2})	H (MJ m^{-2})	λE (MJ m^{-2})
59	13.53	1.78	8.03	3.72
60	18.80	2.47	10.98	5.35
61	17.76	2.33	10.67	4.76
64	18.33	2.41	8.79	7.13
65	17.30	2.27	8.79	7.07
66	17.00	2.23	6.69	8.08
67	16.74	2.20	7.81	6.73
68	16.57	2.18	9.06	5.33
69	16.83	2.21	6.61	8.01

Table 5.3 Daytime (8:00-18:00) energy balance components for a maize/bean intercrop, net radiation (R_n) and soil heat (G) flux are measured values while latent heat (λE) and sensible heat (H) fluxes are calculated from Bowen ratio energy balance method (The height of the lower level of sensors was at 1.40 m) for the period 11 to 20 March 2003

DOY	R_n (MJ m^{-2})	G (MJ m^{-2})	H (MJ m^{-2})	λE (MJ m^{-2})
70	15.28	2.01	6.91	6.36
72	14.14	1.86	6.10	6.18
73	15.80	2.08	6.17	7.55
76	17.01	2.24	9.87	4.91
78	3.09	0.41	1.18	1.50
79	6.45	0.85	2.61	3.00

5.2.1. Net radiation

Average net radiation inputs on the maize/bean intercrop were 1.60±0.31 MJ m^{-2}, 1.69±0.15 MJ m^{-2} and 1.19±0.57 MJ m^{-2} during the first, second and third time periods respectively. During the first time period relatively lower net radiation was recorded on DOY 48 and 57, being 1.18 MJ m^{-2} and 1.14 MJ m^{-2} respectively. This was due to the partial cloud cover at certain times during the mentioned days. For instance the net radiation on DOY 49 (see Fig. 5.1) abruptly decreased from 15:00 to 17:00 hours due to cloudiness. The net radiation inputs during the second time period had no large difference except on DOY 59 found to be 1.35 MJ m^{-2}, which also accounted for by partial cloud cover. During the third time period low net radiation was recorded as 0.30 MJ m^{-2} and 0.64 MJ m^{-2} on DOY 78 and 79 respectively. This low net radiation was due to the cloud cover for a longer time period across these days. From the hourly observations, net radiation attained its highest value of 3.40 MJ m^{-2} on DOY 51 at 13:00. As it can be seen from Fig. 5.1 and Fig. 5.2 maximum net radiation occurred from 12:00 to 13:00 on all days.

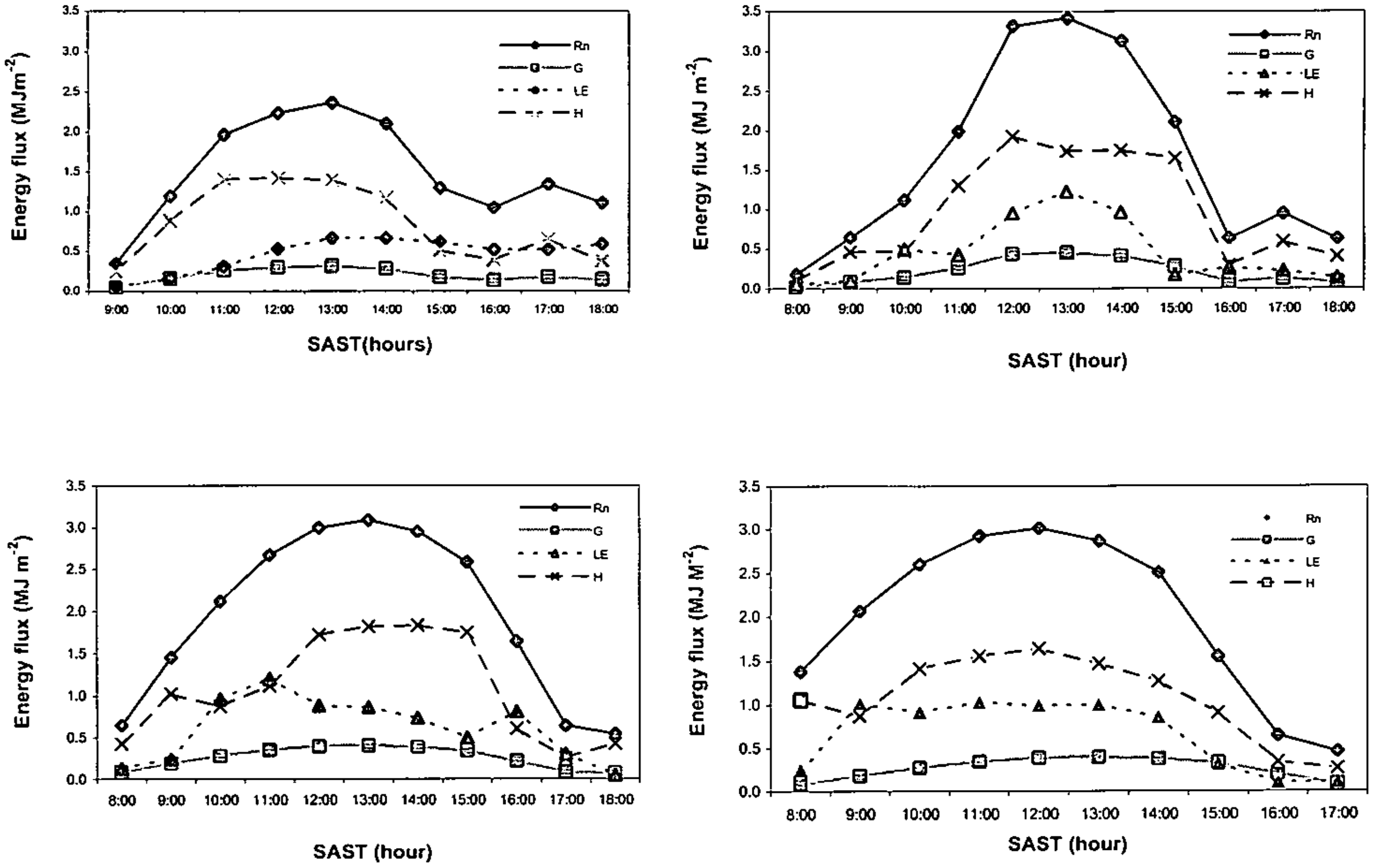


Fig. 5.1. The distribution of energy balance components in Maize/bean intercropping on different days during the growing period (DOY 49,51,52 and 53)

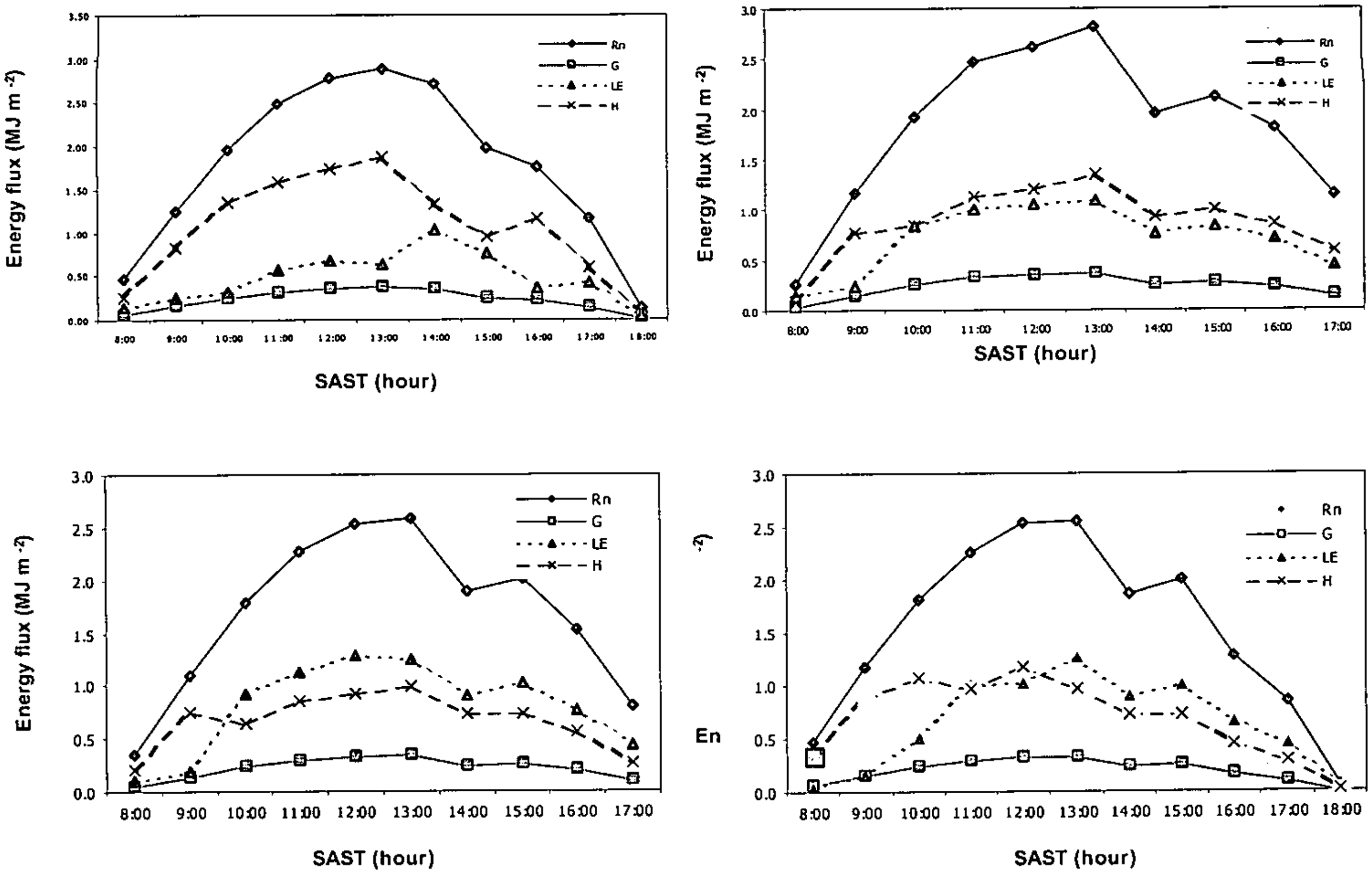


Fig. 5.2. The distribution of energy balance components in Maize/bean intercropping on different days during the growing period (DOY 61, 64, 69 and 70)

5.2.2. Latent heat flux density

The average daytime latent heat flux density from maize/bean intercrop during these times were $0.30R_n$, $0.37R_n$ and $0.41R_n$ respectively. The amount of radiation used for evapotranspiration from the cropped field was between 30 and 41%, which is relatively low. The proportion of the calculated latent heat flux density (as a function of the net radiation) from the cropped field was increasing during the growing period as the crop developed. This shows that the contribution of transpiration was higher as the plant cover became more evident and the leaf area increased. After the soil water had evaporated from the top few millimeter of the soil, there might be little further evaporation from the soil surface. However the plants were acting like a water pump by extracting the water from greater depth in the soil through their roots and it was transpired to the atmosphere.

The general trend of relatively low latent heat flux density calculated from the cropped field could be accounted for by the low soil water status, as the experiment was conducted under rainfed conditions. The experimental site received total rainfall of 213.6 mm during the growing period from DOY 16 to 79, however it must be noted that 57.6% of the rainfall occurred during the last 4 days (DOY 76 to 79). The relatively low wind speed occurred throughout the growing period, in which 66.5% of the hourly wind speed measurement was below 2 ms^{-1}. This could also have contributed to the low latent heat flux density. As a result a relatively large amount of the net radiation was spent in generating higher sensible heat flux density during the growing period. Contrary to the result found in this study, in places where there is favorable soil water, R_n generally sets the upper limit on the amount of energy consumed as latent heat. Lemon, Stewart and Shawcroft (1971), for example, report that R_n in the eastern United States during summertime radiant energy was proportioned as follows: λE (40-90%), H (10-60%), and G (5-10%). The low latent heat flux density found in this study was due to the limited of soil water available during the growing period.

5.2.3. Sensible heat and soil heat flux density

The average sensible heat flux density were $0.56R_n$, $0.50R_n$ and $0.48R_n$ during the three time periods. Although the sensible heat flux density obtained from the cropped field had no large differences the trend was in a decreasing order as the crop developed. This exhibits that the crops were generating less sensible heat as the ground cover increased.

The average soil heat flux density was 0.21 ± 0.04 MJ m^{-2}, 0.22 ± 0.02 MJ m^{-2} and 0.15 ± 0.07 MJ m^{-2}, during the three time periods respectively. This accounts for an average of 13.2% of net radiation throughout the time of measurement. There was no large difference between the soil heat flux density measured during the growing period in relation to the percentage of net radiation partitioned to soil heat flux density. This was similar to the study made by Todd *et al.* (2000), where they found that when the soil water content varied from 0.32 m^3m^{-3} by 25%, the soil heat flux density changed by less than 0.02 MJ m^{-2} for about 88% of the half-hour measurements.

Maximum latent heat flux density from the crop field in this study was recorded 396.5 Wm^{-2} on DOY 47 at 13:00 hour. In most cases sensible heat flux density were much higher than latent heat flux density during the growing period.

5.3. Components of the Energy Balance from Bare Soil

The components of the energy balance from bare soil, during the fourth time period i.e. from DOY 90 to DOY 100, are presented in table 5.4 and Fig. 5.3.
The daytime energy balance components from the bare soil are presented here separately for two reasons. Firstly, the ground cover affects the partition of net radiation and secondly due to the height of the sensors. The second reason was due to the fact that the sensors at different heights were experiencing different wind speed. The sensors were placed at a height of 0.8o m above the soil surface. The net radiation and soil heat flux density presented in table 5.4 are measured values, while the latent and sensible heat flux density are calculated from the Bowen ratio technique.

5.3.1. Net radiation

Average net radiation input during the forth time period, which was measured from the bare soil, was 1.20±0.20 MJ m^{-2}. Generally the net radiation measured from the bare soil was relatively lower than that measured from the maize/bean intercrop field. This trend could be due to the fact that these measurements were conducted after the crop was cut and it was late in the season, thus it was further from the equinox date. As a result this can be accounted for by the variation in sun's altitude during the months of measurement. The sun's altitude is usually higher during December and January and decreases toward June. The sun's altitude determines the intensity of solar radiation thereby the energy received at a specific place. The reduction is about 25% of the value measured in February for comparing clear days.

Table 5.4 Daytime energy balance components (8:00-18:00) for a maize/bean intercrop, net radiation (R_n) and soil heat (G) flux are measured values while latent heat (λE) and sensible heat (H) fluxes are calculated from Bowen ratio energy balance method (The height of the lower level of sensors was at 0.8 m) from March 31 to April 10, 2003

DOY	R_n (MJ m^{-2})	G (MJ m^{-2})	H (MJ m^{-2})	λE (MJ m^{-2})
90	13.23	1.74	5.20	6.28
91	12.01	1.58	4.73	5.70
92	13.82	1.82	5.00	7.01
93	13.76	1.81	4.82	7.13
94	7.48	0.98	-4.84	11.34
95	12.75	1.68	-2.17	13.24
96	13.64	1.79	4.32	7.52
97	12.85	1.69	2.04	9.12
98	11.16	1.47	3.53	6.17
99	12.65	1.66	4.63	6.36
100	9.25	1.22	1.50	6.54

5.3.2. Latent heat flux density

The average latent heat flux density during this time was $0.65R_n$. This indicates that the amount of radiation utilized by evapotranspiration from the bare soil was relatively larger than from the cropped field. As it has been mentioned above more than 60% that is 123.4 mm of the rainfall occurred between DOY 76 to 79. Therefore there was relatively higher soil water content during the measurements from bare soil as compared to most of the cropped field measurements. From the hourly observations, maximum latent heat flux density from the bare soil was 2.71 MJ m^{-2}.The measurement from the cropped field was stopped on DOY 80 due to the hail encountered during this day that caused the crop to be destroyed.

5.3.3. Sensible and soil heat flux density

The average sensible heat flux density was $0.22R_n$ during the fourth time period that was measured above the bare soil. The average soil heat flux density during this time period was 0.17±0.02 MJ m^{-2}, which is similar to that with the crop.

Maximum hourly sensible heat was found to be 657.8 wm^{-2} from the bare soil and minimum sensible heat from the bare soil reached -1.12 MJ m^{-2}. This is illustrated in Fig. 5.3. (DOY95) where the latent heat calculated from the bare soil was higher than net radiation received. Therefore there must have been advection of sensible heat toward the canopy

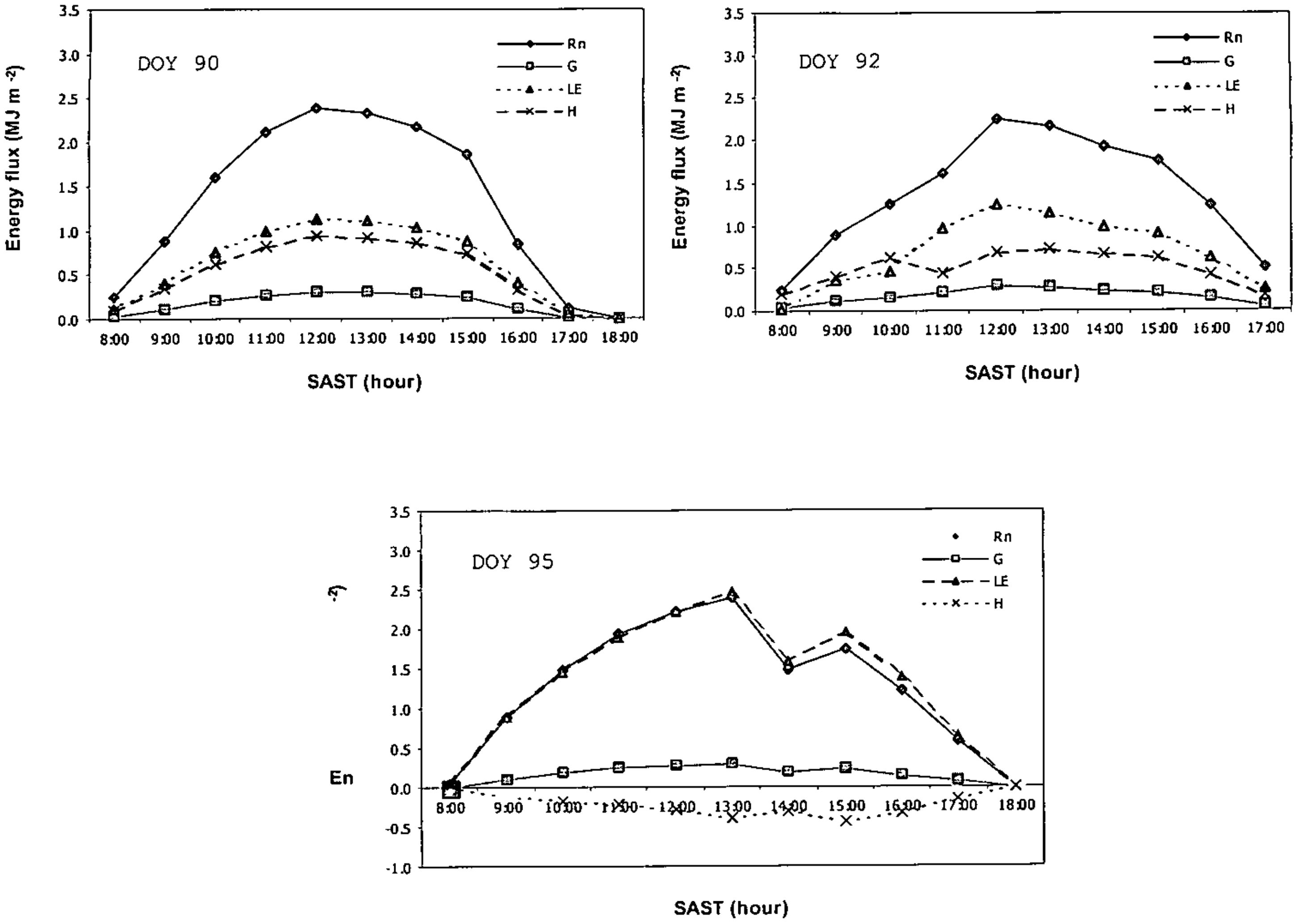


Fig. 5.3. The distribution of energy balance components in bare soil on different days (DOY 90,92 and 95)

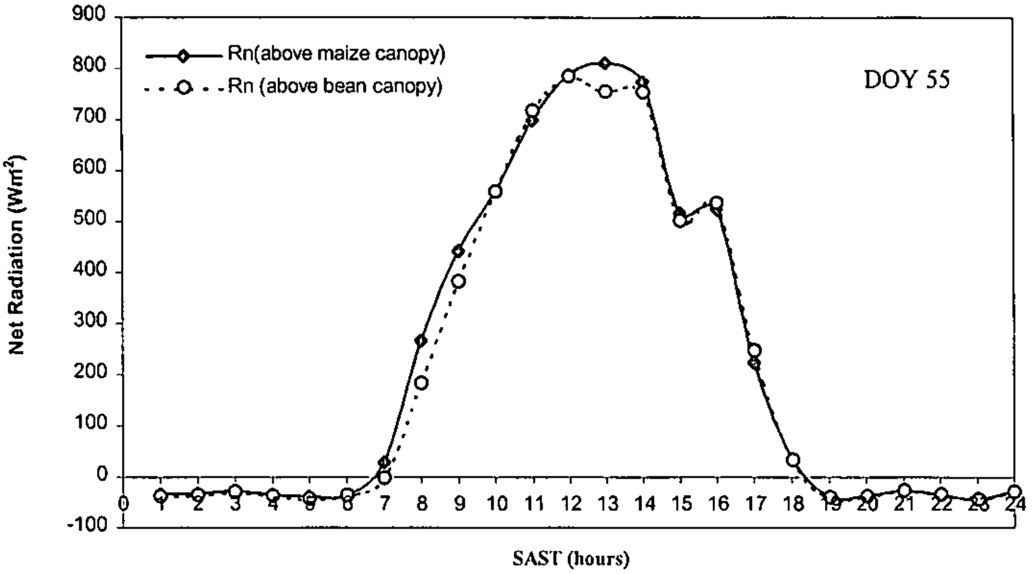
(H dropped to -1.12 MJ m^{-2}) that led to latent heat of 2.62 MJ m^{-2}, which exceeded the net radiation by 50 %. Thus it was discernible that on this particular day the evapotranspiration (latent heat flux density) utilized more than the energy received from solar radiation. A similar result was found by Todd *et al.* (2000) in which the latent heat was greater than R_n, when sensible heat was consumed rather than generated by the alfalfa field. Thus they concluded that there was a sensible heat advection from nearby fields to the alfalfa field. In contrast with the crop no advection of sensible heat flux density was observed to the intercrop field. This could be due to the size of the field used in this experiment, 120 m X 80 m, and that the two measurement levels for temperature and vapour pressure were within the adjusted surface boundary layer.

5.4 Comparison of the Net Radiation Measured above the Maize and the Bean Canopy

The hourly net radiation was measured both just above the maize and bean canopy. These measurements were taken to investigate the shading effect of the maize canopy on the bean crop, as the maize plant is taller than the bean and provides shade. To look at the magnitude and pattern of the net radiation measured at the two levels some graphs are presented in figure 5.4 and figure 5.5.

The net radiation measured above the different crops was statistically analyzed. The hourly data analysis shows that there was no significant difference between the net radiations measured at two levels. The average ratio of net radiation measured above the maize canopy to bean canopy

was 1.19:1. This might indicate that the shading effect by maize canopy was minimal. This minimal shading effect could be explained by the relatively wide space in the inter-row and the relative short height. The relatively short growing season variety of maize used in the experiment and water stress experienced during the growing season contributed to the minimal shading effect. The wilting of the plant was observed during this time. However, as the maize plants were getting taller there was a relatively larger shading effect and this can be observed on DOY 67 (see Fig. 5.5). Therefore, it could be inferred that radiation was not a limiting factor for the growth of bean during the vegetative stages and under this water stress situation.



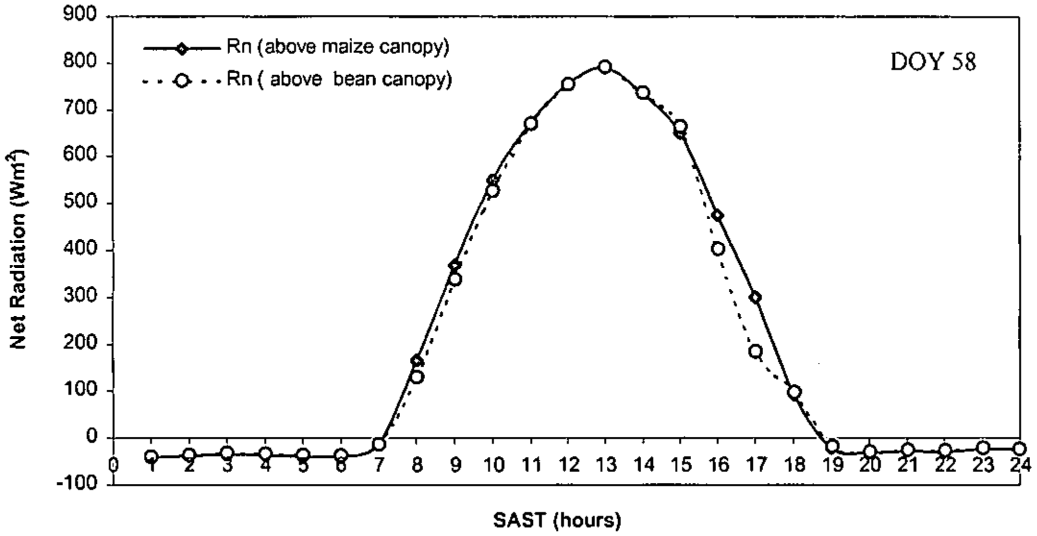
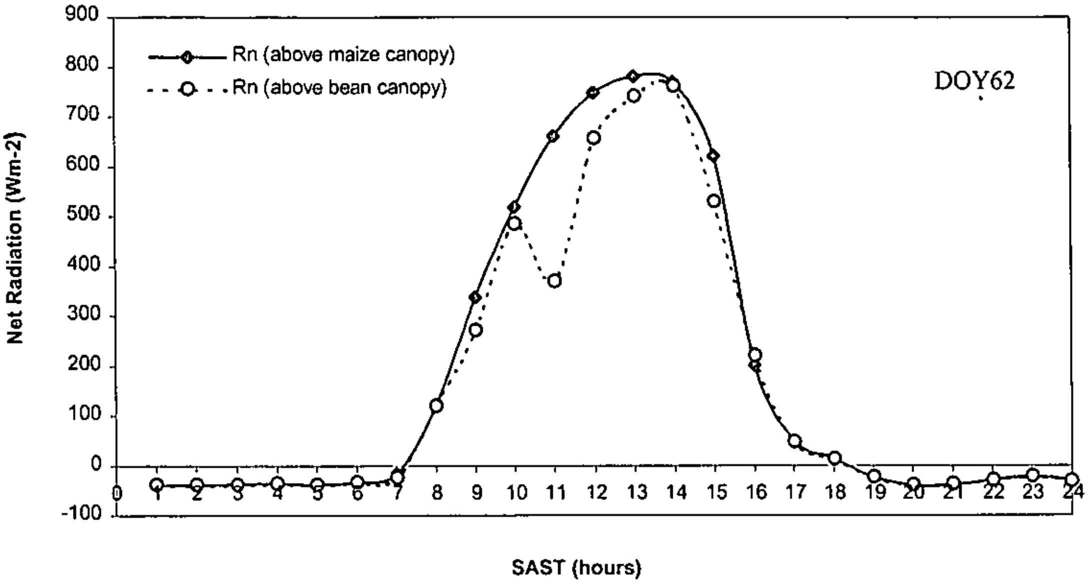


Fig 5.4 Net radiation measured in an intercropping of Maize/Bean, just above the maize canopy and bean canopy (DOY 55 and 58)



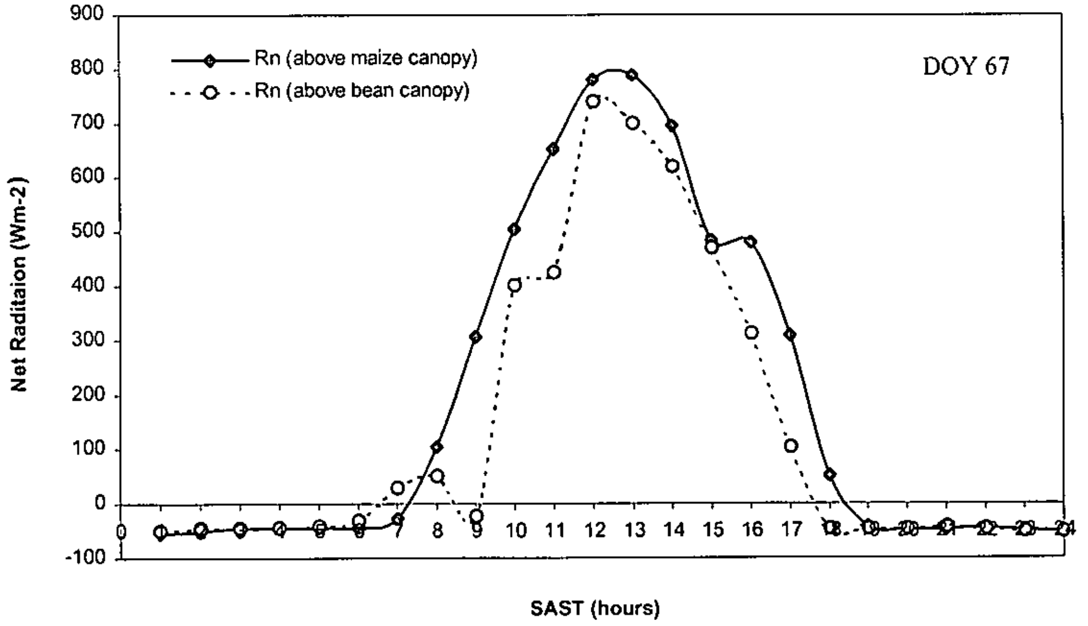


Fig 5.5 Net radiation measured in an intercropping of Maize/Bean, just above the maize canopy and bean canopy. (DOY 62 and 67)

CHAPTER SIX

COMPARISONS OF LATENT HEAT FLUX DENSITY CALCULATED FROM BOWEN RATIO AND PENMAN-MONTEITH METHODS

6.1 Introduction

Et is an important process that is controlled by the interaction of a number of environmental and biological factors (Blanken, Black, Yang, Neumann, Nesic, Staebler, den Hartog, Novak and Lee, 1997; Oren, Ewers, Todd, Phillips and Katul, 1998; Wilson and Baldocchi, 2000). Plant ecosystem parameters, such as soil water content, vegetation productivity, ecosystem nutrient and water budgets are all influenced by evapotranspiration (Linda, Lawrence and Peter, 2002). The partitioning of evapotranspiration (latent heat flux density) and sensible heat flux density at a vegetation surface also affects several aspects of weather and climate (Dirmeyer, 1994). There has been a great interest, therefore, to study evapotranspiration in a variety of plant ecosystems. This may help to better understand the nature of the controlling interactions and the performance of the different techniques used for the estimation of ET namely Bowen ratio-energy balance, Penman-Monteith and soil water balance. These methods were used to compare the evapotranspiration estimated from this maize/bean intercropping.

6.2 Comparisons of Latent Heat Flux Density.

6.2.1 Hourly Evapotranspiration

The hourly ET obtained from Bowen ratio and Penman-Monteith techniques were analyzed using t-test statistics by assuming unequal variance. The hourly observations were classified into different groups based on the height of the sensors. The heights of the sensors were changed with an increase in plant height as the crop grew. The hourly evapotranspiration observations for the Maize/bean intercrop were classified as follows: the first set was from DOY 47-58 (Fig. 6.1), the second set from DOY 59-69 (Fig. 6.2), the third set from DOY 70-79 (Fig. 6.3). Finally there were observations taken from the bare soil from DOY 90-100 (Fig. 6.4).

According to the statistical analysis in the first data set no significant difference ($P = 0.05$) was found between the hourly evapotranspiration from the Penman-Monteith and Bowen ratio methods. This exhibits that both methods produced similar result during the early growth period under relatively favorable soil water condition (Fig. 6.1). However in the remaining two sets of data taken from the intercropped field a significant difference ($P = 0.05$) was observed between the methods (Fig. 6.2 and 6.3).

The evapotranspiration estimated using Penman-Monteith was found to be relatively higher than Bowen ratio observations in the second data set. However the evapotranspiration calculated from Bowen ratio was much higher than Penman-Monteith during the third data set. This could be probably due soil water stress condition during the third time period. The reference evapotranspiration was corrected by calculating the water stress coefficient (Ks).

Similarly there was a significant difference (P = 0.05) between evapotranspiration estimated from bare soil using the two techniques (Fig. 6.4). The evapotranspiration estimated from the two techniques was not consistently larger or smaller each other, but showed large variation.

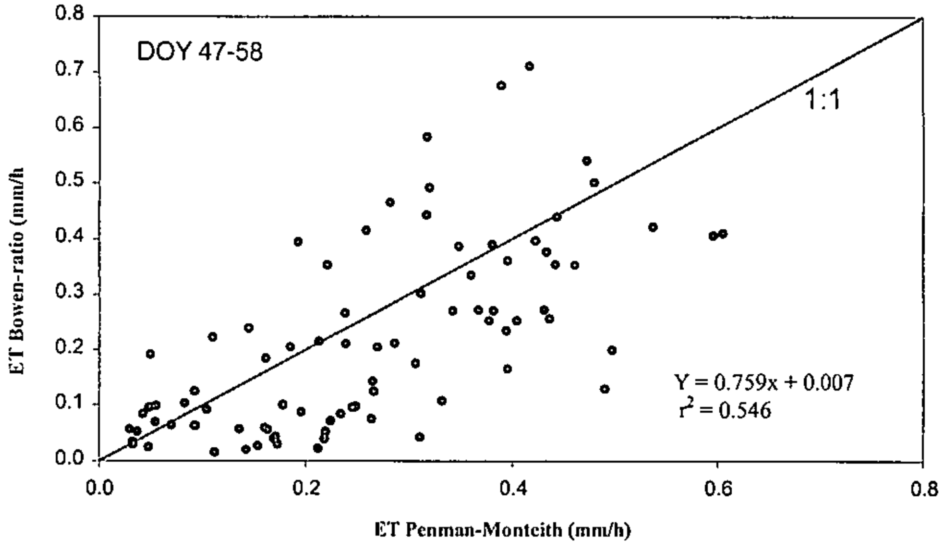


Fig. 6.1 ET calculated from intercrop in hourly time step from Penman-Monteith FAO method (Allen *et al.*, 1998) and Bowen-ratio energy balance technique for DOY 47 to 58 (n = 85)

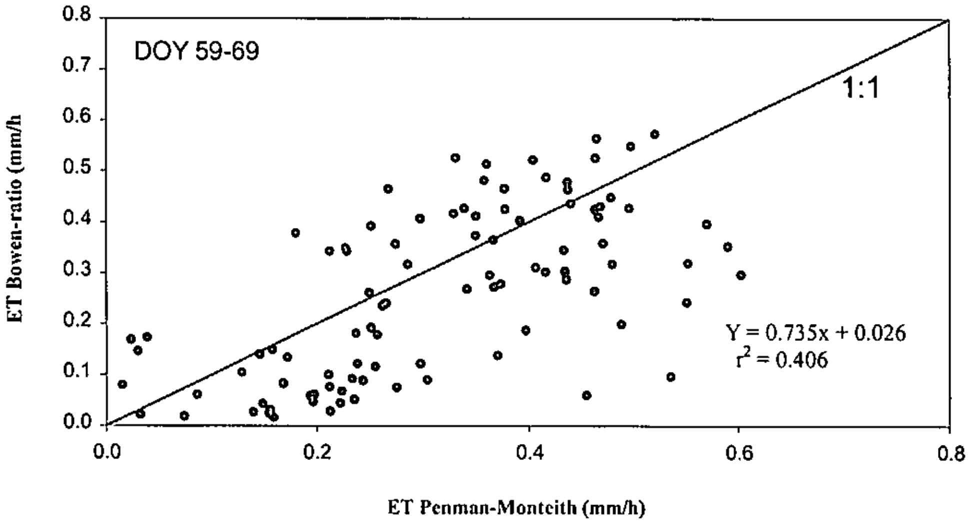


Fig. 6.2 ET calculated from intercrop in hourly time scale from Penman-Monteith FAO method (Allen *et al.*, 1998) and Bowen-ratio technique for DOY 59 to 69 (n = 96)

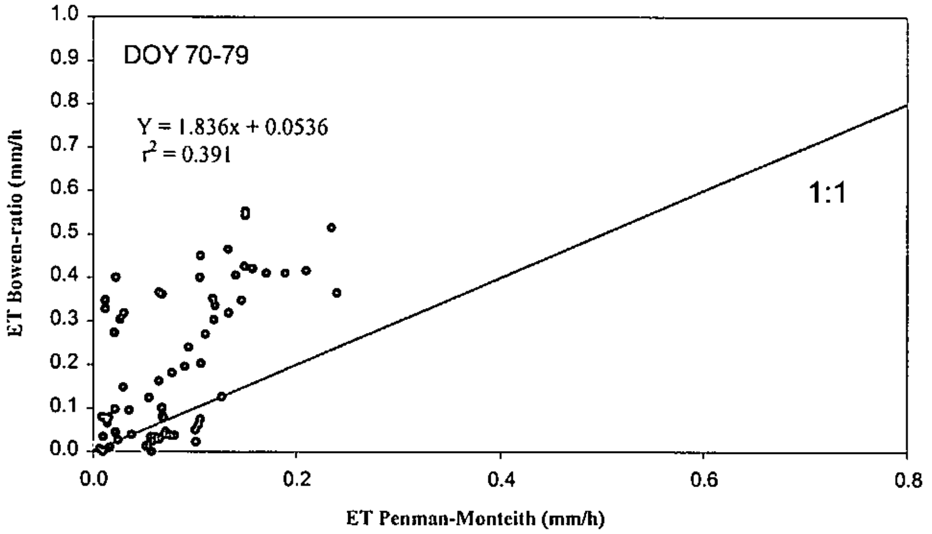


Fig. 6.3 ET calculated from intercrop in hourly time scale from Penman-Monteith FAO method (Allen *et al.*, 1998) and Bowen-ratio technique, when the crops were experiencing water stress for DOY 70 to 79 (n = 67)

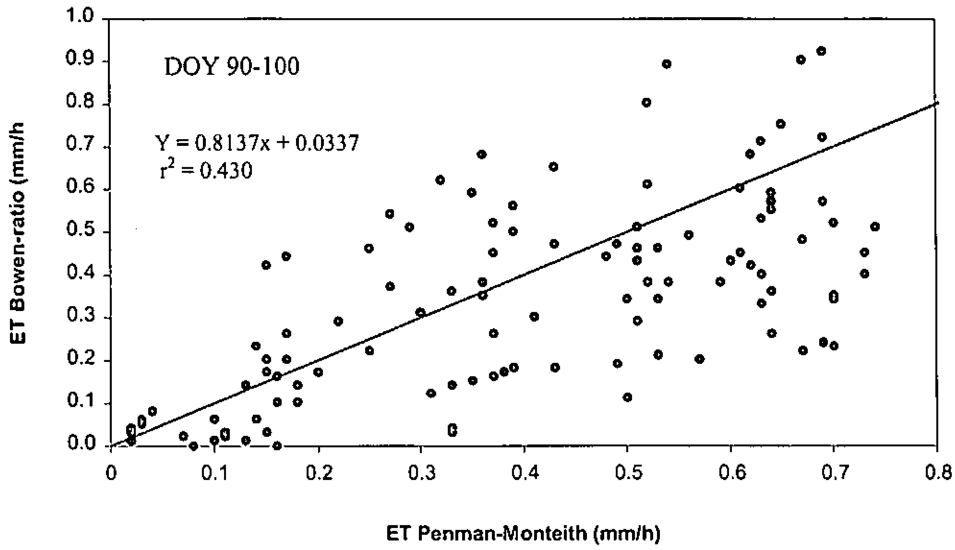


Fig. 6.4 ET calculated from bare soil in hourly time scale from Penman-Monteith FAO method (Allen *et al.*, 1998) and Bowen-ratio technique for DOY 90-100 (n = 114)

As the experiment was conducted under rainfed condition, crop water stress was evident during the growing period especially toward the end of measurement period. As a result, it became less likely that the soil would be able to supply enough water to meet the atmospheric evaporative demand that is represented here by potential ET. Therefore evapotranspiration gradually changed from being energy limited to soil water limited. This change was observed from DOY 67-78 when the difference of the crop evapotranspiration and potential evapotranspiration became significantly large.

The average hourly latent heat from Bowen ratio for dataset one was 0.52±0.40 MJ m^{-2}, dataset two 0.63±0.40 MJ m^{-2}, dataset three 0.50±0.41 MJ $m^{-2}$and dataset four (from the bare soil) was 0.92±0.65 MJ m^{-2}. Peak hourly latent heat flux density attained 1.74 MJ m^{-2}, 1.40 MJ m^{-2}, 1.35 MJ m^{-2} and 3.12 MJ $m^{-2}$for datasets one, two, three and four respectively.

6.2.2. Daily Evapotranspiration

A statistical analysis was done for the total daytime (summed from hourly data) evapotranspiration calculated from Bowen ratio, Penman-Monteith and soil water balance from the intercrop field from DOY 47 to 79. The observations are plotted against one another in Fig.6.5, Fig.6.6 and Fig.6.7.

Since the soil water content was monitored weekly the evapotranspiration obtained from the soil water balance was converted into daily evapotranspiration by multiplying the ratio of daily evapotranspiration from Penman-Monteith to its corresponding weekly evapotranspiration. Therefore the evapotranspiration obtained from soil water balance was not independent. There was no significant difference (P = 0.05) among the daytime observations from the three methods.

The average Bowen ratio and Penman-Monteith evapotranspiration for the four data sets are presented in table 6.1.Generally evapotranspiration calculated using the Penman-Monteith method was relatively lower than evapotranspiration from Bowen ratio except in the data set three.

For the 22 days of only daylight hours measurements, the cumulative Bowen ratio evapotranspiration was 55.67 mm and Penman-Monteith evapotranspiration was 56.95 mm. This exhibits that both methods might be complementary, for long period of time in the range of day or more.

Table 6.1 Sum total daylight ET from Bowen and Penman-Monteith corrected by the crop factor and stress factor during the vegetative period (DOY 47-79) and potential ET from bare soil (DOY 90-100)

DOY	**ET from Bowen ratio (mm day^{-1})**	**ET from Penman-Monteith (mm day^{-1})**
47-58	2.78±1.08	2.03±0.72
59-69	3.33±0.56	2.73±0.62
70-79	0.87±0.52	2.18±1.04
90-100	4.77±0.72	3.85±1.31

Table 6.1 shows that the mean daylight evapotranspiration during the second time period (DOY 59-69) was relatively higher than that from the other time periods calculated from the crop field using both methods. This could be due to the higher leaf area that enhances transpiration during this time period. Conversely low ET was found during the DOY 70-79 due to low availability of soil water. The value of evapotranspiration calculated from the bare soil (DOY 90-100) was larger compared to evapotranspiration from cropped field. This could be due to relatively higher soil water content during this period so that it could run closer potential evapotranspiration rates. There was free evaporation from the soil surface, as there was no ground cover and a wet surface layer of soil.

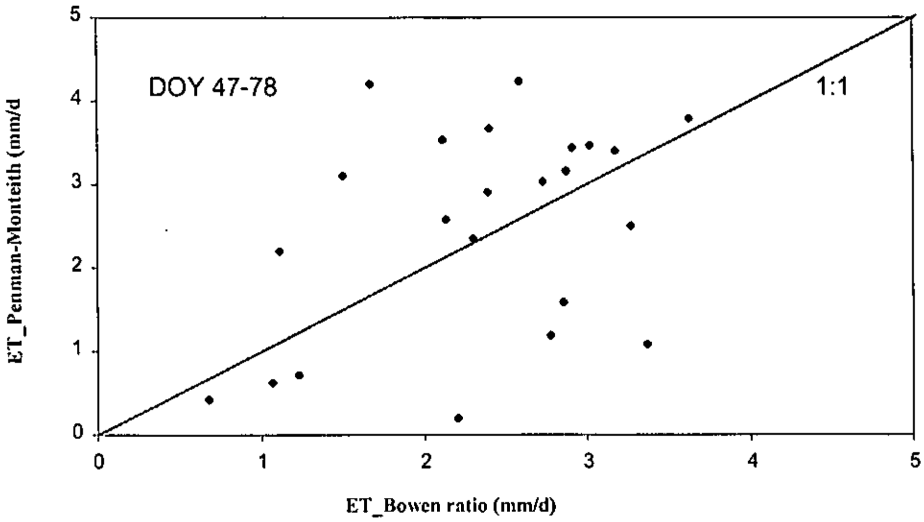


Fig. 6.5 Intercrop ET summed for the daytime (8:00-18:00) step from Penman-Monteith method (Allen *et al.*, 1998) and Bowen-ratio technique for DOY 47 to 78

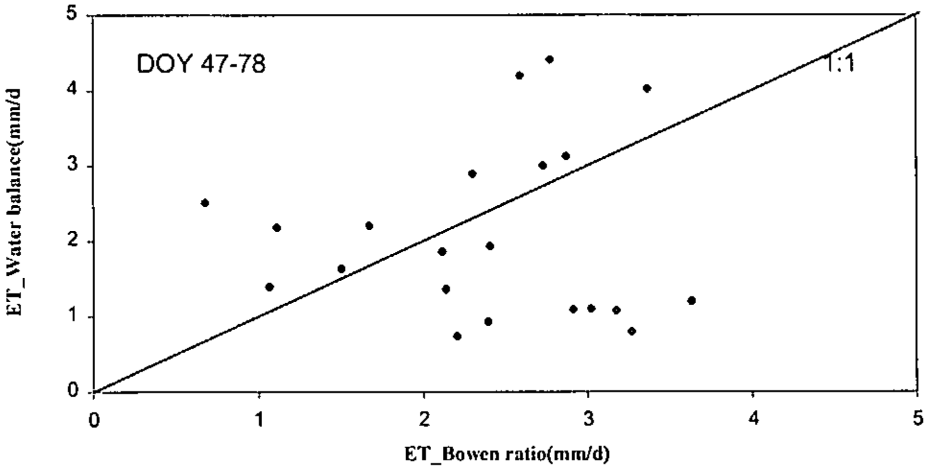


Fig. 6.6 Intercrop ET summed for the daytime (8:00-18:00) step from soil water balance and Bowen-ratio technique for DOY 47 to 78

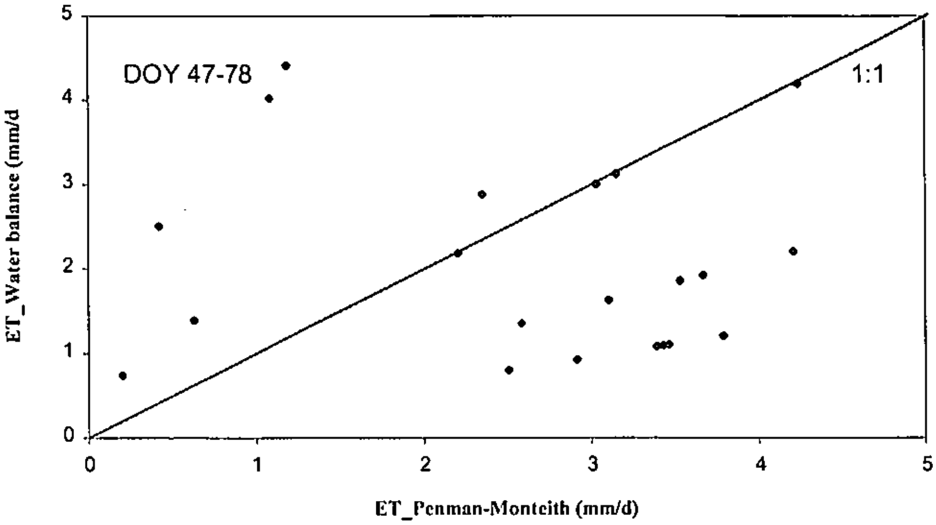


Fig. 6.7 Intercrop ET calculated in daytime (8:00-18:00) step from soil water balance and Penman-Monteith methods for DOY 47 to 78

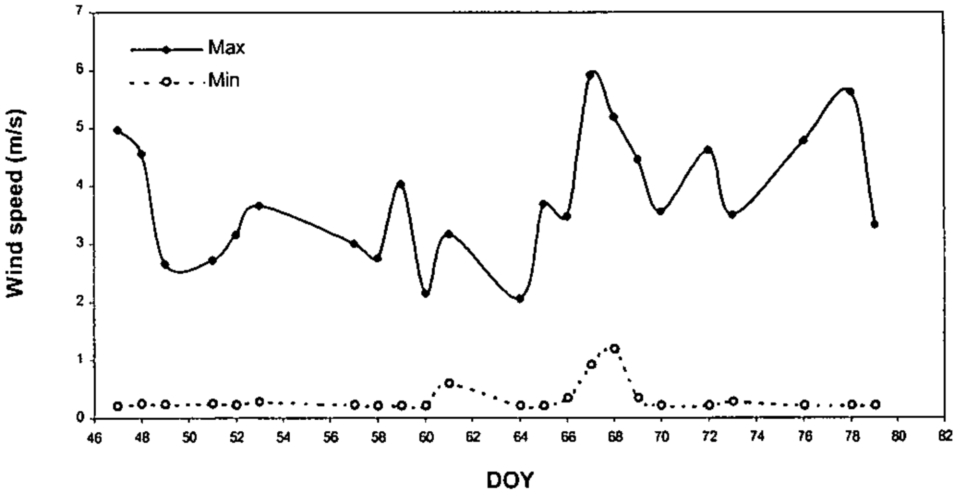


Fig. 6.8 Daily (for the period of 24 hours) maximum and minimum wind speed during the time of measurement from automatic weather station (DOY 47-79)

Table 6.2.Comparison of hourly latent heat flux estimated by Bowen ratio energy balance and Penman-Monteith (from 8:00-18:00)

DOY	n*	Bowen ratio Mean latent heat (MJ m^{-2})	Penman-Monteith Mean latent heat (MJ m^{-2})	RMSD	IA
47-58	85	0.52	0.63	0.13	0.21
59-69	96	0.63	0.76	0.14	0.24
70-79	67	0.48	0.19	0.18	0.27
90-100	114	0.78	1.12	0.29	0.30

* Number of hourly observations.

The mean latent heat flux density calculated from Penman-Monteith (λE_{FAO_P-M}) was higher than latent heat flux density calculated (λE_B) from Bowen ratio method during the first and second data sets. However it was by far lower during the third data set (DOY 70-79). This could be probably due to low availability of soil water. The soil water stress factor (Ks) was very low during this period, which was calculated from the soil water balance to correct the reference ET calculated from Penman-Monteith method. As it can be shown from table 6.2 that generally there was very low agreement between the observations obtained from the two methods.

The mean latent heat flux density estimated from bare soil was higher when compared to the latent heat flux density from intercrop field. The mean latent heat flux density from Penman-Monteith was much higher than mean latent heat flux density from Bowen ratio calculated from the bare soil. This was because of the ET calculated using Penman-Monteith from bare soil was the potential ET that represents the evaporative demand of the atmosphere.

6.3 The Effect of the Inter-row Spacing on Soil Water Extraction

The spacing between the inter-rows was not the same. The distance from the maize to the bean was either 0.4 m or 0.7 m on either side. The neutron probe access tubes were installed in-between the Maize-bean, bean-bean and bean-maize plant rows to investigate at the effect of plant spacing on water extraction. In addition, access tubes were also put into the intra-rows within the maize, bean (with 0.4 m away from maize) and bean (with 0.7 m away from maize). The soil water extraction during the growing period both in inter-rows and intra-rows are presented in Fig. 6.9 and Fig. 6.10. The readings of soil water taken from these the different plant spacing were not statistically significant, although the wider row reading do appear higher (Fig. 6.10). This could be due to the water stress during the measurement period. Besides there could have been redistribution of soil water within the soil profile.

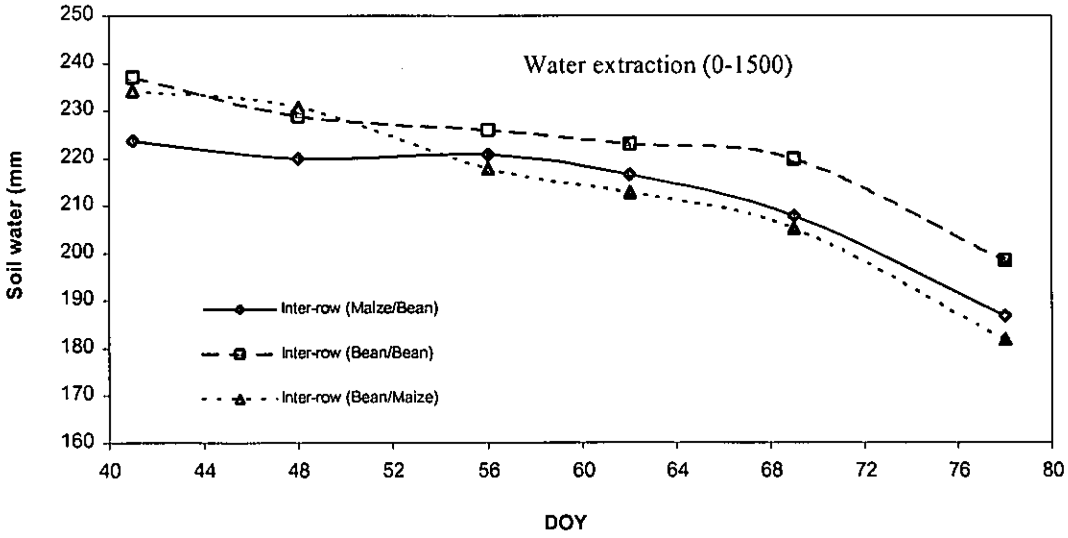


Fig.6.9. Soil water extraction during the vegetative period in the inter-row of Maize/bean intercrop

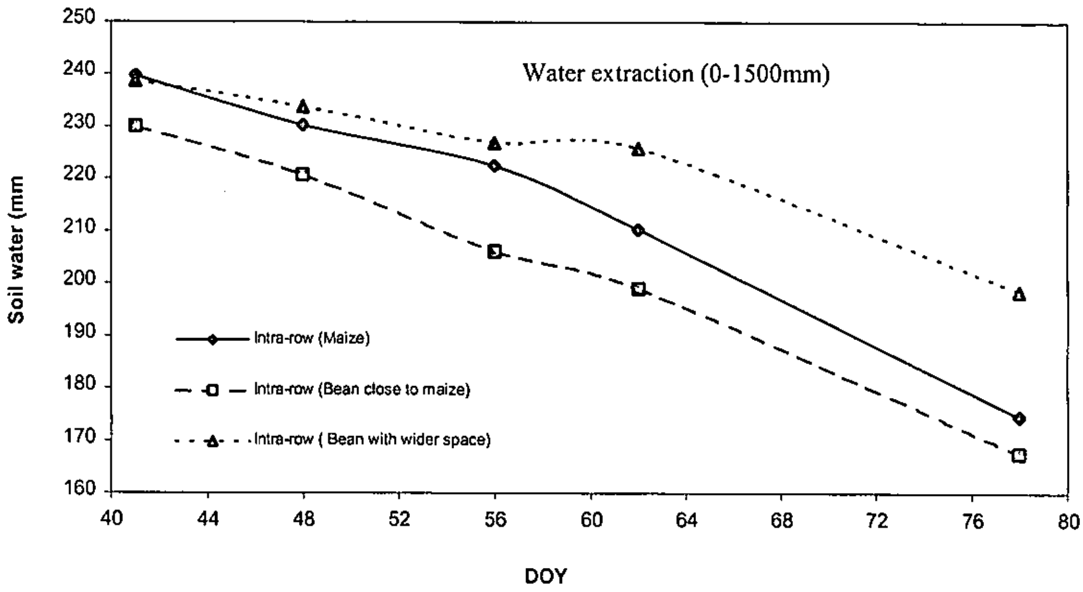


Fig. 6.10. Soil water extraction during the vegetative period in the intra-row of Maize/bean intercrop

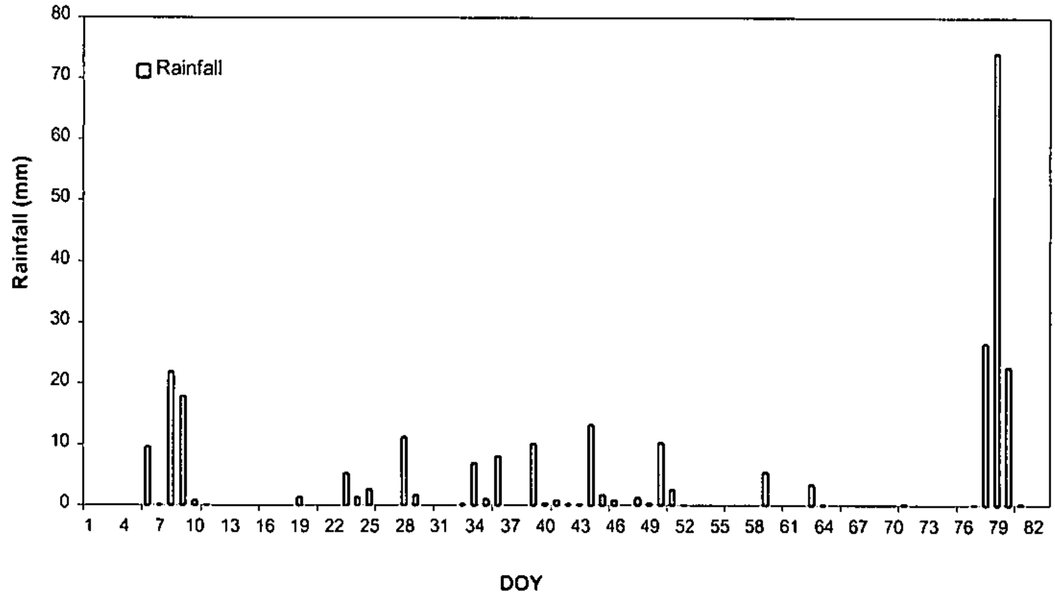


Fig. 6.11. Rainfall distribution during the growing period of 2003 (DOY 1-80)

6.4. Conclusion

A comparison of the hourly evapotranspiration calculated from Bowen ratio and Penman-Monteith methods show an inconsistent correlation. The hourly evapotranspiration calculated from both methods had no significant difference in the first time period. However there was significant difference the remaining time periods both from cropped field and bare soil. In contrast there was no significant difference in the daylight evapotranspiration calculated from the cropped field. This shows both methods could be complimentary for long time scale like a day or probably more.

Due to the fact that the spacing between the inter-rows was not the same as in the case of beans, from the investigation made to look at the effect of water extraction, the soil water measurements show that there was no significant difference between the beans planted with different spacing. This could be due to the limited water content during the time of measurement. It is also suspected that rearrangement of soil water within the soil had taken place.

CHAPTER SEVEN

CONCLUSION

An intercropping system appears to make better use of the natural resources of radiation, land, and water (Mukhala, 1998; Tsubo, 2000; Connolly, Goma and Rahim, 2001; Ogindo, 2003). Hence the study of partitioning energy balance components in an intercropping system would be important. This partition of net radiation into latent heat, sensible heat and soil heat flux density from a Maize/bean intercrop could be helpful in the study of water use efficiency, crop water relations in addition to evaluation and validation of crop growth models. Generally the net radiation utilized by ET was small during the vegetative period. A larger proportion of the net radiation was expended in generating sensible heat flux density. Thus it was evident that the rate of ET was limited by inadequate soil water rather than by the availability of radiation energy.

Bowen ratio and Penman-Monteith could be complementarily in estimating ET for a time scale of a day or more. Although it was found that hourly ET estimated from each method was not significantly different in the first time period during which there was adequate soil water. The two methods need to be studied under conditions of adequate soil water content.

This study exhibits that the Bowen ratio technique requires a simple measurement of temperature and vapour pressure at two levels. Although measuring net radiation requires relatively high cost equipment. Besides it avoids any requirement of information about aerodynamic characters. Moreover this technique enables one to estimate fluxes on a fine time scale of less than an hour. Though during rainfall, cloudy days, and when the Bowen ratio approach to -1 there was a discontinuity, which could be mentioned as a disadvantage of the technique.

Bennie, Strydom and Very (1994) observed that bare soil evaporation during fallow period could amount to 60-70% of rainfall. This was observed under similar conditions to this experiment, that is, in a semi-arid area of South Africa. Higher ET rate was found from bare soil as compared to ET from intercropped field. Although the soil water content during the measurement from the bare soil was relatively higher than from the cropped field, due to higher available soil water following the hail storm, the result found in this study was similar to the observation mentioned above.

This experiment was conducted under rainfed condition. Thus taking into account the variability of rainfall further studies should be made on similar cropping system if a general conclusion is to be made.

Although temperature controls the development rate of plants there are also some other factors that affect its development (Hodges, 1991; Wallace and Enriqueze, 1980). This study reveals that there was delay in the development of maize to reach silking even if it had accumulated the required growing degree-days as found by Pannar Seed

Company (2002). Therefore there could have been some other factors affecting its development rather than temperature. The main factor that could be mentioned here is the inadequacy of the rainfall during the vegetative period. Thus predicting development rate of maize could be possible by the growing degree days required if there are no other limiting factors beside temperature. Where as in the case of the bean development it was found to be similar with the growing degree-days reported by High Plains Regional Climate Center (2003) for short and medium maturity variety. Thus the development of bean was not hampered by the competition involved in intercrop for radiation nutrients and water.

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APPENDICES

APPENDIX I

Table A1. Daylight time ET (summed up from hourly) from maize/bean intercrop using the two methods (Penman-Monteith(PM), Bowen ratio energy balance and by soil water balance methods).

DOY	P-M ET (ETo) (mm/day)	P-M ET (ETc) (mm/day)	ET(Bowen ratio) (mm/day)	Water balance ET(mm/day)
47	4.53	2.35	2.30	2.89
48	1.21	0.63	1.06	1.40
49	4.25	2.19	1.88	2.39
51	6.08	3.15	2.87	3.41
52	5.85	3.03	2.73	3.28
53	6.06	4.10	2.68	3.40
57	4.55	3.10	1.50	1.55
58	5.80	3.39	2.94	1.98
59	6.01	4.20	1.67	1.97
60	5.53	3.67	2.40	1.89
61	4.17	2.58	2.14	1.42
64	5.69	3.43	2.91	1.19
65	6.02	3.40	3.18	1.27
66	6.21	3.79	3.63	1.57
67	6.36	3.47	3.02	1.61
68	5.94	2.91	2.39	1.50
69	6.07	2.5	3.27	1.45
70	5.39	1.59	2.86	3.35
72	6.81	1.19	2.78	4.23
73	6.54	1.14	3.39	3.86
76	1.10	0.20	2.20	0.71
78	2.32	0.42	0.68	2.67
79	3.99	0.71	1.22	1.49

Table A2. Daily ET calculated from bare soil using the two methods (Penman-Monteith and Bowen ratio energy balance methods)

DOY	P-M ET (ETo) (mm/day)	ET(Bowen) (mm/day)
90	4.54	3.25
91	4.79	2.95
92	3.26	3.41
93	4.65	3.35
94	5.17	5.86
95	4.64	6.84
96	4.36	3.55
97	4.84	4.28
98	3.20	2.90
99	4.58	3.43
100	3.92	3.07

Table A3. Soil water content measured using neutron probe during the vegetative period (M stands for maize and B stands for bean)

Depth 0-1500mm

	DOY					
	41	**48**	**56**	**62**	**69**	**78**
MB inter rows	223.60	219.97	220.76	216.57	207.72	186.73
BB inter rows	237.05	228.85	225.89	223.03	219.77	198.39
BM inter rows	234.19	230.86	217.80	212.86	205.25	181.77
MM intra rows	239.64	230.27	222.54	210.34	-	174.66
BB intra rows (close space)	230.00	220.71	206.17	199.12	-	167.61
BB intra rows (wide space)	238.74	233.86	227.01	225.97	-	198.57
Mean	**233.87**	**227.42**	**220.03**	**220.03**	**210.91**	**184.62**

Table A4. The hourly ET obtained from maize/bean intercrop using Bowen ratio (ET B) and Penman-Monteith (ETc) methods

DOY	Method	Hourly ET (mm/hour)										
		SAST										
		8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
47	ETc	0.09	0.10	0.18	0.26	0.32	0.32	0.28	0.24	0.23	0.22	0.11
	ET B	0.06	0.09	0.10	0.14	0.44	0.58	0.46	0.26	0.08	0.05	0.01
48	ETc	0.03	0.04	0.04	0.08	0.09	0.11	0.05	0.05	0.05	0.05	0.03
	ET B	0.03	0.05	0.08	0.10	0.06	0.22	0.10	0.19	0.09	0.07	0.06
49	ETc	0.05	0.07	0.09	0.21	0.34	0.38	0.38	0.28	0.24	0.14	0.00
	ET B	0.02	0.06	0.12	0.21	0.27	0.27	0.25	0.21	0.21	0.24	0.00
51	ETc	0.15	0.17	0.18	0.31	0.38	0.42	0.42	0.39	0.33	0.24	0.16
	ET B	0.03	0.04	0.20	0.17	0.39	0.71	0.40	0.68	0.11	0.09	0.06
52	ETc	0.16	0.18	0.19	0.32	0.39	0.44	0.31	0.27	0.36	0.26	0.14
	ET B	0.06	0.10	0.39	0.49	0.36	0.35	0.30	0.20	0.33	0.12	0.02
53	ETc	0.25	0.26	0.43	0.54	0.60	0.60	0.46	0.49	0.31	0.17	0.00
	ET B	0.10	0.41	0.37	0.42	0.40	0.41	0.35	0.13	0.04	0.04	0.00
57	ETc	0.21	0.22	0.22	0.39	0.50	0.44	0.39	0.40	0.16	0.14	0.03
	ET B	0.02	0.04	0.07	0.23	0.20	0.25	0.16	0.25	0.18	0.06	0.03
58	ETc	0.17	0.20	0.22	0.35	0.43	0.47	0.48	0.44	0.37	0.26	0.00
	ET B	0.03	0.09	0.35	0.39	0.27	0.54	0.50	0.44	0.27	0.07	0.00
59	ETc	0.21	0.24	0.28	0.44	0.53	0.59	0.60	0.55	0.45	0.30	0.00
	ET B	0.03	0.09	0.07	0.28	0.09	0.35	0.29	0.32	0.06	0.09	0.00
60	ETc	0.22	0.24	0.25	0.40	0.50	0.55	0.57	0.49	0.24	0.15	0.07
	ET B	0.04	0.05	0.26	0.52	0.43	0.24	0.39	0.20	0.12	0.14	0.02
61	ETc	0.09	0.13	0.17	0.26	0.37	0.46	0.46	0.41	0.16	0.04	0.03
	ET B	0.06	0.10	0.13	0.23	0.28	0.26	0.42	0.31	0.15	0.17	0.02
64	ETc	0.19	0.21	0.23	0.35	0.44	0.48	0.48	0.43	0.36	0.26	0.00
	ET B	0.06	0.10	0.34	0.41	0.43	0.45	0.32	0.34	0.29	0.18	0.00
65	ETc	0.17	0.20	0.23	0.34	0.42	0.46	0.44	0.42	0.34	0.25	0.14
	ET B	0.06	0.08	0.35	0.42	0.49	0.52	0.48	0.30	0.27	0.19	0.02
66	ETc	0.20	0.22	0.25	0.38	0.46	0.52	0.50	0.47	0.37	0.27	0.16
	ET B	0.04	0.07	0.39	0.46	0.56	0.57	0.55	0.36	0.36	0.24	0.03
67	ETc	0.02	0.21	0.27	0.38	0.44	0.47	0.47	0.43	0.37	0.26	0.15
	ET B	0.07	0.17	0.35	0.42	0.46	0.43	0.41	0.30	0.27	0.11	0.02
68	ETc	0.03	0.17	0.21	0.30	0.36	0.39	0.40	0.37	0.30	0.23	0.16
	ET B	0.08	0.14	0.34	0.40	0.48	0.40	0.19	0.14	0.12	0.09	0.01
69	ETc	0.02	0.15	0.18	0.27	0.33	0.36	0.35	0.33	0.29	0.24	0.00
	ET B	0.04	0.08	0.38	0.46	0.52	0.51	0.37	0.41	0.31	0.18	0.00
70	ETc	0.10	0.10	0.11	0.17	0.21	0.23	0.24	0.19	0.11	0.08	0.05
	ET B	0.02	0.06	0.20	0.41	0.42	0.51	0.36	0.41	0.27	0.18	0.01
72	ETc	0.07	0.07	0.06	0.11	0.13	0.15	0.16	0.15	0.13	0.10	0.07
	ET B	0.05	0.08	0.36	0.45	0.32	0.54	0.42	0.35	0.13	0.05	0.04
73	ETc	0.07	0.06	0.07	0.10	0.13	0.15	0.15	0.14	0.12	0.09	0.06
	ET B	0.08	0.16	0.36	0.40	0.46	0.55	0.42	0.40	0.33	0.19	0.02
76	ETc	0.01	0.02	0.03	0.02	0.03	0.02	0.01	0.01	0.02	0.01	0.01
	ET B	0.03	0.07	0.30	0.08	0.32	0.40	0.35	0.33	0.27	0.06	0.00
78	ETc	0.01	0.01	0.02	0.06	0.05	0.07	0.08	0.06	0.03	0.02	0.01
	ET B	0.03	0.08	0.10	0.03	0.12	0.10	0.04	0.03	0.09	0.04	0.01
79	ETc	0.02	0.06	0.06	0.08	0.10	0.12	0.12	0.09	0.03	0.04	0.00
	ET B	0.00	0.01	0.03	0.04	0.07	0.30	0.35	0.24	0.15	0.04	0.00

Table A5. The hourly ET obtained from bare soil using Bowen ratio (ET_B) and Penman-Monteith (ETo) methods

DOY	Methods	Hourly ET (mm/hour)											Total mm
		SAST											
		8:00	9:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	
90	ET_O	0.03	0.15	0.33	0.43	0.63	0.7	0.67	0.62	0.49	0.33	0.16	4.54
	ET B	0.06	0.2	0.36	0.47	0.53	0.52	0.48	0.42	0.19	0.03	0	3.26
91	ET_O	0.03	0.16	0.38	0.51	0.74	0.59	0.73	0.64	0.51	0.35	0.15	4.79
	ET B	0.05	0.16	0.17	0.46	0.51	0.38	0.4	0.36	0.29	0.15	0.03	2.96
92	ET_O	0.02	0.15	0.25	0.25	0.35	0.27	0.49	0.6	0.41	0.31	0.16	3.26
	ET B	0.01	0.17	0.22	0.46	0.59	0.54	0.47	0.43	0.3	0.12	0.1	3.41
93	ET_O	0.02	0.17	0.36	0.51	0.61	0.7	0.73	0.61	0.48	0.33	0.13	4.65
	ET B	0.04	0.2	0.35	0.43	0.6	0.35	0.45	0.45	0.44	0.04	0.01	3.36
94	ET_O	0.5	0.17	0.37	0.53	0.64	0.7	0.67	0.65	0.52	0.32	0.1	5.17
	ET B	0.11	0.44	0.52	0.34	0.55	0.34	0.9	1.23	0.8	0.62	0.01	5.86
95	ET_O	0.07	0.15	0.36	0.54	0.66	0.71	0.65	0.69	0.43	0.3	0.08	4.64
	ET B	0.02	0.42	0.68	0.89	1.04	1.16	0.75	0.92	0.65	0.31	0	6.84
96	ET_O	0.04	0.14	0.27	0.39	0.64	0.69	0.69	0.56	0.5	0.33	0.11	4.36
	ET B	0.08	0.23	0.37	0.5	0.57	0.57	0.24	0.49	0.34	0.14	0.03	3.56
97	ET_O	0.14	0.17	0.37	0.52	0.63	0.69	0.67	0.62	0.54	0.39	0.1	4.84
	ET B	0.06	0.26	0.45	0.61	0.71	0.72	0.22	0.68	0.38	0.18	0.06	4.33
98	ET_O	0.11	0.18	0.37	0.5	0.35	0.39	0.43	0.52	0.22	0.13	0	3.2
	ET B	0.02	0.14	0.26	0.34	0.59	0.56	0.18	0.38	0.29	0.14	0	2.9
99	ET_O	0.02	0.37	0.53	0.64	0.7	0.68	0.57	0.51	0.36	0.2	0	4.58
	ET B	0.04	0.16	0.21	0.26	0.23	1.27	0.2	0.51	0.38	0.17	0	3.43
100	ET_O	0.02	0.37	0.53	0.64	0.63	0.63	0.52	0.29	0.18	0.11	0	3.92
	ET B	0.03	0.26	0.46	0.59	0.33	0.4	0.38	0.51	0.1	0.02	0	3.08

Table A6. Mean daily weather variables (temperature, humidity, solar radiation and wind speed) taken from automatic weather station situated on the Bainsvlei Soil Science experimental site from 1 January to 10 April 2003

	Mean Temp.	Max Temp.	Min Temp.	Humidity	Solar radiation	Wind speed	Rainfall
DOY	°C	°C	°C	%	MJday^{-1}m^{-2}	m/s	mm
1	25.80	32.36	19.29	44.04	31.60	2.94	0
2	26.13	33.92	17.73	37.38	32.86	2.55	0
3	25.87	34.03	20.36	43.95	26.24	2.07	0
4	25.97	35.11	17.18	43.43	35.36	2.19	0
5	25.30	32.24	17.71	48.38	31.32	2.79	0
6	24.36	34.40	17.87	51.42	29.83	2.66	9.6
7	22.27	27.54	17.69	62.59	23.80	1.65	0.1
8	18.40	20.20	16.92	83.91	6.17	1.50	21.9
9	17.88	25.23	14.75	80.39	21.82	1.47	17.9
10	16.70	21.89	14.44	80.66	18.00	1.50	0.8
11	19.34	26.75	11.86	64.88	34.96	1.58	0.1
12	22.59	29.79	14.19	55.74	32.91	1.23	0
13	25.56	35.30	16.10	39.22	35.30	2.59	0
14	24.88	32.32	16.13	38.89	36.21	1.48	0
15	24.64	33.81	16.24	39.68	35.90	1.81	0
16	25.55	34.87	14.65	30.67	35.42	2.27	0
17	24.43	33.65	15.19	41.09	35.42	1.88	0
18	25.39	33.15	16.97	43.78	30.19	1.93	0
19	24.89	33.43	17.16	49.34	30.99	2.66	1.3
20	24.43	32.99	17.70	40.73	35.83	1.65	0
21	23.35	33.82	11.24	28.98	35.77	1.86	0
22	25.17	34.97	17.05	34.27	35.90	2.43	0
23	21.10	30.53	16.23	48.94	18.41	2.61	5.2
24	21.01	29.86	15.20	61.26	30.81	2.59	1.3
25	21.19	29.15	13.85	64.67	29.36	1.67	2.7
26	24.48	33.38	14.34	43.06	34.50	1.40	0
27	25.67	33.74	17.64	47.63	32.30	2.18	0
28	25.70	34.40	17.84	52.89	29.34	2.00	11.2
29	24.40	31.96	17.35	55.88	33.83	2.05	1.6
30	26.19	35.01	18.01	41.71	34.18	1.61	0
31	25.86	35.12	14.89	29.55	34.50	2.09	0
32	25.15	35.22	14.07	33.41	31.86	1.70	0
33	21.78	24.75	19.73	56.46	8.36	1.41	0.2
34	22.89	30.95	17.98	60.60	20.31	2.56	6.9
35	24.77	32.57	17.16	59.60	30.24	1.06	0
36	26.27	33.83	19.42	49.37	32.48	2.03	0
37	23.61	32.91	17.95	64.10	23.43	1.73	10.1
38	21.76	29.34	17.91	74.01	26.68	2.30	0.3
39	21.47	27.92	17.41	71.07	18.55	1.51	0.8

Continued from previous table

40	23.44	31.80	16.59	57.65	28.35	1.96	0.2
41	24.92	33.10	16.80	52.64	31.97	1.34	0.2
42	25.38	33.42	18.24	51.08	30.08	2.18	13.1
43	19.01	23.29	16.18	81.45	14.30	1.85	1.6
44	21.63	29.69	14.56	63.06	32.60	0.99	0.8
45	23.53	31.53	14.63	54.03	29.55	1.67	0
46	23.46	29.04	17.88	55.62	20.24	1.60	1.2
47	22.39	28.57	17.80	65.34	22.13	2.54	0.3
48	18.42	19.21	17.84	90.36	7.09	2.07	10.3
49	21.21	27.03	17.59	76.68	24.09	1.13	2.6
50	21.74	30.36	14.83	62.84	31.02	1.40	0.1
51	22.34	31.77	13.42	50.22	31.45	1.27	0
52	23.89	33.39	15.50	47.46	27.73	1.46	0
53	24.57	34.49	14.38	46.28	28.85	1.63	0
54	19.93	24.77	15.41	62.77	12.60	1.39	0
55	22.11	30.12	15.42	56.49	19.63	1.41	0
56	24.12	32.18	15.90	47.75	29.15	1.58	0
57	23.04	32.77	17.90	57.47	21.97	1.30	5.4
58	23.07	30.97	15.29	58.90	29.80	1.38	0
59	24.44	33.43	16.74	52.50	29.55	1.63	0
60	24.67	34.23	15.64	47.29	25.66	0.99	0
61	22.92	31.6	17.94	58.01	17.75	2.07	3.4
62	23.09	31.27	16.85	53.56	27.14	1.48	0.1
63	22.96	31.43	14.17	39.41	29.98	1.22	0
64	23.45	32.56	13.03	35.15	29.39	1.21	0
65	24.14	32.86	16.81	41.12	28.66	1.68	0
66	24.89	35.22	15.91	45.66	28.25	1.97	0
67	25.75	34.05	18.05	35.96	27.96	3.01	0
68	25.02	32.89	18.55	43.13	27.42	3.06	0
69	24.68	34.7	16.72	42.51	27.78	1.91	0.2
70	23.42	33.61	14.48	44.84	24.09	1.09	0
71	23.64	33.17	12.30	36.27	28.13	1.70	0
72	23.10	32.51	11.18	19.73	28.62	1.79	0
73	23.39	32.37	15.42	20.55	28.98	1.60	0
74	22.96	33.35	10.87	32.43	27.33	1.42	0
75	23.97	31.48	17.07	36.09	15.99	2.77	0.1
76	16.88	21.46	13.25	85.31	5.44	2.23	1.3
77	14.76	19.34	10.71	88.58	8.36	3.20	26.5
78	17.32	23.14	13.64	82.90	12.05	2.20	74.1
79	19.61	26.91	13.87	76.18	22.04	0.66	22.6
80	15.34	21.59	7.93	73.88	22.18	2.05	0
81	10.55	15.71	4.83	67.13	25.19	1.62	0
82	10.66	13.83	7.29	80.50	11.73	1.00	0.2
83	13.28	20.87	6.04	69.97	25.84	0.94	4.1
84	16.22	24.56	9.00	62.34	25.91	1.06	0
85	19.33	27.54	11.32	53.89	25.72	1.11	0
86	20.21	28.58	13.81	54.46	25.15	1.69	0
87	20.73	29.75	13.24	51.13	23.85	1.53	0
88	22.36	31.15	15.70	46.36	22.50	1.31	0
89	20.85	27.95	15.99	54.63	20.20	2.32	0

Continued from previous table

90	20.95	29.17	14.27	52.24	21.84	1.72	0
91	21.88	30.23	14.87	48.84	22.48	1.51	0
92	21.54	30.26	16.68	51.16	13.11	1.61	0
93	21.77	29.01	17.00	56.32	22.74	1.79	0
94	21.62	30.77	14.13	55.91	22.67	1.06	0
95	22.85	31.61	15.99	45.01	22.16	1.31	0
96	22.17	30.29	16.23	47.36	19.29	1.65	0
97	19.72	28.46	11.15	46.17	22.74	1.30	0
98	18.02	24.54	13.46	47.93	15.45	1.32	0
99	21.29	30.31	12.85	54.87	20.33	2.87	0
100	21.81	28.35	17.06	49.54	18.66	2.16	0.1

APPENDIX II

Table A7. Above-ground dry matter accumulation of maize (gm^{-2})

DAP	**Samples taken from 8 rows**								**Mean**	**SE**
	SR1	**SR2**	**SR3**	**SR4**	**SR5**	**SR6**	**SR7**	**SR8**		
34	86.28	67.44	62.64	55.38	111.48	74.16	76.56	39.66	**71.70**	**21.44**
40	164.22	157.74	246.24	162.84	176.04	200.16	142.14	91.92	**178.48**	**34.80**
47	252.00	195.54	276.12	200.88	404.40	368.58	324.06	322.80	**293.05**	**75.52**
54	585.12	468.60	543.30	516.60	522.66	405.96	567.60	710.22	**540.01**	**89.20**
61	643.80	541.20	454.20	532.20	556.20	774.00	522.00	733.80	**594.68**	**111.60**

SR= Sample taken from randomly selected row
SE= Standard error
The numbers indicate sample numbers taken from different rows

Table A8. Above-ground dry matter accumulation of bean with close space (gm^{-2})

DAP	**Samples taken from 8 rows**								**Mean**	**SE**
	SR1	**SR2**	**SR3**	**SR4**	**SR5**	**SR6**	**SR7**	**SR8**		
34	25.62	12.60	42.12	15.06	30.06	32.22	35.22	14.82	**25.96**	**10.85**
40	32.04	19.92	65.64	16.44	44.40	44.10	48.54	28.62	**37.46**	**16.32**
47	49.92	55.08	45.66	37.08	48.84	46.56	94.98	42.48	**52.57**	**17.93**
54	192.60	189.48	170.52	186.60	152.46	183.12	219.36	209.82	**187.99**	**20.96**
61	120.60	111.60	108.00	99.00	81.00	75.00	111.60	103.20	**101.25**	**15.77**

Table A9. Above-ground dry matter accumulation of bean with wide space (gm^{-2})

	Samples taken from 8 rows									
DAP	**SR1**	**SR2**	**SR3**	**SR4**	**SR5**	**SR6**	**SR7**	**SR8**	**Mean**	**SE**
34	22.02	53.82	12.78	30.96	18.06	50.52	70.86	56.82	39.48	21.25
40	58.80	69.66	43.68	40.62	58.92	57.18	62.40	53.04	55.54	9.57
47	76.38	88.08	79.26	102.00	73.98	63.00	98.28	70.80	81.47	13.57
54	231.66	231.24	217.68	168.00	183.00	276.96	316.44	275.16	237.52	49.96
61	100.80	120.00	100.20	130.20	120.00	150.00	157.20	132.60	126.38	20.64