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RADIATION INTERCEPTION AND USE
IN A MAIZE AND BEAN INTERCROPPING SYSTEM

BY

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I declare that the dissertation hereby submitted by me for the degree of Doctor of Philosophy at the University of the Orange Free State is my own independent work and has not previously been submitted by me at another university/faculty. I furthermore cede copyright of the dissertation in favour of the University of the Orange Free State.

Mitsuru Tsubo

M. Tsubo

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List of Symbols and Abbreviations

b	coefficient of the conversion of mass yield into energy value (subscript EV) or monetary value (subscript MV) for beans
CGR	crop growth rate
d	the index of agreement
DM	dry matter (subscripts M for maize; B for beans)
EV	energy value (subscripts M for sole maize; B for sole beans; I for intercrop)
E	chemical energy stored in yield (subscripts BY for biological yield; EY for economic yield)
F	the fraction of radiation intercepted (subscripts M for maize; B for beans)
g	the G-function of canopy extinction coefficient (subscripts ψ for solar zenith angle; M for maize; B for beans; M/B for maize/bean mixture; A for the atmosphere)
h	canopy height (subscripts M for maize canopy; B for bean canopy)
HI	harvest index
I	the intensity of radiation at the surface of soil
I_0	the intensity of radiation at the top of canopy
k	the K-function of canopy extinction coefficient (subscripts g for grass; l for legume; M for maize; B for beans; ψ for solar zenith angle)
K	canopy extinction coefficient on a daily basis (subscripts M for maize; B for beans) (Chapters 3 and 4)
	the ratio of diffuse to global radiation (subscripts SR for solar radiation; PAR for photosynthetically active radiation) (Chapter 5)
K_T	the ratio of global to extraterrestrial solar radiation
LAD	leaf area density (subscripts M for maize; B for beans; A for the atmosphere)
LAI	leaf area index (subscripts g for grass; l for legume; M for maize; B for beans)
LER	land equivalent ratio (subscripts M for maize partial LER; B for bean partial LER; T for total LER)

m	coefficient of the conversion of mass yield into energy value (subscript EV) or monetary value (subscript MV) for maize
MBE	mean bias error
MV	monetary value (subscripts M for sole maize; B for sole bean; I for intercrop)
n	number of plant species (Chapter 3) the number of the paired set data (Chapter 4)
N	plant density (Chapter 3) the integer number of units of inter-row spacing traversed by radiation (Chapter 4)
PAR	photosynthetically active radiation
RMSE	root mean square error
RUE	radiation use efficiency (subscripts M for maize; B for beans)
s	radiation path length (subscripts ψ,ϕ for the length of the radiation path from the top to bottom of rectangular hedgerow; θc for the length of the component of $s_{\psi,\phi}$ in rectangular hedgerow cross-section; θb for the length of the horizontal component of $s_{\theta c}$)
s_0	a given distance from the left-side of the last unit row traversed by radiation
s_f	a distance from the left-side of the first unit row traversed by radiation
$s_{\theta b}'$	the total path length of the horizontal component in rectangular hedgerow cross-section only for the hedgerow
SC	solar constant
SR	solar radiation
SR_0	extraterrestrial solar radiation on a horizontal surface
t	time
w_{row}	inter-row spacing
w'	rectangular hedgerow cross-section width
x	measured value
y	calculated value

Y	mass yield per unit area (subscripts SM for sole cropped maize cobs; SB for sole cropped bean seeds; IM for intercropped maize cobs; IB for intercropped bean seeds)
δ	solar declination
θ	angle with respect to solar position (subscripts a for the difference between row azimuth and solar azimuth; b for the angle of the radiation within the plane of a cross-section through the hedgerow perpendicular to the direction of the rows; c for the angle between a vertical plane through the zenith and the beam and a vertical plane through the zenith and the hedgerow cross-section) (Chapter 4)
	the hour angle from solar noon (Chapter 5)
ϕ	solar azimuth angle
φ	latitude
Φ	radiant flux density (subscripts PAR for incident PAR; IPAR for PAR intercepted by plants)
χ	the ratio of vertical to horizontal projections of canopy elements (in the ellipsoidal distribution function)
ψ	solar zenith angle

Chapter 1

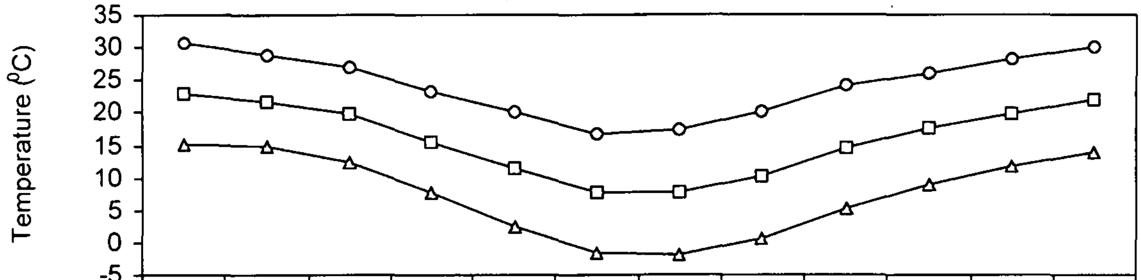
General Introduction

1.1. Introductory remarks

According to FAO Report - the State of Food Insecurity in the World 2000 (FAO, 2000), about 800 million people in the developing countries do not have sufficient food. In southern Africa, large populations are malnourished as well. The bulk of the these populations reside in rural areas, with large numbers experiencing food insecurity (Van Rooyen and Sigwele, 1998). In these areas, small-scale farming, normally based on natural resources such as rainfall and soil fertility, plays an important role in food security. Food insecurity is increased by adverse weather conditions and droughts throughout southern Africa. Variable rainfall is characteristic in southern Africa, with annual rainfall varying from 100 mm in the arid zones to 1500 mm in the humid zones (Le Houérou *et al.*, 1993). This results in high variation in the potential of natural resource based farming. Specifically, seasonally erratic rainfall and sandy soils cause low production in many areas.

More than one-third of the earth's surface lacks sufficient moisture to support a continuous cover of vegetation and vast areas are without vegetation in the drier portions of the arid zones (Oliver and Fairbridge, 1987). In contrast, two-thirds is covered by vegetation, i.e., hyper-humid, humid and sub-humid zones. Semi-arid zones usually occur as transition zones between arid and sub-humid zones. Semi-arid climates are characterised by less precipitation than evaporation. According to the Köppen climate classification, the climate of the study area (Bloemfontein, Free State, South Africa) belongs to a Bsk [arid (steppe) cold and dry climate, with mean annual temperature below 18°C] and according to the Thornthwaite climate classification, it is categorised as a semi-arid warm climate (Schulze, 1947; Schulze and McGee, 1978). The long-term (30 years from 1961 to 1990) mean monthly temperature in the study region (Bloemfontein

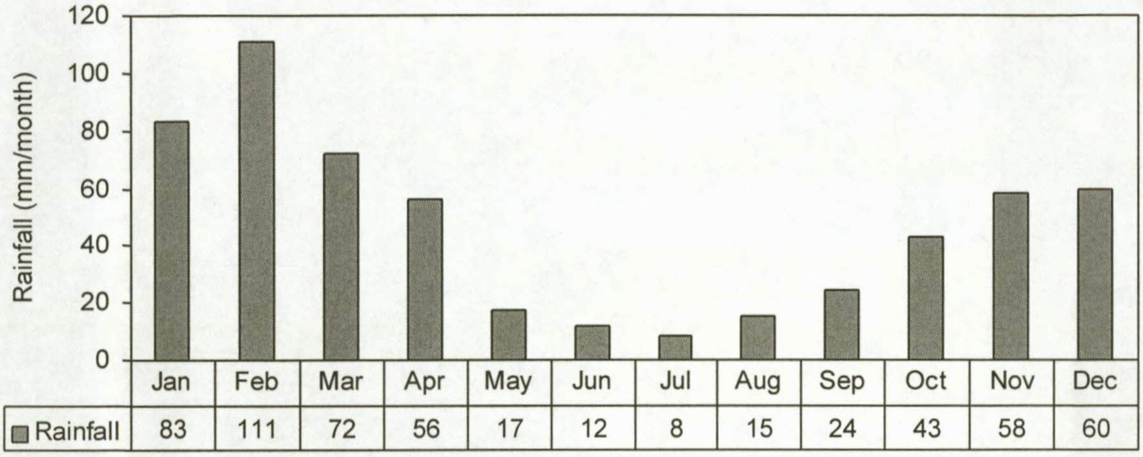
Airport, South Africa, latitude 29°06′S, longitude 26°18′E, altitude 1351 m above sea level) is as shown in Figure 1.1 (as reported by South African Weather Bureau). The mean annual temperature is 15.9 °C. Figure 1.2 presents the long-term mean monthly rainfall, giving a total annual rainfall of 559 mm. Furthermore, the mean annual global solar radiation in semi-arid zones is higher than in the most other climatic zones (excepting arid zones) because the prevalence of cloudiness, influencing transmission of radiation, is lower in semi-arid regions (Barry and Chorley, 1998). The long-term mean monthly solar radiation in the study region is as shown in Figure 1.3 and the mean annual global solar radiation is 244 W m^{-2}.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
—○— Max	30.8	28.8	26.9	23.1	20.1	16.8	17.4	20.0	24.0	26.1	28.1	30.1
—□— Mean	23.0	21.8	19.7	15.4	11.3	7.7	7.7	10.3	14.6	17.6	19.9	22.0
—△— Min	15.3	14.7	12.4	7.7	2.5	-1.5	-1.9	0.5	5.2	9.1	11.7	13.8

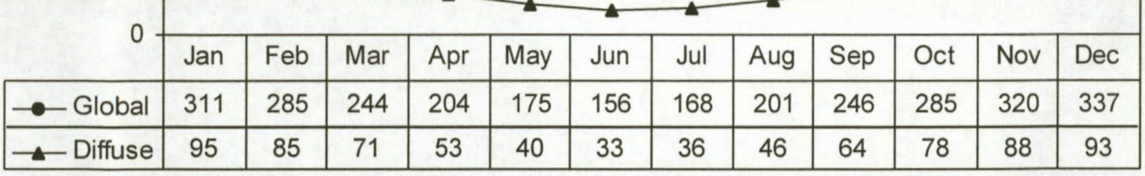
Figure 1.1. Long-term mean monthly temperature at Bloemfontein Airport, South Africa (latitude 29°06′S, longitude 26°18′E, altitude 1351 m above sea level; 30 years from 1961 to 1990).

The soil characteristics of a specific area are directly and indirectly influenced by annual, seasonal and extreme thermal patterns (Oliver and Fairbridge, 1987). According to the soil classification for South Africa by the Soil Classification Working Group (1991), the soil of the field experiment site belongs to a 3 m deep Bainsvlei Amalia (3200) fine sand soil, and the top soil texture and colour are sandy and reddish, respectively. The morphological characteristics and nutrient concentration of Bainsvlei soil are presented in Table 1.1 (Van Rensburg, 1996).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
▨ Rainfall	83	111	72	56	17	12	8	15	24	43	58	60

Figure 1.2. Long-term mean monthly rainfall at Bloemfontein Airport, South Africa (latitude 29°06′S, longitude 26°18′E, altitude 1351 m above sea level; 30 years from 1961 to 1990).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
● Global	311	285	244	204	175	156	168	201	246	285	320	337
▲ Diffuse	95	85	71	53	40	33	36	46	64	78	88	93

Figure 1.3. Long-term mean solar radiation at Bloemfontein Airport, South Africa (latitude 29°06′S, longitude 26°18′E, altitude 1351 m above sea level; 30 years from 1961 to 1990).

Table 1.1. General morphological characteristics of Bainsvlei soil at the field experiment site (Van Rensburg, 1996).

	Horizon			
	Orthic A (Ap)	Red apedal (B1)	Soft plinthic (B2)	Weathered mud-stone (IIC)
Depth (m)	0.00 – 0.35	0.35 – 1.18	1.18 – 1.40	1.40 – 3.00
Texture class	Fine sand	Fine sandy loam	Fine sandy clay loam	Fine sandy clay loam
Structure	Apedal, massive	Rough, weak prismatic	Apedal, massive	Rough, strong, jagged blocky
Color	Red brown	Red brown	Brown	Yellow orange
Mottling	None	None	Grey, yellow, red, black	Yellow, black
P(Olsen)	14 mg/kg			
$Ca(NH_4OAc)$	561 mg/kg			
$Mg(NH_4Oac)$	125 mg/kg			
$K(NH_4Oac)$	122 mg/kg			
Zn(HCl)	2.5 mg/kg			
$pH(H_2O)$	6.9			

The improvement of crop productivity is the common aim of farmers and agriculturists. The key probably lies in increased output per unit area together with arable land expansion. In terms of cropping systems, the solutions may not only involve in the mechanised rotational mono-culture cropping system used in developed countries such as North America and Western Europe, but also the poly-culture cropping system traditionally used in developing countries such as Africa and Latin America (Francis, 1988; Francis and Adipala, 1994; Karlen *et al.*, 1994). The main reason for using a multiple cropping system is the fact that it involves integrating crops efficiently using space and labour (Baldy and Stigter, 1997). Biophysical reasons include better utilisation of environmental factors, greater yield stability in variable environments and soil conservation, and socio-economic reasons include the magnitude of inputs and outputs and its contribution to the stabilization of household food supply (Beets, 1982).

Intercropping, which is one type of multiple cropping system, has been practised traditionally by small-scale farmers in the tropics. In particular, cereal and legume intercropping is recognised as a common cropping system throughout developing tropical countries (Ofori and Stern, 1987). Typically, cereal crops such as maize (*Zea mays*), millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*) are dominant crop/plant species, whereas legume crops such as beans (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*), groundnut (*Arachis hypogaea*), pigeonpea (*Cajanus cajan*) and soybean (*Glycine max*) are the associated plant species. Generally, in southern Africa, maize and beans are staple and supplementary crops respectively. Crops used in the field experiments that were carried out during the 1998/1999 and 1999/2000 growing seasons are maize (*Zea mays* L. cv. SNK 2147) and dry beans (*Phaseolus vulgaris* L. cv. PAN 127). Figures 1.4, 1.5 and 1.6 show maize sole cropping, bean sole cropping and maize-bean intercropping respectively, in the sixth week after sowing during the 1999/2000 growing season. The agronomic characteristics of maize SNK 2147 and dry beans PAN 127 are presented in Table 1.2.

Figure 1.4. Maize sole cropping (6 weeks; the 1999/2000 growing season).

Figure 1.5. Bean sole cropping (6 weeks; the 1999/2000 growing season).

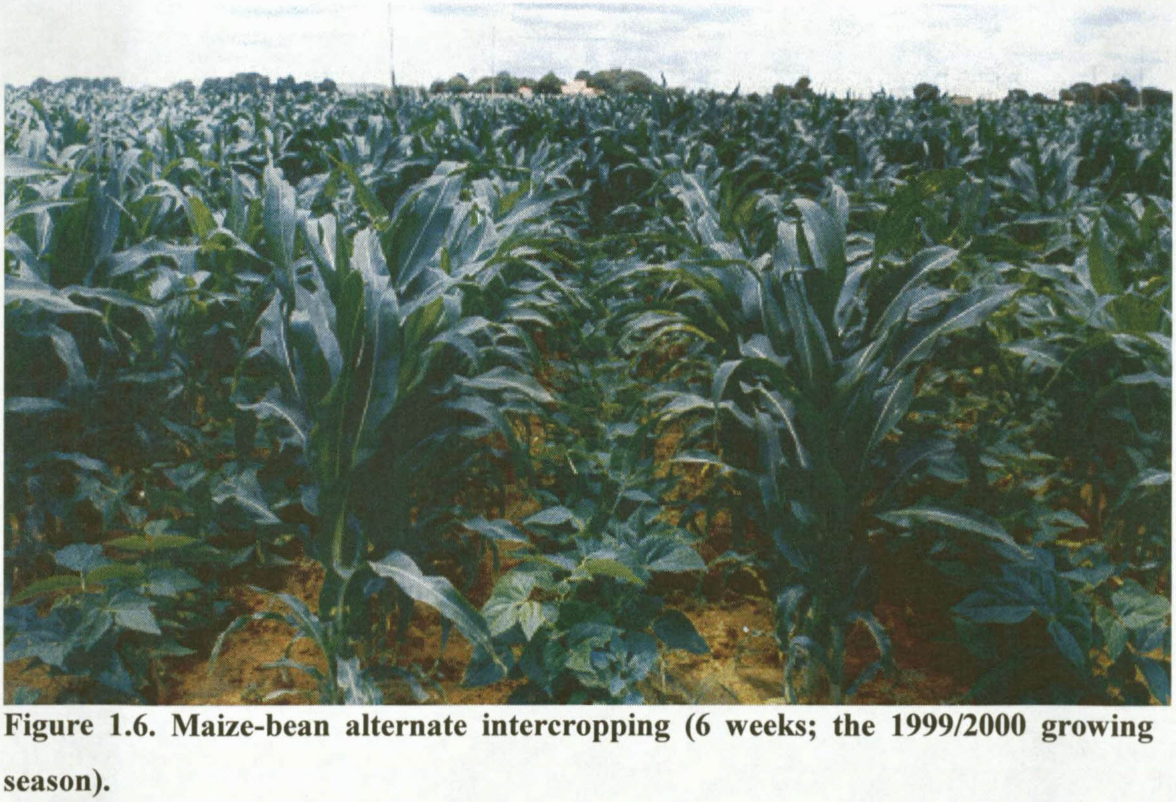


Figure 1.6. Maize-bean alternate intercropping (6 weeks; the 1999/2000 growing season).

Table 1. 2. Agronomic characteristics of maize SNK 2147 and dry beans PAN 127.

	Maize SNK 2147	Dry beans PAN 127
Time from planting to flowering (days)	65 – 102	50 – 55
Time from planting to maturity (days)	130 – 160	105 – 115

Crop modelling has rapidly developed since the 1970's after the dawn of the computer age. Many crop models have been built and introduced by several institutions, as reviewed by Whisler *et al.* (1986). There are four uses of crop modelling: (i) research knowledge synthesis, (ii) crop system decision management (iii) policy analysis and (iv) teaching aid, assisting researchers, farm managers, policy makers and students (Boote *et al.*, 1996; Sinclair and Seligman, 1996). Crop modelling may provide more valuable exercises than field experiment research under time and monetary constraints (Whisler *et al.*, 1986).

Conventionally, crop models are broadly distinguished between as either empirical (regression) models or mechanistic (physiological) models (Loomis, *et al.*, 1979; Whisler *et al.*, 1986; Spitters, 1990; Monteith, 1996; Passioura, 1996). Empirical models describe simple relationships between variables at one hierarchic level while mechanistic models, on the other hand, usually explain causality between variables using several hierarchic levels. The best models may fall somewhere between empirical (simple) and mechanistic (complex) models, and are referred to as semi-empirical models. The simplicity relies on the users' purposes, that is, crop models as practical tools (e.g., farm management) may be close to empiricism while those used as scientific tools (e.g., agronomic research) may be more mechanistic.

Crop production models based on environmental resource factors which limit plant growth, as proposed by de Wit (Penning de Vries, 1982; Penning de Vries, 1983; Penning de Vries *et al.*, 1989), have been successfully applied in agronomic research. The models can be classified into three main production levels: (i) weather dependence (unlimited water and nutrients, the first production level), (ii) water dependence (limited water and unlimited nutrients, the second production level), and (iii) water and nutrient dependence (limited water and nutrients, the third production level). In the third production level, nutrients may be subdivided into several levels such as nitrogen, phosphorus and potassium, etc. In addition, in the second and third production levels, weather (meteorological factors) influences plant growth. The first production level, namely the potential production level, is often referred to as a radiation-based crop model.

Potential crop growth may be explained by the amount of radiation intercepted and used by crops (Warren Wilson, 1967; Monteith, 1981; Russell *et al.*, 1989; Spitters, 1990). Crop growth rate (CGR) is modelled using the following relationship:

$$CGR = F \times RUE \times PAR \qquad (1.1)$$

where F is the fraction of radiation intercepted, RUE is radiation use efficiency and PAR is photosynthetically active radiation (radiant energy for photosynthesis).

With regard to potential crop production, as summarised by Sinclair and Gardner (1998), potential crop yield results from the following four processes. Firstly, the radiation interception by crop canopies provides the energy for crop production. Secondly, the efficiency of conversion of the intercepted radiation to plant mass determines the amount of dry matter produced. Thirdly, the time required for plant mass accumulation determines the total amount of accumulated plant mass. Fourthly, the fraction of the accumulated plant mass allocated to the harvestable part influences crop productivity. These processes are explained by the time-integration of the above equation:

$$Y = HI \int (F \times RUE \times PAR) dt \qquad (1.2)$$

where Y is yield, HI is harvest index, and t is time during a growing season. In association with phenological models for leaf growth, the radiation-based crop model has been validated across years and at many locations (e.g., Spaeth *et al.*, 1987; Muchow *et al.*, 1990). Figure 1.7 illustrates the flow of energy of the crop model.

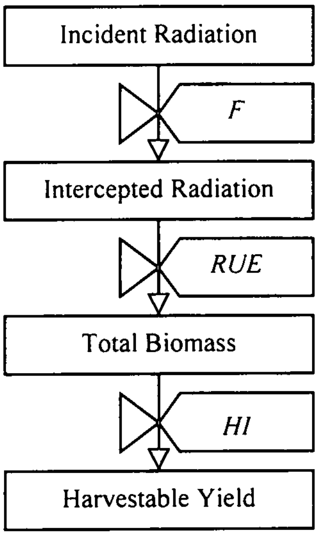


Figure 1.7. A energy flow diagram of the crop model.

1.2. Study aim

Canopy structures and root systems of cereal crops are generally different from those of legume crops. The formative rate is comparatively greater in cereal crops than in legume crops. In the most cereal-legume intercropping, cereal crops form relatively higher canopy structures than the legume crops and the roots of cereal crops grow to a greater depth than those of legume crops. This indicates that the component crops probably have differing spatial and temporal use of environmental resources. In other words, intercrops could in some cases use environmental resources such as radiation, water and nutrients more efficiently (Willey, 1979a, b, 1990). Therefore, this cropping system may help improve productivity of low external input farming, which depends largely on natural resources such as rainfall and soil fertility.

Crop productivity mainly depends on the amount of radiation intercepted by crops when the other factors, such as water, nutrients, disease and weeds, are not limiting factors to plant growth (Loomis and Williams, 1963; Loomis *et al.*, 1971). Many studies have shown the positive correlation of crop production with the amount of radiant energy intercepted by the crop for a variety of crops (e.g., Shibles and Weber, 1966; Monteith, 1977; Gallagher and Biscoe, 1978; Kiniry *et al.*, 1989). Compared with sole cropping, intercropping has greater radiation capture potential and utilisation because of the effect of combination of differing spatio-temporal use of radiation among component crops (Willey 1990; Keating and Carberry, 1993).

Many crop models have been developed for mono-culture production systems, whereas few satisfactory crop models have been introduced to simulate poly-culture (e.g., Thornton *et al.*, 1990; Lowenberg-DeBoer *et al.*, 1991). Because crop modelling is useful for understanding crop growth and production (Loomis *et al.*, 1979; Whisler *et al.*, 1986; Spitters, 1990; Monteith, 1996; Passioura, 1996), there is need for intercrop modelling. The primary aim of this study is, therefore, to analyse and model radiation interception and use in maize-bean intercropping. The secondary aims are to assess maize-bean intercrop yield advantage in this region and to investigate relationships between photosynthetically active and solar radiation above plant canopies. Thus, the dissertation consists of four sections: (i) intercrop yield advantage (Chapter 2), (ii) analysis of radiation interception and use (Chapter 3), (iii) modelling of radiation interception and use (Chapter 4), and (iv) relationship between solar radiation and photosynthetically active radiation (Chapter 5).

Chapter 2

Evaluation of Intercrop Yield Advantage

2.1. Introduction

In assessments of crop productivity of sole cropping systems, a useful expression is mass yield (weight per unit area). However, in intercropping systems, direct comparison is difficult because products are different for the different plant species growing on one piece of land (Beets, 1982). In this case, crop productivity should be evaluated using a common unit. Several different methods of quantitatively evaluating intercrop productivity [summarised by Beets (1982) and Willey (1985)] are introduced in terms of (i) intensity of land use, (ii) production of constituents (calorie, protein, carbohydrate, fat, etc.), and (iii) capital return.

A widely used method is the land equivalent ratio (LER) (Beets, 1982; Willey, 1985). This is defined as the total land area required under mono-culture cropping to give the yields obtained in the poly-culture cropping system (Mead and Willey, 1980). Osiru and Willey (1972) and Willey and Osiru (1972) first used LER to explain the yield advantage of cereal-legume intercropping in Kampla, Uganda (latitude 0°28′N, longitude 32°37′E). Since then, LER has been widely accepted in the evaluation of intercrop yield advantages (e.g., Fisher, 1977a; Rees, 1986a; Lightfoot and Tayler, 1987a; Pilbeam *et al.*, 1994; Mukhala *et al.*, 1999). Mukhala et al. (1999) reported that there was an advantage in maize-bean intercropping over the sole cropping of either in a South African semi-arid region. Fisher (1977a) and Pilbeam *et al.* (1994) also reported that the intercropping was advantageous in semi-arid areas of Kenya during the long rain seasons. However, they recorded a disadvantage from intercropping in short rain seasons, indicating that little benefit from intercropping can be expected under conditions of severe shortage of water.

Secondly, yields expressed as an energy value (EV) converted from mass yields, have been introduced (Beets, 1982; Willey, 1985). Energy returns from biological yield (or plant mass) and economic yield have been termed biological energy yield (or plant energy) and economic energy yield respectively. Normally, the reproductive parts of crops, such as the grain and seed, are used for the energy conversion. The summation of energy yields of component crops in intercropping can be useful in giving the total intercrop energy yield, which is comparable with the sole crop energy yields, because EV is a universal gauge of bio-productivity (Beets, 1977; Clark and Francis, 1985; Mukhala *et al.*, 1999). Clark and Francis (1985) reported that there was no significant difference in energy content between maize-bean intercropping and sole maize cropping though the sole maize crops stored slightly more energy than the intercrops, and that the intercrops and sole maize crops produced more energy than sole bean crops. Mukhala *et al.* (1999), however, found that maize-bean intercrops stored more energy than either maize or bean sole crops.

Thirdly, monetary value (MV) can be used when the crops are marketable cash crops (Beets, 1982; Willey, 1985). Yields can be expressed in terms of gross profits (e.g., Beets, 1977) or if information on costs of production, such as fertiliser, irrigation and labour, are available, the net profits can be calculated and used (Francis and Sanders, 1978). The fluctuation in seasonal prices of products cause several difficulties in the application of this method. Beets (1977) reported that growing maize was more profitable than soybeans, or its intercrop, when the prevailing crop prices in Zimbabwe were used. However, when the price of soybeans was doubled, the intercrop gave higher gross income than the sole crops. Similarly, Francis and Sanders (1978) analysed maize and bean intercrops using net income in Colombia, emphasising the importance of the price ratio of component crops.

There are various agronomic factors influencing intercrop productivity and efficiency (Ofori and Stern, 1987). Plant density is one of the most important factors that can be manipulated to obtain maximum yields. In making a comparison between mono and poly-culture cropping systems, the optimum plant densities must be selected. Many intercropping studies about the effects of plant density, spacing and arrangement have been carried out (Osiru and Willey, 1972; Willey and Osiru, 1972; Beets, 1977; Fisher, 1977b; Rees, 1986a; Lightfoot and Tayler, 1987a; Pilbeam *et al.*, 1994; Mukhala *et al.*, 1999). Mukhala *et al.* (1999) conducted a maize-bean intercrop field trial to investigate the effect of plant density on intercrop yield advantage, and reported that the intercropping at medium density (maize 4.4 plants m^{-2}; beans 8.3 plants m^{-2}) was more advantageous than that at low density (half of medium density) and high density (1.5 times medium density) in terms of LER.

With respect to row orientation effects, several studies in mono-culture cropping have been reported (Larson and Willis, 1957; Stickler *et al.*, 1961; Hunt *et al.*, 1985; Steiner, 1986; Kasperbauer, 1987; Kaul and Kasperbauer, 1988; Karlen and Kasperbauer, 1989). In mono-culture cropping, crops planted in north-south row direction give higher yields than in east-west row direction, as reported by Hunt *et al.* (1985) for soybean, Steiner (1986) for sorghum, Kaul and Kasperbauer (1988) for bush bean, and Karlen and Kasperbauer (1989) for maize. However, not much is known about the effect of row orientation on intercropping, For instance, De (1980) showed that yields of sesame-black gram intercropping were higher in north-south row orientation than those of an east-west one.

It has been concluded earlier that intercropping systems may be beneficial. However, only a few studies on intercropping have been reported from southern African semi-arid regions (Rees, 1986a, b, c; Lightfoot and Tayler, 1987a, b; Mukhala *et al.*, 1999). Consequently, field experiments were undertaken to reassess intercrop yield advantage in the semi-arid region (Bloemfontein, South Africa). The objective in this study was to evaluate intercrop yield advantage in terms of LER, EV and MV, considering the effect of row orientation at an optimal plant population.

2.2. Materials and Methods

2.2.1. Field experiments

The field experiments were conducted at the Bainsvlei Soil Science experimental site of the University of the Orange Free State (latitude 29°01'S, longitude 26°09'E, altitude 1354 m above sea level) during two summer growing seasons (1998/1999 and 1999/2000). According to soil classification for South Africa by Soil Classification Working Group (1991), the soil of the field experiment site belongs to a 3 m depth Bainsvlei Amalia (3200) fine sand soil.

The crops used in the experiment, maize *(Zea mays* L. cv. SNK 2147) and dry beans (*Phaseolus vulgaris* L. cv. PAN 127), were planted on 24 and 25 November 1998 and harvested on 13 and 14 April 1999 for the 1998/1999 growing season. For the 1999/2000 growing season, the planting dates were 23 and 24 November 1999 and the harvest dates were 11 and 12 April 2000. Thus, in both growing seasons, the crops were grown for 140 days. In general, the seedling establishment for both crops was about two weeks from sowing, the flowering occurred eight and ten weeks after sowing for beans and maize respectively. In both growing seasons, full irrigation and fertiliser (171.5 kg N ha^{-1}, 47.0 kg P ha^{-1} and 31.5 kg K ha^{-1}) was applied. The total rainfall and irrigation applied during the 1998/2000 growing season were 196 mm and 440 mm, respectively, totalling 636 mm. The total rainfall during the 1999/2000 growing season was 388 mm with additional irrigation of 335 mm, totalling 723 mm.

2.2.2. Experimental designs

The experimental treatments were three cropping systems and two row orientations as follows:

- sole maize with north-south row orientation (M-NS)
- sole maize with east-west row orientation (M-EW)
- sole beans with north-south row orientation (B-NS)

- sole beans with east-west row orientation (B-EW)
- intercrop with north-south row orientation (I-NS)
- intercrop with east-west row orientation (I-EW)

A randomised complete block design was used with four blocks for the 1998/1999 growing season and with three blocks for the 1999/2000 growing season. The plant densities were 6.67 plants m^{-2} for sole cropped maize, intercropped maize and intercropped beans, and 13.33 plants m^{-2} for sole cropped beans during both the growing seasons. The row spacing was 1.00 m for sole cropped maize and 0.50 m for sole cropped beans and the intercrop. The row ratio of intercropping was one row maize to one row beans (alternative intercropping; see Figure 2.1). The plot size was 10 m × 15 m and 6 m × 6 m for the 1998/1999 and 1999/2000 growing seasons, respectively.

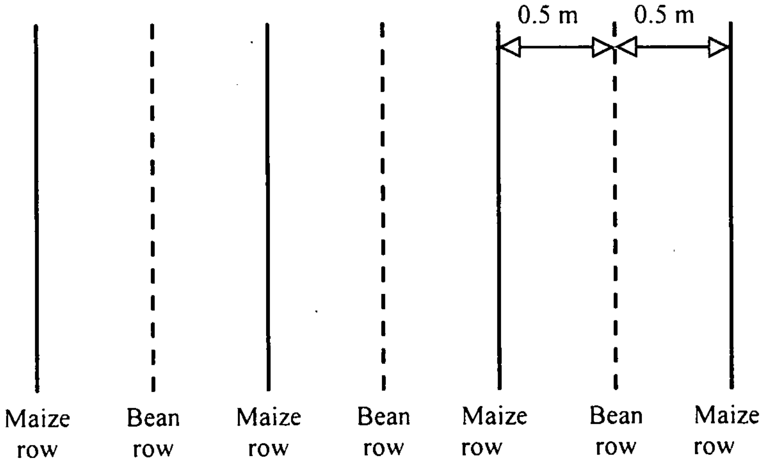


Figure 2.1. A diagram of the alternate intercropping.

2.2.3. Experimental measurements

Crops were harvested at 140 days after planting. The harvest areas for the 1998/1999 and 1999/2000 growing seasons were 15 m^{-2} and 6 m^{-2}, respectively. Calorimetry was carried out for determining the conversion factor of mass value (gram) into energy value (joule), using an oxygen bomb calorimeter.

2.2.4. Calculations

Land equivalent ratio (LER), including maize partial land equivalent ratio (LER_M), bean partial land equivalent ratio (LER_B) and total land equivalent ratio (LER_T) were calculated as follows:

$$LER_M = Y_{IM} / Y_{SM} \qquad (2.1a)$$
$$LER_B = Y_{IB} / Y_{SB} \qquad (2.1b)$$
$$LER_T = LER_M + LER_B \qquad (2.1c)$$

where Y_{IM} and Y_{IB} are mass yields per unit area of intercropped maize cobs and bean seeds respectively, and Y_{SM} and Y_{SB} are mass yields per unit area of sole cropped maize cobs and bean seeds respectively. If LER_T is greater than one ($LER_T > 1$), intercropping has a yield advantage while there is a yield disadvantage from intercropping if LER_T is less than one ($LER_T < 1$) (Beets, 1982; Willey, 1985).

Energy value (EV), including sole maize energy value (EV_M), sole bean energy value (EV_B) and intercrop energy value (EV_I) were calculated as follows:

$$EV_M = m_{EV} \cdot Y_{SM} \qquad (2.2a)$$
$$EV_B = b_{EV} \cdot Y_{SB} \qquad (2.2b)$$
$$EV_I = m_{EV} \cdot Y_{IM} + b_{EV} Y_{IB} \qquad (2.2c)$$

where m_{EV} and b_{EV} are coefficients of the conversion of mass yield into energy yield for maize cobs and bean seeds, respectively (Beets, 1982; Willey, 1985). The average conversion factor for plant materials is 17.5 kJ g^{-1} (Sivakumar and Virmani, 1980).

Monetary value (MV), including sole monetary value (MV_M), sole bean monetary value (MV_B) and intercrop monetary value (MV_I) were calculated as follows:

$$MV_M = m_{MV} \cdot Y_{SM} \qquad (2.3a)$$
$$MV_B = b_{MV} \cdot Y_{SB} \qquad (2.3b)$$
$$MV_I = m_{MV} \cdot Y_{IM} + b_{MV} \cdot Y_{IB} \qquad (2.3c)$$

where m_{MV} and b_{MV} are coefficients of the conversion of mass yield into price for maize and bean, respectively (Beets, 1982; Willey, 1985). Monetary value (MV) used in this study was a gross profit because production costs, such as application of water, nutrients and labourers, were assumed to be equal among cropping systems.

2.3. Results and Discussion

2.3.1. Weather data

Standard meteorological data was recorded at the weather station of the Department of Agrometeorology, University of the Orange Free State (latitude 29°06'S, longitude 26°11'E, altitude 1411 m above sea level), including solar radiation, wind speed and dry and wet bulb temperatures, which were used to estimate daily reference evapotranspiration (ETo). ETo was calculated by using the FAO Penman-Monteith equation (Allen *et al.*, 1998). Rainfall was recorded at the Soil Science experimental site.

The monthly maximum, minimum and mean temperatures and rainfall for each growing season are shown in Table 2.1. The temperatures were generally higher during the 1998/1999 growing season than during the 1999/2000 growing season. The temperatures in January showed a remarkable difference between seasons. Rainfall was higher during the 1999/2000 growing season than during the 1998/1999 growing season. In both seasons the February rainfall figure was extraordinarily lower than the long-term average rainfall. The cumulative ETo during the growing seasons is shown in Figure 2.2. The cumulative ETo during the 1998/1999 growing season was greater than the cumulative ETo during the 1999/2000 growing season. The total cumulative ETo for the 1998/1999 and for the 1999/2000 growing seasons were 698 and 543 mm respectively. The difference may have resulted from the different temperatures. In December and January the monthly mean temperatures for the 1998/1999 growing season were close to or higher than the long-term mean temperatures. In contrast, the temperatures for the 1999/2000 growing season were lower. Thus, low rainfall, high temperature and high evapotranspiration were recorded during the 1998/1999 growing season, compared to the 1999/2000 growing season because.

Table 2.1. Maximum, mean and minimum temperatures at the weather station of the Department of Agrometeorology, University of the Orange Free State (latitude 29°06'S, longitude 26°11'E), and rainfall at the Soil Science experimental site (latitude 29°01'S, longitude 26°09'E) during the growing seasons.

1998/1999 growing season						
Month	Nov	Dec	Jan	Feb	Mar	Apr
Max Temp (°C)	25.9 (-2.2)	28.2 (-1.9)	30.1 (–0.7)	28.9 (+0.1)	29.4 (+2.5)	25.3 (+2.2)
Mean Temp (°C)	19.2 (–0.7)	21.5 (–0.5)	23.5 (+0.5)	22.6 (+0.8)	22.8 (+3.1)	17.7 (+2.3)
Min Temp (°C)	12.2 (+0.5)	14.8 (+1.0)	16.9 (+1.6)	16.4 (+1.7)	16.1 (+3.7)	10.9 (+3.2)
Rainfall (mm)	–	68 (+8)	83 (±0)	17 (-94)	24 (–48)	–
1999/2000 growing season						
Month	Nov	Dec	Jan	Feb	Mar	Apr
Max Temp (°C)	30.1 (+2.0)	25.8 (–4.3)	25.7 (-5.1)	28.1 (–0.7)	26.0 (–0.9)	20.7 (-2.4)
Mean Temp (°C)	22.6 (+2.7)	20.4 (-1.6)	19.8 (-3.2)	22.1 (+0.3)	20.8 (+1.1)	14.7 (–0.7)
Min Temp (°C)	15.3 (+3.6)	15.3 (+1.5)	14.3 (-1.0)	16.4 (+1.7)	15.9 (+3.5)	9.1 (+1.4)
Rainfall (mm)	–	120 (+60)	88 (+5)	36 (-75)	120 (+48)	–

Numbers in parentheses are the differences from the long-term mean monthly data at the Bloemfontein airport (30 years from 1961 to 1990; latitude 29°06'S, longitude 26°18'E, altitude 1351 m above sea level).

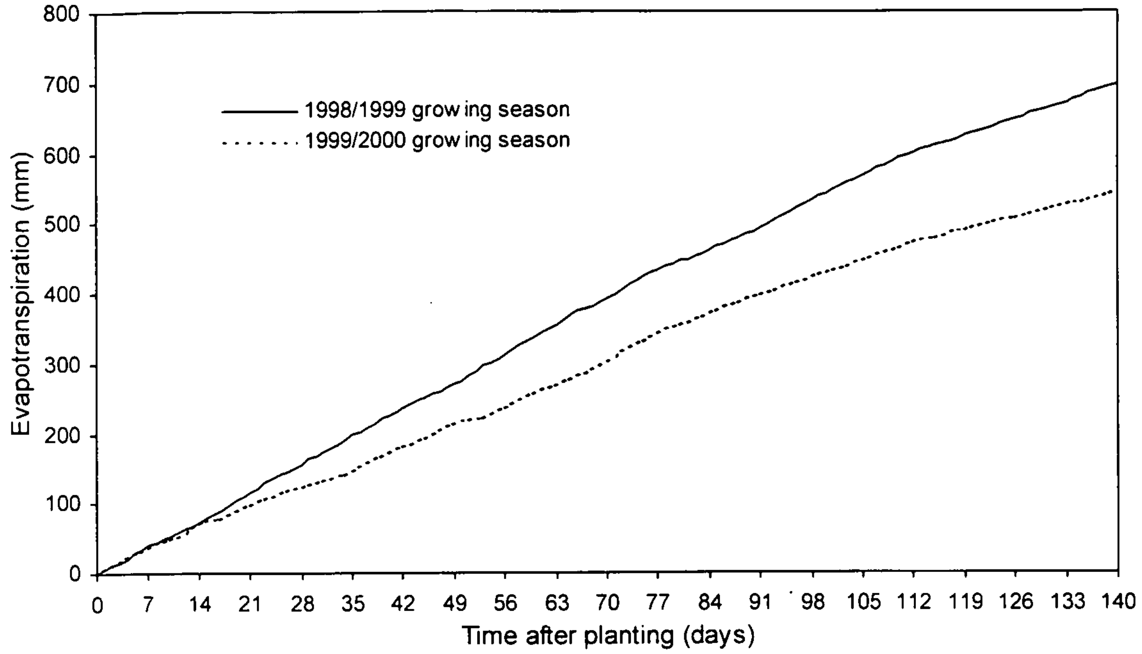


Figure 2.2. Cumulative daily reference evapotranspiration (using the FAO Penman-Monteith equation).

2.3.2. Land equivalent ratio

Mass yields for maize cobs and bean seeds are shown in Table 2.2. In all crops, the yields for the 1999/2000 growing season were slightly (7 to 10 %) higher than the yields for the 1998/1999 growing season. In sole crops, the north-south row (NS) treatment gave slightly (7 %) higher yield of maize than the east-west row (EW) treatment while EW gave 6 % more bean seed production than NS. In intercropping, maize planted in NS direction also had 5 % higher cob yields, and beans in EW direction was equivalent in yield to beans in NS direction. In terms of the effect of bean association on maize yield, it was found that there was no significant different in maize yield between sole cropping and intercropping; in other words, no reduction in yield of maize associated with beans occurred.

Land equivalent ratio (LER) for the 1998/1999 and 1999/2000 growing seasons were calculated (Table 2.3). All of the total LERs (LER_T) were greater than one ($LER_T > 1$).

Table 2.2. Mass yield of maize and beans in sole- and inter-cropping (tonnes ha^{-1}).

Cropping system	Row	1998/1999 growing season	1999/2000 growing season
Sole maize	NS	10.347 ± 1.273	11.128 ± 1.224
	EW	9.541 ± 0.744	10.489 ± 1.292
Sole beans	NS	4.195 ± 0.580	4.203 ± 0.803
	EW	4.272 ± 0.564	4.660 ± 0.692
Intercrop maize	NS	9.930 ± 0.595	10.699 ± 0.999
	EW	9.531 ± 0.402	10.194 ± 1.350
Intercrop beans	NS	0.415 ± 0.083	0.446 ± 0.073
	EW	0.401 ± 0.040	0.443 ± 0.074

(mean ± standard error)

There were no differences between row orientations. The average LER_T was 1.08 in both the growing seasons. This means that the intercropping had an 8 % yield advantage over the sole cropping system. In other words, the sole cropping needed 8 % more land to produce the same yield as produced with intercropping. The partial LER of maize (LER_M) was almost equivalent to one (the mean $LER_M = 0.98$) while the partial LER of beans (LER_B) was around one-tenth (the mean $LER_B = 0.10$). That is, the association of beans in the intercropping did not reduce the maize yield. However, the presence of maize in the intercropping reduced the yield of beans by 90 % although the expected reduction was 50 % because the plant density of intercropped beans was half of the population of sole beans.

Table 2.3. Land equivalent ratio (LER) of the maize-bean intercropping.

Row orientation	LER*	1998/1999 growing season	1999/2000 growing season
North-South	LER_M	0.97 ± 0.07	0.97 ± 0.08
	LER_B	0.10 ± 0.02	0.11 ± 0.04
	LER_T	1.07 ± 0.06	1.08 ± 0.05
East-West	LER_M	1.00 ± 0.04	0.97 ± 0.06
	LER_B	0.09 ± 0.01	0.10 ± 0.02
	LER_T	1.09 ± 0.05	1.07 ± 0.08

(mean ± standard error) * LER_M - maize partial LER; LER_B - bean partial LER; LER_T - total LER

Even though the LER_T was greater than 1.00, the increase of the yield advantage was less than 10 %, indicating that the advantage of intercropping was small. Pilbeam *et al.* (1994) and Mukhala *et al.* (1999) showed a higher yield advantage in similar experiments. A 20 % advantage (LER_T = 1.21, LER_M = 0.74, LER_B = 0.47) was obtained by Pilbeam *et al.* (1994), and Mukhala *et al.* (1999) measured LER_T = 1.15 (LER_M = 0.87 and LER_B = 0.28). Compared with the present result, those higher LER_B might result in the higher LER_T. In all cases, there is a greater effect of crop association on bean yield than on maize yield. In other words, maize yields were not reduced as much by competition from beans, compared with the reduction in bean performance.

The competitive ability of a specific crop relative to an associated crop in intercropping has been evaluated by aggressiveness (Pilbeam *et al.*, 1994). The aggressiveness of the specific crop to the associated crop is determined by subtracting the partial LER of the associated crop from the partial LER of that specific crop (e.g., $LER_M - LER_B$). When the value is positive, the specific crop is dominant in intercropping. All the aggressiveness values of the maize in the present study were positive, indicating that the maize had more competitive ability than the beans. This was also found in the study of Mukhala *et al.* (1999) ($LER_M - LER_B = 0.87 - 0.28 = 0.59$), and these findings are also consistent with the results reported by Pilbeam *et al.* (1994). Crop growth rate is generally higher in C_4 plant species than C_3 plant species (Gardner *et al.*, 1985). As maize is a C_4 plant species whereas beans are C_3 plants, maize grows faster than beans, which was clearly shown from the final yield results. Moreover, maize forms relatively larger upper canopy structures when compared to beans, and the roots of maize grow to a greater depth than those of beans. Thus, in maize-bean intercropping, maize is more competitive than beans, which has been confirmed by the above result.

2.3.3. Energy value

The present results describe the relationship between the total sole maize and bean EV per unit area and the intercrop EV. The conversion factor for maize cob was 17.8 kJ g^{-1} while the conversion factor for bean seed was 16.8 kJ g^{-1}. Based on the conversion factors which were determined in this study, the energy value (EV) of sole maize, sole beans and the intercrop for the 1998/1999 and 1999/2000 growing seasons are shown in Table 2.4. In sole maize, EV was greater in the NS row orientation treatment than in the EW treatment. In contrast, the EV_B was higher in the EW row direction than in the NS row direction. In the intercropping system, the NS row treatment gave a slightly higher EV than the EW treatment. However, there was no significant difference in EV between row orientation treatments in all cropping systems.

In a comparison of intercropping with sole cropping, the intercrop in EW row orientation had a few percent more energy than the sole maize, while in the NS row treatment the EV_I did not differ from the EV_M. Thus, the EV_I was not significantly different from the EV_M in both the growing seasons (Table 2.4). In other words, energy supplied from the intercrop was equivalent in yield to the sole maize. The EV_I, including 4 % energy from beans and 96 % energy from maize on average, and the EV_M significantly exceeded the EV_B (p-values < 0.001) The intercrop produced 157 % more energy than the sole beans, on average. Similarly the sole maize had 154 % more energy than the sole beans.

Table 2.4. Energy value for sole- and inter-cropping of maize and beans (GJ ha^{-1}).

	1998/1999 growing season	1999/2000 growing season
M-NS	184.2 ± 22.7 a	198.1 ± 21.8 a
M-EW	169.8 ± 13.3 a	186.7 ± 23.0 a
B-NS	70.5 ± 9.7 b	70.6 ± 13.5 b
B-EW	71.8 ± 9.5 b	78.3 ± 11.6 b
I-NS	183.7 ± 11.8 a	197.9 ± 16.9 a
I-EW	176.4 ± 7.3 a	188.9 ± 25.3 a

(mean ± standard error)

Means within columns followed by the same letter are not significantly different at $P < 0.05$.

Clark and Francis (1985) found that maize-bean intercrop had a similar energy yield to sole maize and yielded more energy than sole beans. Thus, the intercropping gave more yield than the sole cropping. Those results are similar to the result reported in this study. From the present results, in a given area of land an increase in the area of sole bean planting (or decrease in the area of sole maize planting) results in a lower total sole crop EV. This suggests that the intercropping is more productive than sole maize cropping planted alongside sole beans although under these particular circumstances there is no significant advantage of intercropping when the intercrop is compared with 100 % of sole maize.

Mukhala *et al.* (1999), however, reported that maize-bean intercrop yielded 11 % and 32 % more energy than sole maize and beans respectively. This probably results from higher yields in the intercropped beans (LER_B = 0.47), compared with the result in this study (LER_B = 0.10). Mukhala *et al.* (1999) used a double alternate row arrangement of the legume component crop, while the single alternate row arrangement was used in this study. Several authors have reported a yield increase in legume component crops when the crops were planted in double alternate rows rather than single alternate rows (Ofori and Stern, 1987). Thus, the high LER_B of Mukhala *et al.* (1999) is supported by the previous findings.

2.3.4. Monetary value

Figure 2.3 shows the price ratio of beans to maize in South Africa from 1966 to 1999 (National Department of Agriculture, 2000). The mean price ratio of beans to maize was five to one (standard deviation = 1.1). Based on the maize price in 1999, the conversion factor for maize was 755 Rand (South African currency) per tonne, and that for beans was 755 × 5 = 3775 Rand per tonne.

Based on the above conversion factors, the monetary value (MV) of sole maize, sole beans and the intercrop for the 1998/1999 and 1999/2000 growing seasons are presented in Table 2.5. There was no significant difference in MV between row orientation treatments similar to EV. In both the growing seasons, money returned from the sole beans was 77 % and 109 % higher than that from the intercrop and the sole maize,

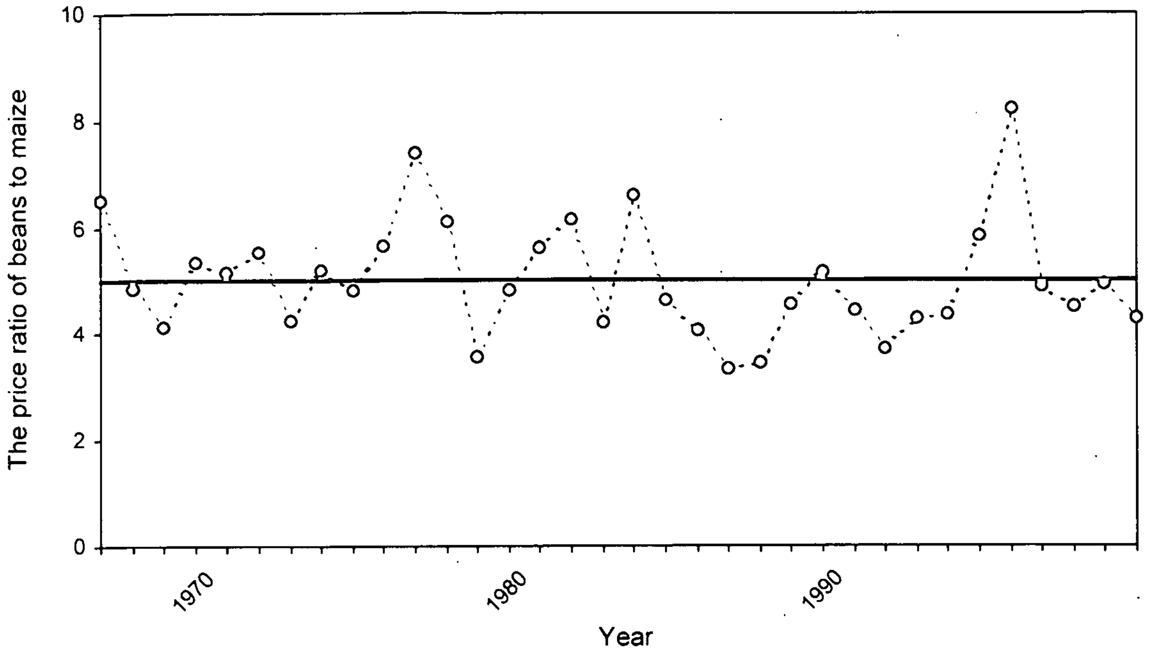


Figure 2.3. The fluctuation of the price ratio of beans to maize in South Africa (National Department of Agriculture, 2000).

respectively (p-values < 0.001). Although the intercrop had an 18 % higher monetary return than the sole maize, there was no statistically significant difference between them. An average of 17 % of the monetary return of the intercrop came from the associated beans. The MV contribution of beans to the intercrop was different from that in EV (17 % versus 4%) because the ratio of the conversion factors of beans to maize in MV was greater than that in EV.

The intercrop planted in a given area of land is equivalent in monetary return to the sole maize. When the partial planting area for beans in sole cropping increases, the difference in monetary return from the intercrop and the total sole crop increases, showing that there is no monetary advantage of intercropping with this combination of the two crops. The price ratio of beans to maize used in this study was fixed (5:1). However, the bean price over the maize price from 1966 to 1999 fluctuated between 3.33 and 8.22 (see Figure2.3). Moreover, if the price ratio were less than 2:1, there would be a monetary advantage

Table 2.5. Monetary value for sole- and inter-cropping of maize and beans (Rands ha^{-1}).

	1998/1999 growing season	1999/2000 growing season
M-NS	7812 ± 961 a	8402 ± 924 a
M-EW	7203 ± 562 a	7919 ± 975 a
B-NS	15834 ± 2190 b	15868 ± 3031 b
B-EW	16126 ± 2129 b	17592 ± 2611 b
I-NS	9063 ± 742 a	9760 ± 593 a
I-EW	8711 ± 363 a	9368 ± 1297 a

(mean ± standard error)

Means within columns followed by the same letter are not significantly different at $P < 0.05$.

of intercropping. This re-emphasises that the fluctuation of seasonal prices of crops is the main difficulty in using this evaluation method. Francis and Sanders (1978) reported similar effects from the fluctuation of the price ratio of beans to maize on monetary returns (net incomes) in Colombia (range 3:1 to 5:1 from 1950 to 1975).

2.4. Conclusions

The field experiments were conducted in a semi-arid region under full irrigation, since small-scale or subsistence farmers in this region provide supplementary irrigation to their crops (Mukhala, 1998), and intercropping of maize and beans is assessed using the three evaluation methods. The results of LER are basically consistent with those of EV, and it was concluded that the intercropping renders higher productivity than sole cropping in the semi-arid region, supporting previous intercropping studies (Mukhala, 1998). No effect from row orientation treatments was found on yield. Consequently, it may be better to cultivate maize associated with beans than maize or beans alone in either row direction. The results of MV contrast with those of indices based on biological values. The price of crops is dependent on supply and demand for crops. Thus, this value is influenced by the fluctuation of the price ratio of crops. In developing areas, a cash economy sometimes does not exist (Beets, 1977) where the majority of farmers are subsistence farmers. The analytical method in terms of monetary returns is not always useful for assessing intercrop yield advantage. Therefore, it is recommended that the yield advantage of intercropping systems is evaluated using LER and EV rather than MV unless a cash economy exists.

Chapter 3

Analysis of Radiation Interception and Use

3.1. Introduction

Higher plants intercept incident radiation by their leaves (or foliage), utilise the absorbed radiant energy for photosynthesis and then partition the photosynthetic products in the accumulation of plant mass. Analysing this process is meaningful, especially under disease-free, non-stressed environmental conditions such as ample available water and fertile soil, because radiation is the key driving force in the ideal growth environment. For analysing this, three important indices may be pointed out, as summarised by Biscoe and Gallagher (1977): (i) the fraction of radiation intercepted (F), (ii) radiation use efficiency (RUE) and (iii) harvest index (HI).

F and RUE are measures of the radiation harvest of plants. Radiation interception is strongly dependent on the expanse of the leaf area (Biscoe and Gallagher, 1977). Therefore, it increases with crop growth and development (e.g., Natarajan and Willey, 1980b, 1985; Sivakumar and Virmani, 1980, 1984; Reddy and Willey, 1981; Watiki *et al.*, 1993). The transformation of radiant energy to chemical energy occurs in the chloroplast, and the chemical energy is utilised for the dry matter production. Indeed, many studies have shown a positive correlation of the amount of plant mass with radiation intercepted by crops in both sole cropping systems (e.g., Shibles and Weber, 1966; Monteith, 1977; Kiniry *et al.*, 1989) and intercropping systems (e.g., Natarajan and Willey, 1980b; Sivakumar and Virmani, 1980, 1984). General reviews of radiation interception and use have recently been made by Sinclair and Muchow (1999), and Keating and Carberry (1993) specifically for intercropping systems.

When dealing with an intercropping system, a major challenge concerning radiation interception and use is that it is extremely difficult to determine how much of the radiation is used by each of the component crops, hence F and RUE can be investigated only for the integrated system as a whole (Willey, 1990). It is not difficult to measure overall intercrop F. Overall intercrop RUE based on mass value is, however, not acceptable because of the different species of component crops. When plant ecologists compare production of different ecosystem, including several plant species, they express it as an energy (or caloric) value (Long, 1934; Golley, 1961). Likewise, it may be convenient to express RUE as a percentage of the energy value of plants per radiant energy captured by the plants, which is often referred to as growth efficiency (e.g., Gallagher and Biscoe, 1978; Fasheun and Dennett, 1982). So, in intercropping studies, it may be valuable to use the energy-based RUE because energy is a universal gauge of bio-productivity (e.g., Sivakumar and Virmani, 1980).

As emphasised by Niciporovic (1956), a distinction must be made between economic yield and total biological yield. Biological yield is the sum of the daily increment in dry matter and economic yield is limited to the product that is used for economic gain such as grain, fruit or tuber. Its relationship is expressed as the coefficient of effectiveness of formation of the economic part as a portion of the total biological yield (Niciporovic, 1956). This coefficient is called the harvest index (Donald, 1962). Since high HI with high biological yield achieves successful crop production, HI is widely used in agronomic research as it makes a notable contribution to the understanding of crop performance (Donald and Hamblin, 1976). In addition, Sinha *et al.* (1982) found that in cereals HI expressed on an energy basis was close to HI on a dry-matter basis, while in oil seeds energy-based HI was higher than HI on a dry-matter basis, indicating that the expression of HI on a dry weight basis is not adequate for comparing partitioning photosynthetic products in different crops. Thus, the energy-based HI should be used when comparing between different plant species, as discussed by Sinha *et al.* (1982), and among different cropping systems.

The spatial and temporal distribution of radiation transmission have been reported by several investigators in sole row crop canopies (e.g., Larson and Willis, 1957; Shaw and

Weber, 1967) and in intercrop canopies (e.g., Gardiner and Craker, 1981; Marshall and Willey, 1983; Matthews and Saffell, 1987). There are differences among locations where radiation transmitted through a crop canopy is measured between the rows. Particularly, at solar noon, the locations closer to crop rows have lower radiation transmitted. This suggests that radiation interception by crops during the vegetative growth periods must be spatially and temporally measured to determine F, as pointed out by Matthews and Saffell (1987). Tube solarimeters or linear quantum sensors have been adequate for these measurements (Szeicz *et al.*, 1964; Williams and Austin, 1977).

Many studies on radiation interception and use have been reported from other semi-arid regions (e.g., Natarajan and Willey, 1980b, 1985; Sivakumar and Virmani, 1980, 1984; Reddy and Willey, 1981; Marshall and Willey, 1983; Muchow and Coates, 1986; Azam-Ali *et al.*, 1990). However, little information concerning the production efficiency factors (F, RUE and HI) is available for the southern African semi-arid region. Therefore, the objective of this study was to compare intercrop production efficiency with sole crop production efficiency in terms of F, RUE and HI.

3.2. Materials and Methods

3.2.1. Field experiments

See Section 2.2.1 in Chapter 2.

3.2.2. Experimental designs

See Section 2.2.2 in Chapter 2.

3.2.3. Experimental measurements

Photosynthetically active radiation (PAR, 0.4 to 0.7 μm in wavelength) was measured above and beneath the plant canopies with the SunScan Canopy Analysis System (Delta-T Devices Ltd., Cambridge, England, U.K.) The System has a single quantum sensor (the

Beam Fraction sensor) and a linear quantum sensor (the SunScan probe, one metre long with 64 photodiodes equally spaced along its length gives 64 individual readings of PAR) for measuring PAR above and beneath plant canopies respectively. The readings from the radiation sensors were stored in a lightweight, robust field unit (the Data Collection Terminal). While the single quantum sensor was placed at the top of plant canopies, the linear quantum sensor was set perpendicular to the crop row from maize to maize at the soil surface. The PAR measurements were conducted at intervals of one week from 28 to 126 days after planting (DAP) for the 1998/1999 growing season and at intervals of two and three weeks from 42 to 126 DAP for the 1999/2000 growing season. PAR was measured between 8:30 and 9:30, between 11:30 and 12:30 and between 14:30 and 15:30 of South African Standard Time (SAST) during the 1998/1999 growing season, and between 10:00 and 14:00 of SAST in the 1999/2000 growing season. To determine daily incident PAR, solar radiation (SR) was recorded at the weather station of the Department of Agrometeorology, University of the Orange Free State (latitude 29°06'S, longitude 26°11'E, altitude 1411 m above sea level), using the LI-200SA pyranometer sensor (LI-COR Inc., Lincoln, Nebraska, U.S.A). The daily conversion of SR to PAR was assumed to be 0.5 (Monteith and Unsworth, 1990; Campbell and Norman, 1998).

Four above-ground plants per plot for each crop were harvested at intervals of one week or two weeks (from 28 to 126 DAP) for the 1998/1999 growing season. The plant samples were separated into the following components: leaf, stalk, ear and cob for maize, and leaf, stem, pod and seed for beans. The harvested samples were dried in an oven at 80 °C for 72 hours (3 days). Similarly, for the 1999/2000 growing season, two above-ground plants per plot for each crop were harvested at intervals of two or three weeks (from 42 to 126 DAP). Calorimetry was conducted for the determination of plant energy value using an oxygen bomb calorimeter, CP400 (Digital Data Systems Ltd., R.S.A.). The dry matter samples of 42, 70, 98 and 126 DAP in the 1998/1999 growing season were used for the analysis.

Leaf area of the plant samples for the 1998/1999 growing season was measured during the vegetative stages (28, 35, 42, 49, 56 and 70 DAP; i.e., until canopy closure) using a leaf area meter, L-3100 (LI-COR, Inc., Lincoln, Nebraska, U.S.A.). There is a positive linear correlation between leaf area and leaf weight; the ratio of leaf area to leaf weight depends on a plant species, or cultivar. This ratio is referred to as specific leaf area (SLA). Leaf area for the 1999/2000 growing season was estimated using the leaf area-weight linear regression analysis determined during the 1998/1999 growing season (using SLA).

3.2.4. Definitions

The fraction of radiation intercepted (F) is defined as the ratio between the radiation intercepted by plants and the incident radiation above the canopy (Sinclair and Muchow, 1999) and can be written as follows:

$$F = \frac{\sum_{i=1}^{n} \Phi_{IPAR} i}{\Phi_{PAR}} \qquad (3.1)$$

where n is number of plant species, Φ_{PAR} is the flux density of incident PAR and $\Phi_{IPAR}i$ is the flux density of PAR intercepted by plant species i.

Radiation use efficiency (RUE) is defined as the ratio between the chemical energy stored and the radiant energy intercepted by plants (Gallagher and Biscoe, 1978) and can be written as follows:

$$RUE = \frac{\sum_{i=1}^{n} NiE_{BY} i}{\sum_{i=1}^{n} \Phi_{IPAR} i} \qquad (3.2)$$

where Ni is the density of plant species i, $E_{BY}i$ is chemical energy stored in biological yield (above-ground dry matter) of plant species I, and is referred to as growth efficiency (Gallagher and Biscoe, 1978).

Havest index (HI) is defined as the ratio between the energy stored in economic yield (maize cobs and bean seeds) and the energy stored in biological yield (above-ground dry matter) (Sinha *et al.*, 1982) and can be written as follows:

$$HI = \frac{\sum_{i=1}^{n} NiE_{EY}i}{\sum_{i=1}^{n} NiE_{BY}i} \qquad (3.3)$$

where $E_{EY}i$ is chemical energy stored in economic yield of plant species i.

3.3. Results and Discussion

3.3.1. Radiation interception and leaf area

Careful measurements of radiation transmission (or interception) are essential for reducing the experimental errors, as emphasised by Matthews and Saffell (1987). They stated that a description of the spatial distribution of systematically distributed areas of shade beneath crop canopies is needed to explain a yield advantage in intercropping. In this experiment, the linear quantum sensor was set perpendicularly to the crop row to obtain the horizontal radiation profiles (64 individual readings). In all treatments, it was observed that during the vegetative stages, the closer locations to crop rows, the higher the PAR intercepted by crops, as found by several scientists (Gardiner and Craker, 1981; Marshall and Willey, 1983; Matthews and Saffell, 1987). This suggests that the radiation transmission should be measured not at one position but spatially between inter-rows.

Changes in the fraction of PAR intercepted (F) between 9:00 and 15:00 at a vegetative stage (42 DAP) in the 1998/1999 growing season are shown in Figure 3.1. In all cropping systems, F was higher at 9:00 and at 15:00 than at 12:00, supporting previous findings (e.g., Muchow *et al.*, 1982). Cropping systems in NS row direction had greater diurnal variation in F than those in EW row direction. Particularly, sole maize displayed a remarkable difference due to the wider row spacing, compared with sole beans and the intercrop. Thus, it is very important to consider time at which radiation transmission is measured in wide-spaced and NS-oriented row cropping when the measurements are conducted at a given time (because of the experimental limitations). Of course, there are no problems if it is measured continuously from sunrise to sunset.

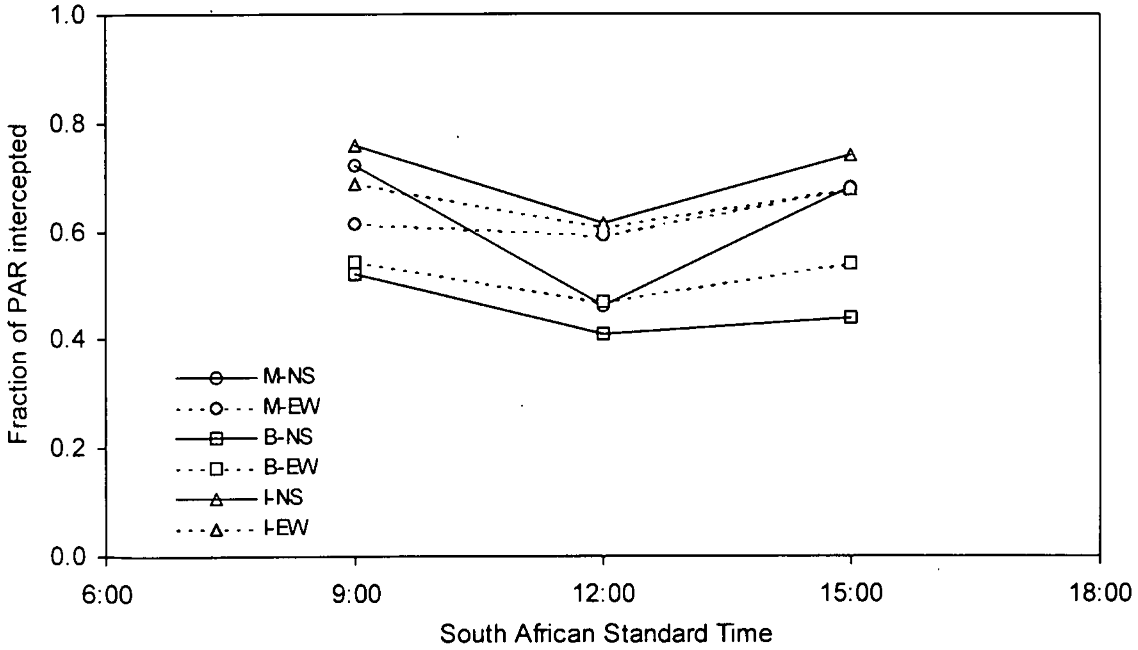


Figure 3.1. Diurnal changes in the fraction of PAR intercepted on 42 DAP (1998/1999 growing season).

There was no difference between the daily amounts of the intercepted radiation calculated on the basis of three F (at 9:00, 12:00 and 15:00) and on the basis of the mean F in the 1998/1999 growing season. For example, at 42 DAP, total incident radiation was 29.0 MJ

m^{-2} day^{-1}, and F for sole maize of north-south row (M-NS) at 9:00, 12:00 and 15:00 were 0.723, 0.460 and 0.680, averaging 0.621. Figure 3.2 shows the diurnal cycle of mean incident solar radiation of the 1998/1999 growing season. The cumulative solar radiant energy between sunrise and 10:30, between 10:30 and 13:30, and between 13:30 and sunset were 27 %, 41 % and 32 % respectively of the total energy. When calculated using the three F basis, the intercepted radiation was 17.4 MJ m^{-2} day^{-1}, whereas on the mean F basis, the intercepted radiation was 18.0 MJ m^{-2} day^{-1}. Thus, a difference of less than 5 % was observed. So, for the daily F during the 1998/1999 growing season, the mean F was used while F was measured between 10:00 and 14:00 during the 1999/2000 growing season.

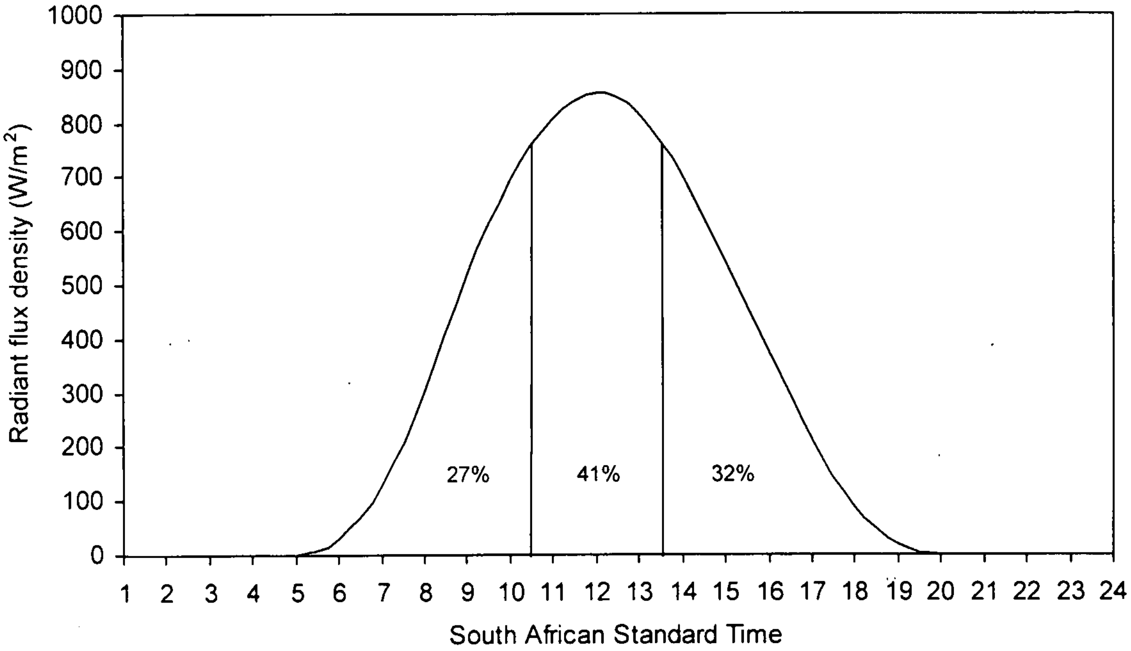
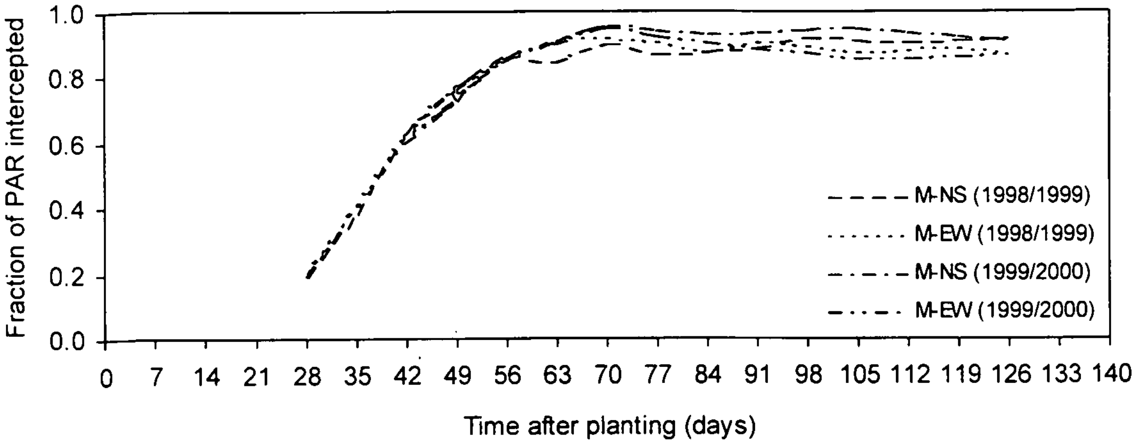


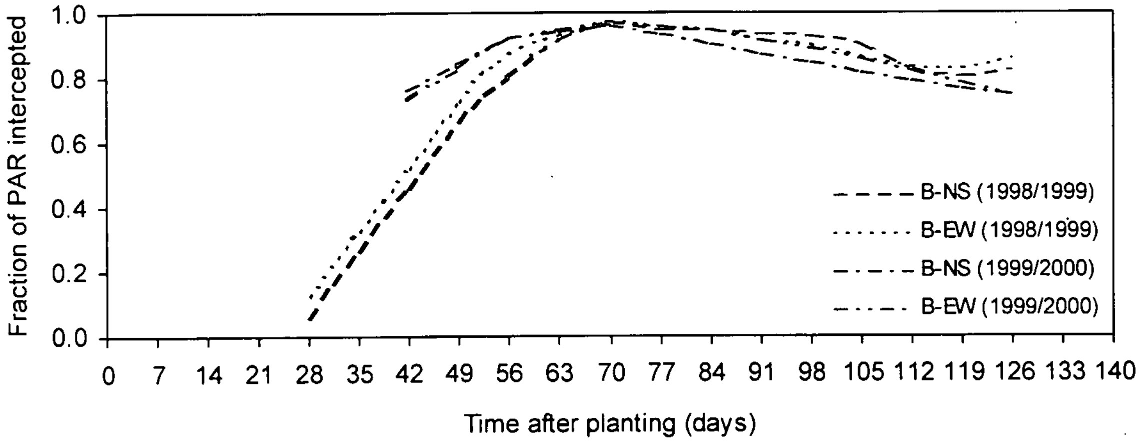
Figure 3.2. Mean incident solar radiation of the 1998/1999 growing season.

Figure 3.3 shows seasonal changes in F by sole cropped maize, sole cropped beans and the intercrop. The 1999/2000 growing season showed an analogous trend in F to the 1998/1999 growing season except for the vegetative growth stage of sole beans which was slightly higher F. In general, after seedling establishment (14 DAP), the F curve

(a) maize sole cropping



(b) bean sole cropping



(c) maize-bean intercropping

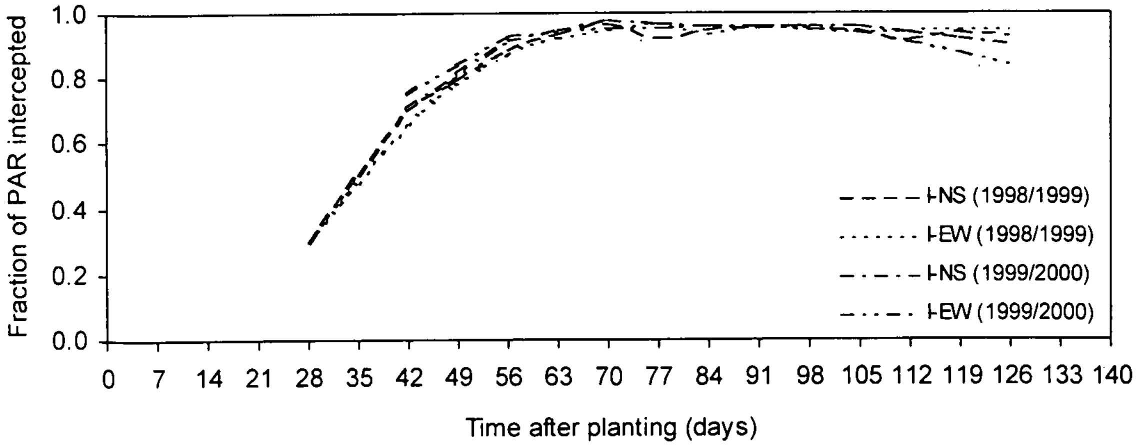


Figure 3.3. Seasonal changes in the fraction of PAR intercepted for the three cropping systems with NS and EW row directions.

showed a steep rise until canopy closure and the peak at 70 DAP. After that, it remained constant for sole maize and the intercrop and a slow decrease for sole beans was measured. This suggests that in all cropping systems, green leaves were retained until the end of the growing season, and this was in fact observed in the field. Similar F curves were reported for beans by Coulson (1985), sorghum by Muchow and Coates (1986), sorghum-pigeonpea intercropping by Natarajan and Willey (1985) and maize-cowpea intercropping by Watiki *et al.* (1993). In contrast, Sivakumar and Virmani (1980, 1984) reported that the F curves dropped steeply after the peak in maize-pigeonpea intercropping at ICRISAT Research Center, Hyderabad, India (17.5°N, 78.5°E and 545 m altitude), and Reddy and Willey (1981) also showed a similar trend in millet-groundnut intercropping, indicating that leaf senescence occurred soon after the peak of F.

In all systems (maize sole cropping, bean sole cropping and the intercropping), there was basically little difference in F between NS and EW row directions. When comparing between the cropping systems, during the vegetative stages, the intercrop had higher radiation interception than sole maize followed by sole beans in the 1998/1999 growing season (see Figure 3.3). This indicates that the intercrop canopy does close more quickly than the others. However, during the vegetative stages in the 1999/2000 growing season, the F for sole beans was equivalent in F to the intercrop and higher than sole maize. Sole beans showed higher F in the 1999/2000 growing season than in the 1998/1999 growing season until the peak was reached.

Specific leaf area (SLA) for sole cropped maize and bean and intercropped maize and beans is shown in Table 3.1. Intercropped beans had on average 34 % greater SLA than sole cropped beans while maize SLA was similar between sole cropping and intercropping. The difference found was remarkable in beans. Intercropped beans were shaded by maize due to tall growth pattern of maize. This shading resulted in thicker leaves. Similar effects of shading on legume have been reported by several authors (e.g., Bowes *et al.*, 1972; Crookston *et al.*, 1975; Hang *et al.*, 1984; Stirling *et al.*, 1990). LAI in the 1999/2000 growing season was estimated by multiplying the SLA by measured leaf dry matter.

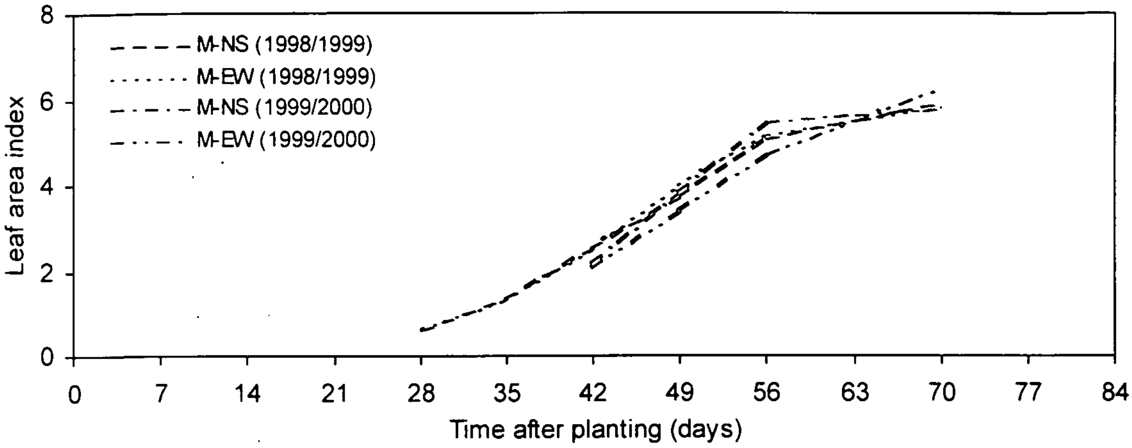
Table 3.1. Specific leaf area (SLA) of sole- and inter-cropped maize and beans (m^2 g^{-1}).

Crop	Cropping system	Row	Specific leaf area (SLA)	r-square (r^2)
Maize	Sole cropping	NS	0.0173	0.99
		EW	0.0170	0.99
	Intercropping	NS	0.0168	0.99
		EW	0.0173	0.99
Beans	Sole cropping	NS	0.0184	0.96
		EW	0.0195	0.96
	Intercropping	NS	0.0248	0.97
		EW	0.0258	0.92

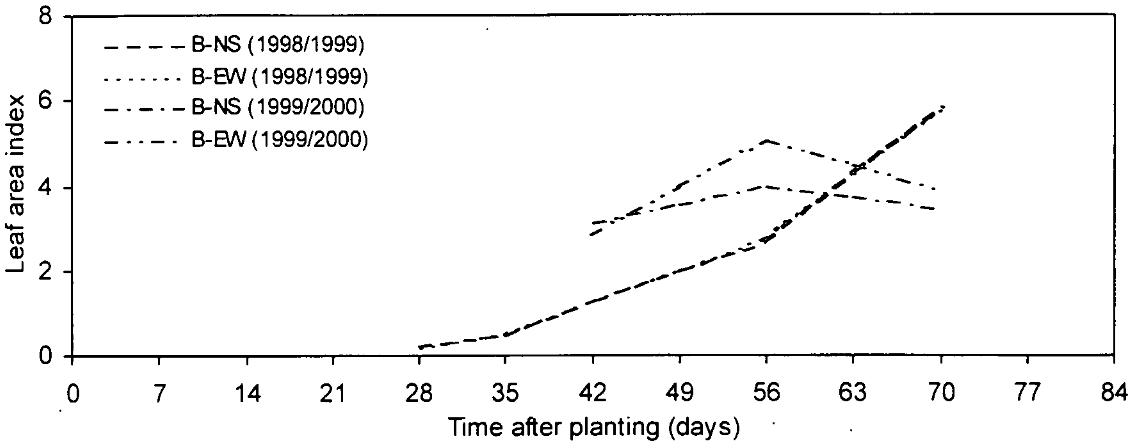
Changes in LAI during the vegetative periods are shown in Figure 3.4. Whereas in sole maize and under intercropping, LAI for the 1999/2000 growing season fit the curves of LAI for the 1998/1999 growing season, the leaf growth of sole beans was faster in the 1999/2000 growing season than in the 1998/1999 growing season, causing the higher F during the vegetative stage as noted above. This may result from the higher water availability during seedling establishment during the 1999/2000 growing season. It has been found by several authors that LAI patterns follow the patterns of radiation interception (Reddy and Willey, 1981; Sivakumar and Virmani, 1984; Watiki *et al.*, 1993). The present findings confirm those findings.

The relationship between radiation interception and leaf area is presented in Figure 3.5. There was significant correlation between the natural logarithm of radiation transmission and LAI in all cropping systems (r-square ≥ 0.85). The slope is often referred to as the extinction coefficient (K), generally explaining the average projection area of canopy elements onto a horizontal surface (Campbell and Norman, 1989). In this study, K was

(a) maize sole cropping



(b) bean sole cropping



(c) maize-bean intercropping

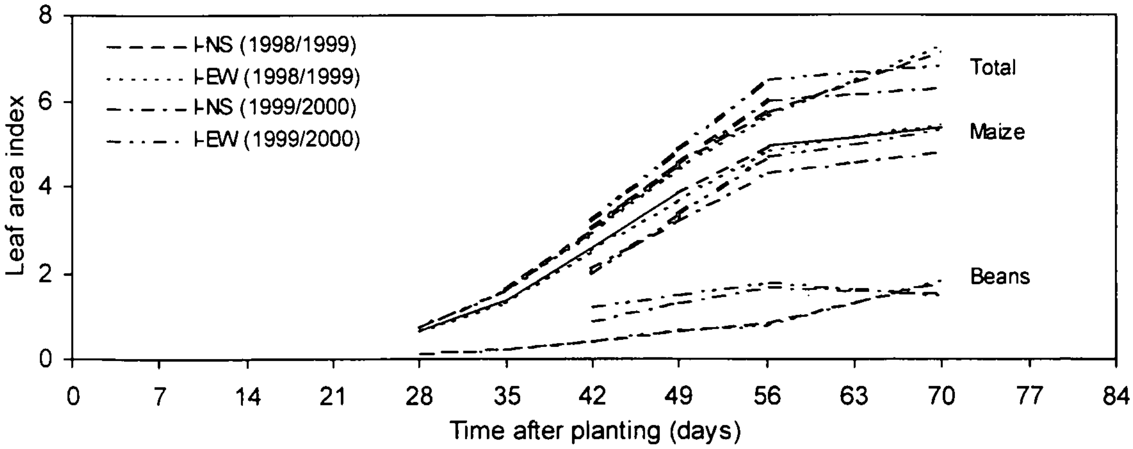


Figure 3.4. Changes in leaf area index for three cropping systems during the growing season of 1998/1999 (measured) and 1999/2000 (calculated).

calculated on a daily basis. There was no difference in the K value calculated from NS and EW row orientation treatments. The intercrop had overall K = 0.45 almost equal to that of sole maize (K = 0.43), and they both had a smaller K than sole beans (K = 0.64). It has been found empirically that K varies from 0.3 to 1.5; K values of less than 1.0 are obtained for non-horizontal leaves or clumped leaf distributions whereas K greater than 1.0 is obtained for horizontal leaves or regular leaf distributions (Jones, 1992). In this study, although all of the cropping systems had K less than 1.0, indicating non-horizontal leaves, sole beans tended to have more horizontal leaves than the others shown by the greater K values.

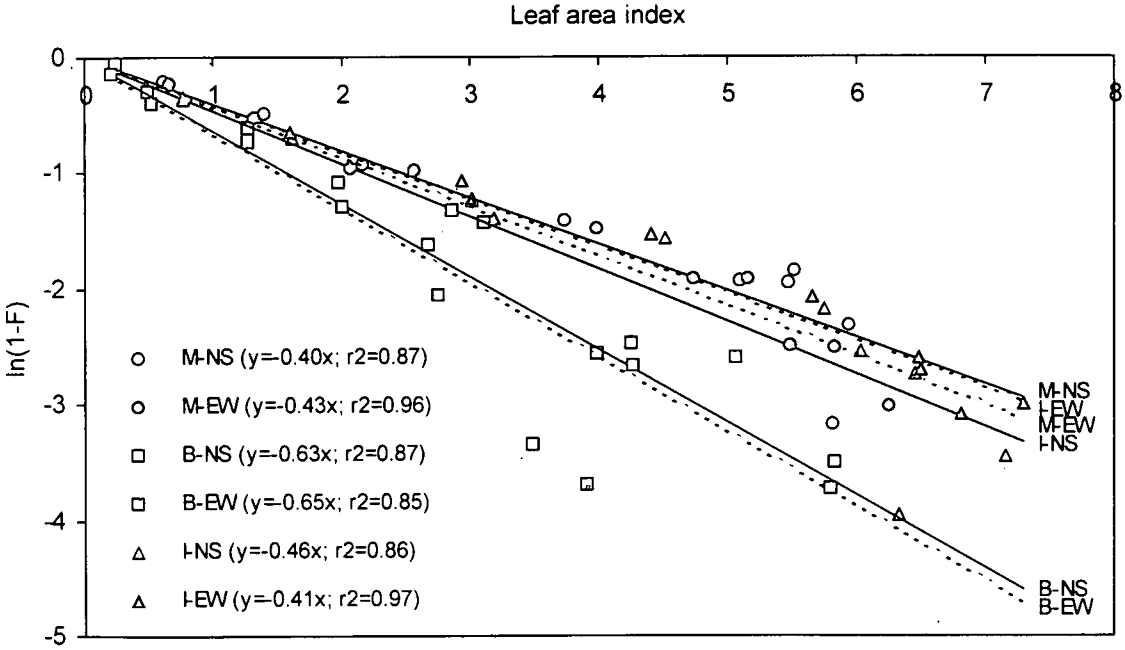


Figure 3.5. Extinction coefficient of sole maize and beans and the intercrop (data from both seasons).

3.3.2. Plant energy and intercepted radiation

The conversion factors from mass to energy of different plant components (leaf, stalk, ear and cob for maize and leaf, stem, pod and seed for beans) were obtained at the different growth stages (early and late vegetative stages, reproductive stage and maturity) (Table

3.2). There was little difference in average energy content between maize (17.0 kJ g^{-1}) and beans (16.7 kJ g^{-1}) nor in energy content of each component between maize and beans: between maize leaves (17.6 kJ g^{-1}) and bean leaves (16.7 kJ g^{-1}), between maize stalks (16.2 kJ g^{-1}) and bean stems (16.4 kJ g^{-1}), between maize ears (17.4 kJ g^{-1}) and bean pods (17.8 kJ g^{-1}), and between maize cobs (17.8 kJ g^{-1}) and bean seeds (16.8 kJ g^{-1}). The differences were less than 6 %. Various conversion factors have been reported for plant components of maize (Ovington and Lawrence, 1967; Lieth, 1968, 1975; Girardin, 1985). The ranges for leaf, stalk and ear components of maize are from 16.5 kJ g^{-1} to 17.8 kJ g^{-1}, from 15.8 kJ g^{-1} to 17.6 kJ g^{-1} and from 16.9 kJ g^{-1} to 18.4 kJ g^{-1}, respectively. The average conversion factors presented here fell within those ranges. For beans, the present average energy content was slightly greater than the previous findings ranging 15.9 kJ g^{-1} to 16.8 kJ g^{-1} (Lieth, 1968).

Table 3.2. The conversion factor of mass value to energy value for maize and beans (kJ g^{-1}).

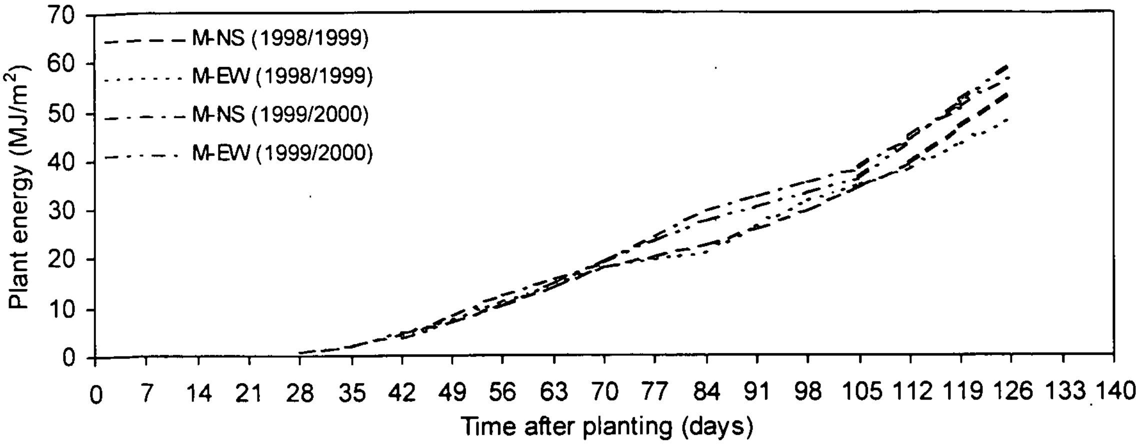
Growth stage	Plant components	Maize	Beans
42 DAP (early vegetative)	Leaf	18.5	17.6
	Stalk or Stem	16.6	16.5
70 DAP (late vegetative)	Leaf	17.1	17.0
	Stalk or Stem	15.5	17.1
	Ear or Pod	17.1	18.3
98 DAP (reproductive)	Leaf	17.1	15.5
	Stalk or Stem	16.4	15.6
	Ear or Pod	17.7	17.3
126 DAP (maturity)	Cob or Seed	17.8	16.8
	Other	16.0	15.6
Overall		17.0 ± 0.9	16.7 ± 0.9

Based on the above conversion factors, plant energy (PE), defined as chemical energy (calories) stored in plant mass, was calculated. Seasonal changes in PE were shown in

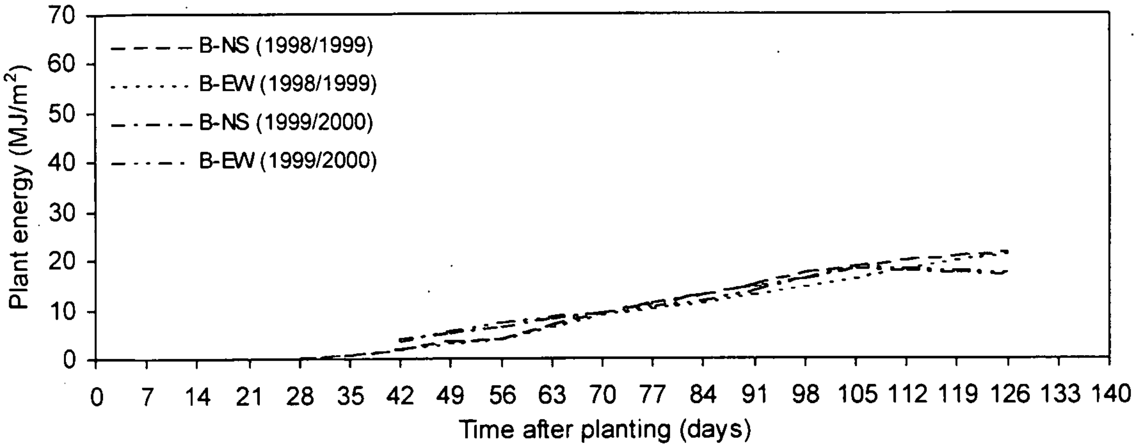
Figure 3.6. Basically, the data of the 1999/2000 growing season fits the growth curve in the 1998/1999 growing season except for the data on 126 DAP. An ideal plant growth curve is an S-shape (the logistic, the Gompertz, the Chanter and the Richards growth curves) (France and Thornley, 1984; Thornley and Johnson, 1990). However, the growth rate of crops under optimum environmental conditions is constant during most of the growing season (Goudriaan and Monteith, 1990; Monteith, 2000). Goudriaan and Monteith (1990) proposed that the plant growth curve transitioned from exponential to linear, referred to as the expolinear growth curve, showing the linear growth in most of the growth stages. The present growth curves for all cropping systems were also linear-like (r-squares > 0.92 in linear regression analysis of all cropping systems and row orientation treatments). Correspondingly, seasonal changes in the cumulative PAR intercepted (IPAR) tended to be linear (Figure 3.7), indicating a linear relationship between PE and IPAR.

The relationships between IPAR and PE are presented in Figure 3.8 (excluding the data from 126 DAP). The regression line should intercept zero because radiation is the driving force in the ideal growth environment; that is, at zero intercepted radiation, there is no biomass accumulation on the basis of its photosynthetic system. Highly positive correlations were found for all cropping systems (r-square > 0.96). The slope of this regression line is normally called the radiation use efficiency (RUE). The crops planted in NS row direction tended to have slightly higher RUE than those in EW row orientation. Although no significant difference in RUE was found between sole maize and the intercrop, on average the sole maize RUE (0.047) was 9 % higher than the intercrop RUE (0.043). Sole beans had a value of approximately a half of RUE of sole maize cropping and the intercropping (0.024). The higher RUE of sole maize resulted from the greater energy conversion ability of C_4 plant species. The RUE of the intercrop may be explained by the mixed RUE of maize (C_4 plants) and beans (C_3 plants, the lower energy conversion plants than C_4 plants). Also, Sivakumar and Virmani (1980) reported that RUE was 0.053 for sole maize, which is higher than the present finding. For beans, the present result was higher than the value of 0.017 reported by Coulson (1985).

(a) maize sole cropping



(b) bean sole cropping



(c) maize-bean intercropping

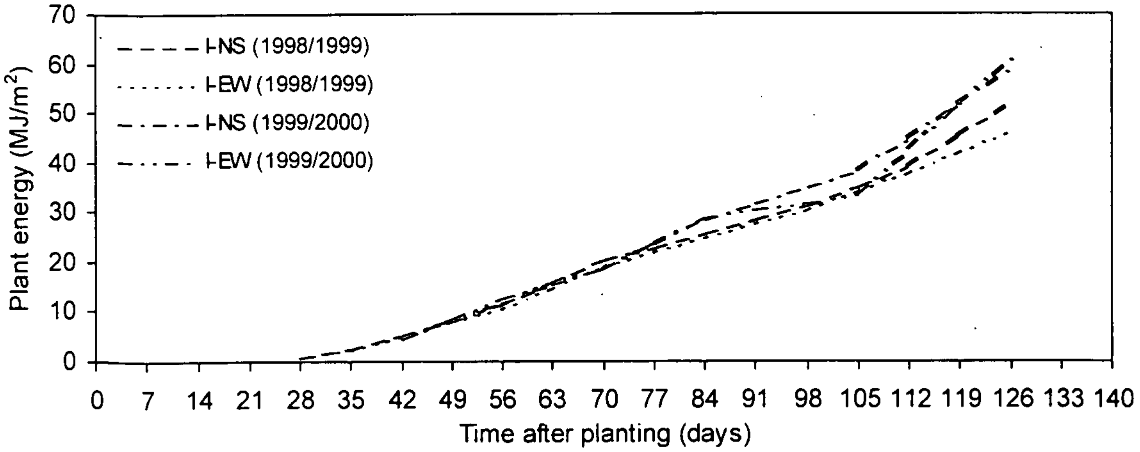
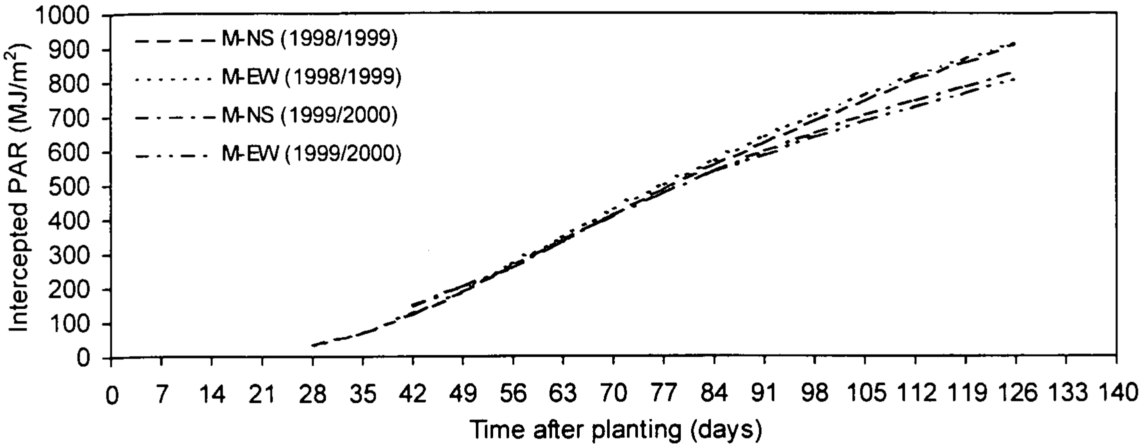
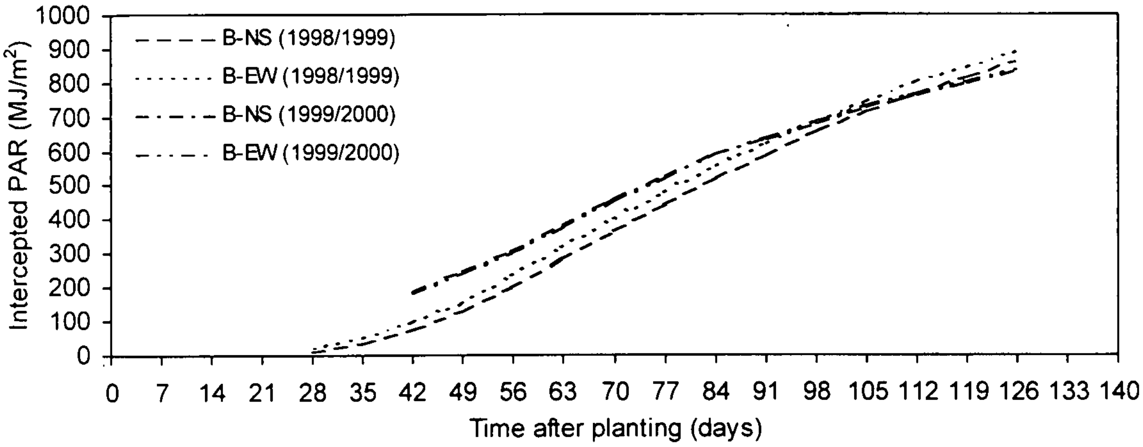


Figure 3.6. Seasonal changes in plant energy for the three cropping systems for the 1998/1999 and 1999/2000 growing seasons.

(a) maize sole cropping



(b) bean sole cropping



(c) maize-bean intercropping

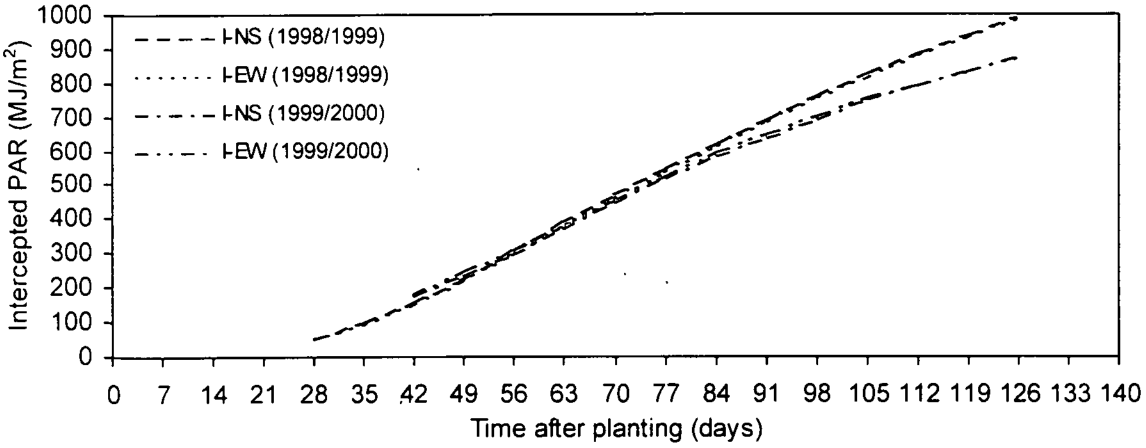


Figure 3.7. Seasonal changes in the cumulative PAR intercepted for the three cropping systems for the 1998/1999 and 1999/2000 growing seasons.

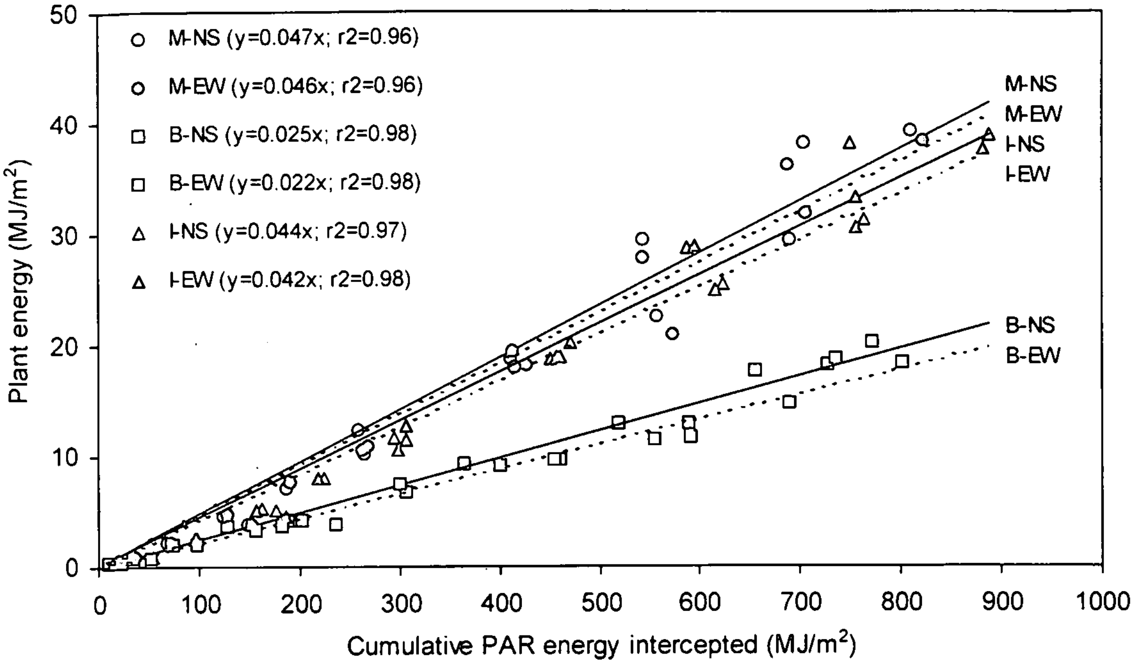


Figure 3.8. Radiation use efficiency (as slope of energy intercepted and plant energy accumulated in biomass) of sole maize and beans and the intercrop (including both seasons).

Another analytical method for RUE is that RUE can be calculated from the difference in plant mass (plant energy) between two consecutive harvests, divided by the corresponding amount of radiation intercepted. However, this method suffers from large errors associated with calculated differences (Sinclair and Muchow, 1999). The means and standard deviations, including both seasons, are presented in Table 3.3. No difference was found in RUE between row orientation treatments in all cropping systems. The sole maize RUE (0.053 on average) was 10 % higher than the intercrop RUE (0.048) followed by the sole bean RUE (0.024). RUE calculated here for sole maize and the intercrop was more than 10 % higher than RUE based on the linear regression method whereas RUE for sole beans was similar between methods. Figure 3.9 shows seasonal changes in RUE for three cropping systems. All of the seasonal changes in RUE tended to fluctuate over seasons and the high standard deviation could be an explanation for the fluctuation of

RUE. Because this fluctuation may result in errors in the determination of RUE, the linear regression method is recommended and therefore these values will be used.

Table 3.3. Means and standard deviations of RUE* for the three cropping systems (including both seasons).

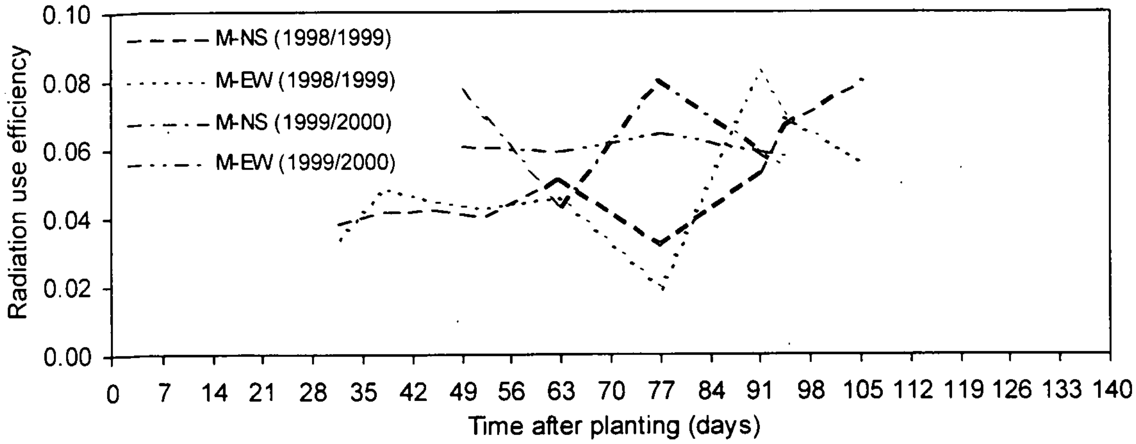
	NS row orientation	EW row orientation
Sole maize	0.053 ± 0.017	0.052 ± 0.016
Sole beans	0.025 ± 0.008	0.023 ± 0.011
Maize-bean intercrop	0.049 ± 0.011	0.046 ± 0.013

*RUE was calculated from the difference in plant energy between two consecutive harvest divided by the corresponding amount of PAR intercepted.

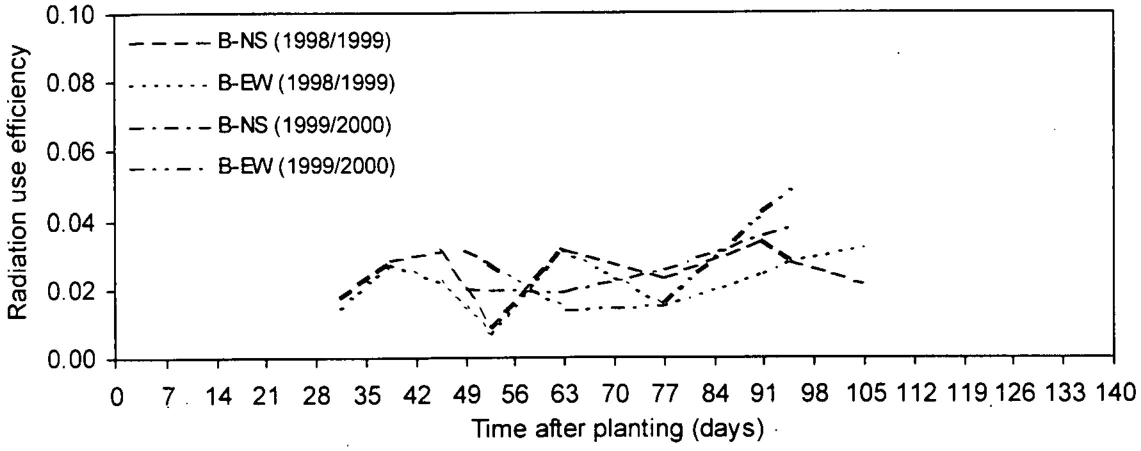
3.3.3. Harvest index

In both growing seasons, there was no statistically significant HI difference in cropping systems and row orientations (Table 3.4). On average, the HI of sole maize, sole beans and the overall intercrop were 0.45, 0.41 and 0.46, respectively. The HI of the components of the intercrop were 0.46 for maize and 0.31 for beans. In individual crops, while no significant difference in HI was found between sole cropped maize and intercropped maize, sole cropped beans had a significantly greater HI than intercropped beans in both growing seasons (p-values < 0.05). Intercropped beans were shaded by maize intercroped with them, the growth was limited and probably little partition of photosynthetic products into pods occurred. Zimmermann *et al.* (1985) reported that beans intercropped with maize had smaller HI than sole cropped beans, which is echoed in the present experiment. By contrast, Natarajan and Willey (1980a, 1985) found that the HI of pigeonpea intercropped with sorghum was larger than that of sole pigeonpea. They explained that the increased HI in intercropping was not a direct effect of shading by sorghum because sole pigeonpea was similar in the relative partition of dry matter (roots, leaves and stems) to intercropped pigeonpea at the harvest of sorghum, which is an earlier maturing crop than pigeonpea. After sorghum harvest, intercropped pigeonpea

(a) maize sole cropping



(b) bean sole cropping



(c) maize-bean intercropping

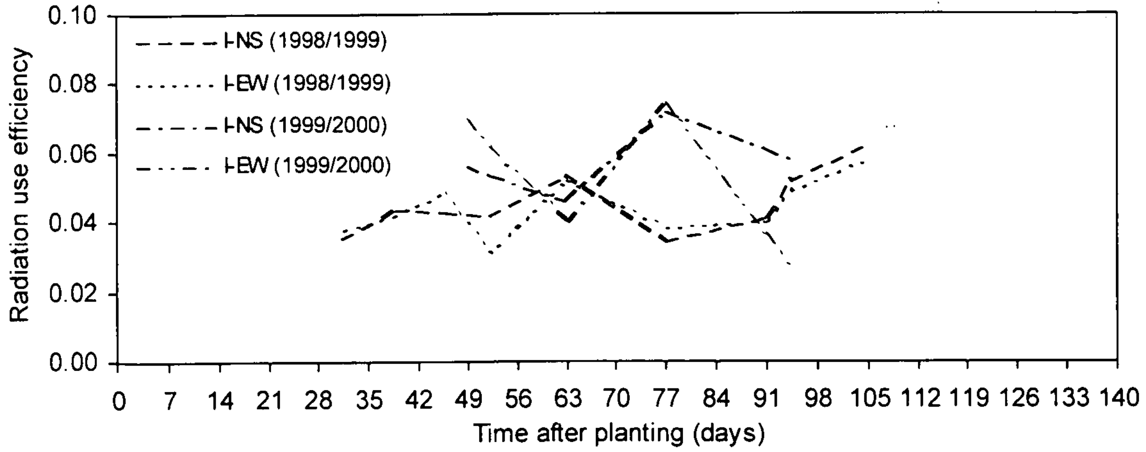


Figure 3.9. Seasonal changes in radiation use efficiency for the three cropping systems for the 1998/1999 and 1999/2000 growing seasons.

accumulated a greater proportion of dry matter and pod growth. It is not clear why intercropping gave higher HI of pigeonpea associated with sorghum.

Table 3.4. Harvest index (based on energy value) of sole- and inter-cropped maize and beans (mean ± standard error).

Cropping system		1998/1999 growing season	1999/2000 growing season
M-NS		0.45 ± 0.03	0.47 ± 0.07
M-EW		0.43 ± 0.07	0.44 ± 0.02
B-NS		0.42 ± 0.06	0.43 ± 0.05
B-EW		0.38 ± 0.08	0.42 ± 0.07
I-NS	Overall	0.46 ± 0.04	0.43 ± 0.07
	Maize	0.47 ± 0.04	0.43 ± 0.08
	Beans	0.29 ± 0.04	0.31 ± 0.12
I-EW	Overall	0.47 ± 0.05	0.46 ± 0.05
	Maize	0.48 ± 0.05	0.47 ± 0.04
	Beans	0.30 ± 0.04	0.34 ± 0.12

3.4. Conclusions

The main findings in this study were as follows: firstly, the intercrop intercepted more PAR energy than sole maize and sole beans; secondly, sole maize utilised radiant energy more efficiently than the intercrop, and it had greater RUE than sole beans; and thirdly, no difference in HI was found between the cropping systems. The higher F of intercrop resulted from the high LAI and the higher RUE of sole maize resulted from the great energy conversion of C_4 plant species. Thus, because the intercrop had higher F and lower RUE than sole maize, the intercropping may be equivalent to maize sole cropping in the overall efficiency of radiation interception and use. In sole maize and bean production systems in a given area of land, increase in the area of sole bean planting (or decrease in the area of sole maize planting) results in a lower total sole crop efficiency of radiation interception and use because of the lower RUE of sole beans. Consequently, when it is considered that both maize and beans would be planted, the intercropping system has higher efficiency of radiant energy harvests than the sole cropping systems. This agrees with the conclusion in intercrop productivity reported in the previous study. In addition, it seemed that NS row direction gave higher RUE and HI, but there was no clear difference in F, RUE and HI between NS and EW row orientations. The effect of row orientation on intercrop efficiency is therefore negligible.

Chapter 4

Modelling of Radiation Interception and Use

4.1. Introduction

Radiation transmission through plant canopies is dependent on the magnitude of leaf area because leaves constitute the turbid medium, i.e., the absorber and the reflector. The other important factor affecting the radiation transmission is the leaf angle distribution, which influences the canopy extinction coefficient. The extinction coefficient describes the average projection area of canopy elements onto a surface normal to the direction of the projection (the G-function) or the average projection area of canopy elements onto a horizontal surface (the K-function), depending on solar zenith angle ψ (Figure 4.1) (Campbell and Norman, 1989). The G-function (g) is related to the K-function (k) by:

$$k = g\cos\psi \tag{4.1}$$

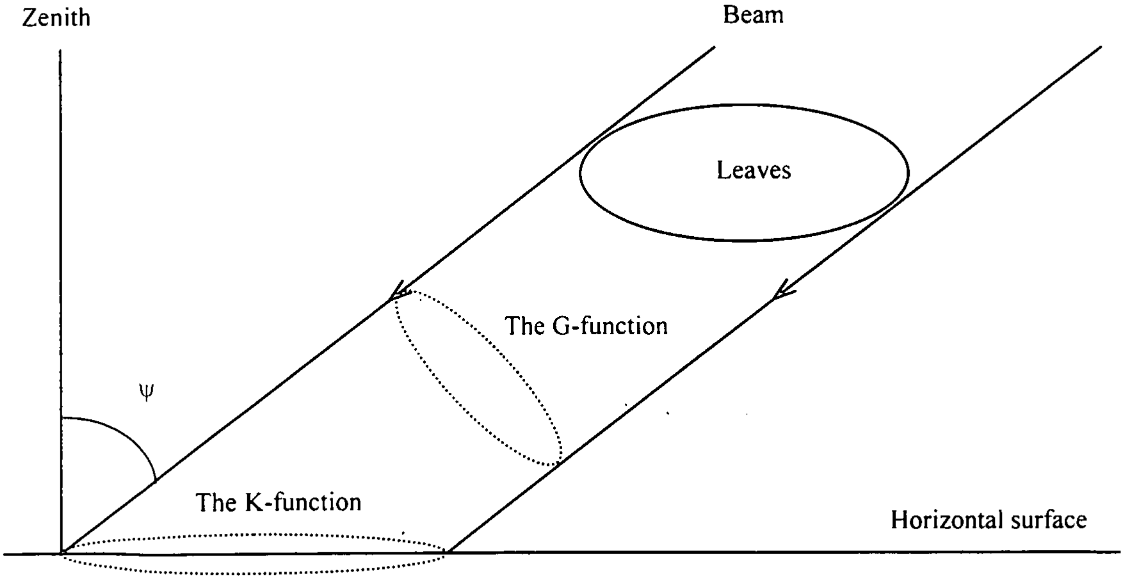


Figure 4.1. Schematic explanation of the G- and K-functions.

The extinction coefficient may be determined using the integral of a leaf angle distribution function of solar zenith angle (Campbell and Norman, 1989). Several classes of leaf angle distributions have been proposed: i.e., planophile (horizontal leaves), erectophile (vertical leaves), plagiophile (inclined leaves), spherical (same proportion of leaf angles at any angles) and ellipsoidal (Ross, 1981; Campbell and Norman, 1989). The ellipsoidal distribution function jointly represents planophile, erectphile, plagiophile and spherical distribution functions (Campbell, 1986, 1990).

Radiation transfer models for plant canopies are broadly grouped into two types: the statistical and geometrical methods (Lemeur and Blad, 1974). Plant canopies are described as a turbid layer in the statistical method and as a geometrical figure in the geometrical method. The former method has been discussed in horizontally homogeneous canopies by several authors (Monsi and Saeki, 1953; Monteith, 1965; Anderson, 1966; Cowan, 1968; Miller and Norman, 1971; Mann *et al.*, 1977). In contrast, the geometrical method may be used for heterogeneous canopies (Allen, 1974; Charles-Edwards and Thorpe, 1976; Goudriaan, 1977; Palmer, 1977; Mann *et al.*, 1980; Norman and Welles, 1983; Gijzen and Goudriaan, 1989; Nilson, 1992).

In a horizontally homogeneous plant canopy, Monsi and Saeki (1953) presented a simple model of radiation attenuation within the plant canopy based on the Poisson distribution, describing the random dispersion of foliage (leaves). The model is written as the exponential function of the product of canopy extinction coefficient and leaf area index (LAI):

$$I = I_0 \exp(-kLAI) \qquad (4.2)$$

where I and I_0 are the intensity of radiation at ground level and above the plant canopy respectively. The equation is analogous to the Beer's Law for radiation absorption in a homogeneous medium in the atmosphere. Thereafter, the model has been modified with regard to radiation transmissivity of leaves, solar elevation, foliage dispersion, etc.

(Kasanaga and Monsi, 1954; Saeki, 1963; Anderson, 1966; Duncan *et al.*, 1967; Cowan, 1968; Monteith, 1969; Norman, 1975). Monteith (1965) introduced the simple radiation attenuation models based on binomial distributions, which describe the regular (the positive binomial) and clumped (the negative binomial) dispersion of foliage. Nilson (1971) theoretically explained the Poisson and the binomial distribution models, and Mann *et al.* (1977) derived the radiation transfer model for all cases, referred to as the general model, emphasising that the Poisson distribution model was a specific case of the radiation transfer models. Independently, Miller and Norman (1971) theorised a radiation transfer model based on the size distribution of sunflecks (the distribution of gap fraction).

In a horizontally heterogeneous plant canopy, Allen (1974) assumed the plant canopy to be a rectangular hedgerow. Many researchers have since used the hedgerow model (Fukai and Loomis, 1976; Goudriaan, 1977; Cohen and Fuchs, 1987; Gijzen and Goudriaan, 1989; Yang *et al.*, 1990a, b; Thevenard *et al.*, 1999). Normally, assuming random dispersion of foliage within the hedgerow, the radiation attenuation model is given by:

$$I = I_0 \exp(-gLADs) \tag{4.3}$$

where LAD is leaf area density and s is radiation path length. Also, Palmer (1977) introduced the triangle hedgerow canopy model, and Charles-Edwards and Thorpe (1976) introduced the ellipsoid hedgerow canopy model. In three-dimensional canopy models, Mann *et al.* (1980), Norman and Welles (1983), Whitfield (1986), Röhrig *et al.* (1999) and Mariscal *et al.* (2000) modelled radiation attenuation into ellipsoid plant canopies. Also, corn, cube and cylinder shapes have been exploited by several researchers (Jahnke and Lawrence, 1965; Brown and Pandolfo, 1969; Arkin, *et al.*, 1978; Kuuluvainen and Pukkala, 1987).

With respect to a two-plant species canopy, Ross *et al.* (1972) first applied the Poisson distribution model to a grass-legume mixture. The model for the grass and legume mixture (denoted by subscripts g and l respectively) is given by:

$$I = I_0 \exp\left(-k_g LAI_g - k_l LAI_l\right) \qquad (4.4)$$

This model estimates the total radiation intercepted by the mixture. Thereafter, models have been developed for multiple plant species and multiple canopy layers (Spitters and Aerts, 1983; Ryel *et al.*, 1990; Sinoquet *et al.*, 1990; Sinoquet and Bonhomme, 1991; Kropff and Spitters, 1992; Lantinga *et al.*, 1999).

Wallace *et al.* (1990, 1991) introduced a one-dimensional radiation transfer model in sugar cane and maize intercropping. The canopy was assumed to be vertically homogeneous. Sinoquet and Bonhomme (1992) introduced a two-dimensional radiation transfer model for an intercrop canopy (intercropping of maize at early vegetative stages and maize at late vegetative stages) based on turbid medium analogy. They divided the space into cells according to horizontal layers and vertical slices parallel to row orientation because of the spatially heterogeneous canopy. Recently, Ozier-Lafontaine *et al.* (1997) studied radiation interception models in a maize-sorghum intercrop canopy using both models mentioned above. They verified that both models predicted radiation intercepted by the intercrop canopy with high accuracy. In that study, as well as the study of Wallace *et al.* (1990, 1991), similar plant stands were used, i.e., maize and sorghum. Also, Sinoquet and Bonhomme (1992) used the same plant species (maize) and planted on different dates in order to create a tall and short maize intercropping canopy. Thus, no study on the radiation modelling in cereal-legume intercropping canopies was reported.

Radiation partitioning in multiple cropping may be necessary to determine radiation interception by each crop. However, it is difficult to distinguish the contribution of each crop to the radiation interception (Ozier-Lafontaine *et al.*, 1997). Several authors have presented models for partitioning radiation intercepted by each plant component (e.g., Marshall and Willey, 1983; McMurtrie and Wolf, 1983; Rimmington, 1984, 1985; Wallace *et al.*, 1990, 1991; Sinoquet and Bonhomme, 1992; Keating and Carberry, 1993). For example, Marshall and Willey (1983) and Wallace *et al.* (1991) developed radiation partitioning models in millet-groundnut intercrop canopy and a sugar cane-maize intercrop canopy respectively.

Intercropping plays an important role in subsistence and food production in developing countries. In the past, many studies were carried out on intercrop radiation interception (e.g., Sivakumar and Vermani, 1980, 1984; Reddy and Willey, 1981; Natarajan and Willey, 1985; Watiki *et al.*, 1993), however, only a few crop radiation interception or transmission models for intercropping have been reported (e.g., Wallace *et al.*, 1991; Sinoquet and Bonhomme, 1992; Ozier-Lafontaine *et al.*, 1997). For the instantaneous radiation transmission in early plant growth stages, or in the wide spacing plant canopies, the geometrical method may be more accurate than the statistical method, as has been reported by many scientists (e.g., Allen, 1974; Charles-Edwards and Thorpe, 1976; Mann *et al.*, 1980; Norman and Welles, 1983; Whitfield, 1986; Gijzen and Goudriaan, 1989; Röhrig *et al.*, 1999; Mariscal *et al.*, 2000). In contrast, the statistical method may be used for the daily radiation transmission model. The objective in this study was, therefore, to build and test an instantaneous radiation transmission model for an intercrop canopy using the geometrical method and the daily model using the statistical method. Also, it may be necessary to estimate radiation interception and use by each component crop, so the additional objective is to estimate the daily amount of radiation intercepted and used by each component crop.

4.2. Materials and Methods

In this section, firstly the instantaneous and daily radiation models were developed, secondly the partitioning radiation models were described, and thirdly the data collection for model validation and the method of model evaluation were explained.

4.2.1. Model description of the instantaneous radiation transmission

In a row crop, the inter-row spacing is much wider than the intra-row spacing. Neglecting the intra-row spacing, the row can be assumed to be a rectangular hedgerow. Radiation turbid mediums between canopy and soil surfaces are crop foliage and the atmosphere (whose turbidity is assumed to be nil). The turbid layer thickness is the hedgerow height, and the vertical boundary between crop foliage and the atmosphere is determined by the hedgerow width and the inter-row spacing. In maize (*Zea mays* L.) and bean (*Phaseolus vulgaris* L.) alternative intercropping, the cross-section of rectangular hedgerows is divided into two horizontal layers: (i) between the top of maize and the top of beans (the first turbid layer) and (ii) between the top of beans and the surface of soil (the second turbid layer) to account for maize hedgerows being taller than bean hedgerows. The horizontal boundaries are determined by the hedgerow heights of maize and beans. The turbid mediums in the layers include maize foliage, bean foliage, maize/bean mixed foliage and the atmosphere. The vertical boundaries are determined by the hedgerow width of maize and beans and its inter-row spacing. The horizontal and vertical boundaries determine a specific turbid medium cell. The various possible types of the maize-bean intercrop canopy are shown in Figure 4.2. The maximum number of turbid mediums are two for the first turbid layer and three for the second turbid layer, while the minimum turbid mediums are one for both layers. In each turbid layer, a vertical stripe of the turbid mediums is formed, and the combination of the stripe layers has a systematic pattern.

Assuming that both maize and beans have black leaves and random leaf dispersion and separating the product of g, LAD and s into the four classes of the turbid mediums, the direct radiation transmission on a horizontal surface from canopy surface to soil surface is given by the Beer's Law:

$$\begin{aligned} I = I_0 \exp\big[& - g_{\psi,M} LAD_M s_{\psi,\phi,M} - g_{\psi,B} LAD_B s_{\psi,\phi,B} \\ & - \left(g_{\psi,M} LAD_M + g_{\psi,B} LAD_B \right) s_{\psi,\phi,M/B} - g_{\psi,A} LAD_A s_{\psi,\phi,A} \big] \end{aligned} \tag{4.5}$$

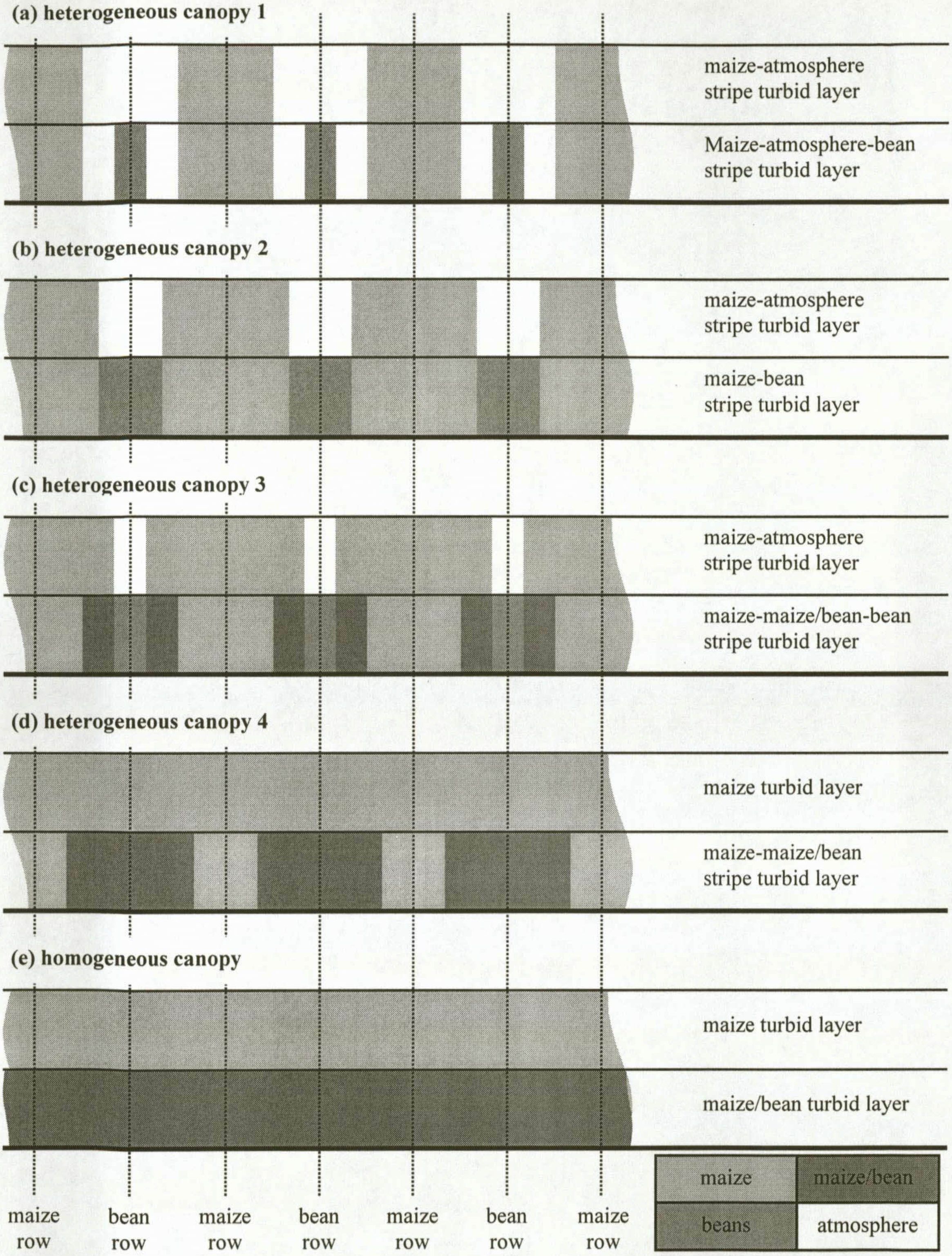


Figure 4.2. Types of the cross-section plane of the maize-bean intercrop rectangular hedgerow.

where I and I_0 are direct radiant flux densities at the surface of soil and the top of canopy respectively, g_ψ is canopy extinction coefficient (the G-function) at a given zenith angle ψ, LAD is leaf area density, $s_{\psi,\phi}$ is the total radiation path length from the top of the canopy surface to the soil surface at a given solar position (zenith angle ψ, azimuth angle ϕ), Subscripts of M, B, M/B and A denote maize, bean, the maize/bean mixture and the atmosphere. Actually, the product of $g_{\psi,A}$, LAD_A and $s_{\psi,\phi,A}$ is zero, so that the equation is rewritten as follows:

$$I = I_0 \exp\left[- g_{\psi,M} LAD_M \left(s_{\psi,\phi,M} + s_{\psi,\phi,M/B}\right) - g_{\psi,B} LAD_B \left(s_{\psi,\phi,B} + s_{\psi,\phi,M/B}\right)\right] \tag{4.6}$$

where $s_{\psi,\phi,M} + s_{\psi,\phi,M/B}$ and $s_{\psi,\phi,B} + s_{\psi,\phi,M/B}$ are equal to radiation path length for the maize hedgerow and the bean hedgerow respectively.

The total diffuse radiation transmission can be derived by integrating the direct radiation attenuation function over the hemisphere (all zenith and azimuth angles), assuming a uniform overcast sky (Campbell and Norman, 1998). In order to compare the geometrical method with the statistical method, the direct radiation transmission model is based on the statistical method. The assumption is made that maize and bean canopies in the intercropping are horizontally homogeneous (see Figure 4.2e), and the equation is given by:

$$I = I_0 \exp\left(- k_{\psi,M} LAI_M - k_{\psi,B} LAI_B\right) \tag{4.7}$$

where $k_{\psi,M}$ and $k_{\psi,B}$ are canopy extinction coefficients (the K-function) for maize and beans, and LAI_M and LAI_B are LAI for maize and beans respectively.

The G- and K-functions are given by:

$$g_{\psi} = \frac{\sqrt{\chi^2 \cos^2 \psi + \sin^2 \psi}}{\chi + 1.774(\chi + 1.182)^{-0.733}} \qquad (4.8)$$

$$k_{\psi} = \frac{\sqrt{\chi^2 + \tan^2 \psi}}{\chi + 1.774(\chi + 1.182)^{-0.733}} \qquad (4.9)$$

where χ is the ratio of vertical to horizontal projections of canopy elements; $\chi \rightarrow 0$ for predominantly vertical leaf angle distributions and $\chi \rightarrow \infty$ for predominantly horizontal leaf angle distributions, and also $\chi = 1$ for a spherical leaf angle distribution (Campbell and Norman, 1989). Figure 4.3 shows the ellipsodial leaf angle distribution functions for maize and beans, which were determined during the 1998/1999 growing season. The calculated canopy χ is 0.85 for maize and 2.12 for beans. The type of the maize leaf angle is spherical while the bean leaf angle type is more planophile.

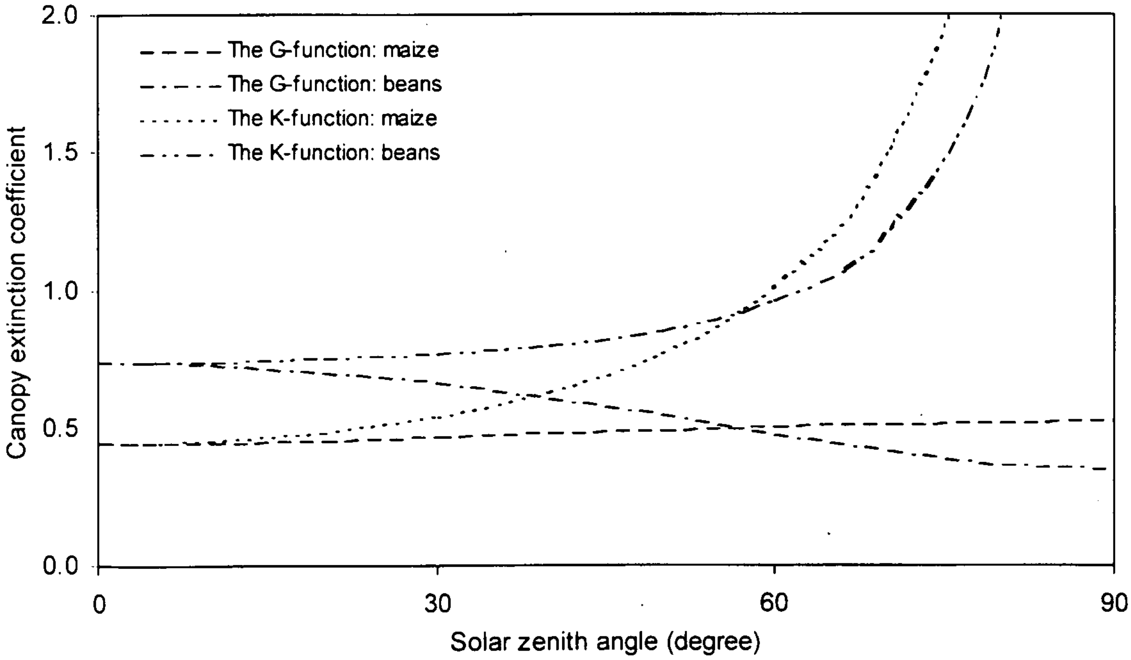


Figure 4.3. The canopy extinction coefficient as a function of solar zenith angle.

Assuming uniform LAD in the hedgerow, LAD can be calculated weighting LAI by the ratio between the inter-row spacing (w_{row}) and the hedgerow cross-section width (w′), which is less than w_{row}:

$$LAD = \frac{w_{row} LAI}{w' h} \tag{4.10}$$

where h is a canopy height (of maize or beans).

The path length of each $s_{\psi,\phi}$ component is individually calculated using the method of Gijzen and Goudriaan (1989). Figure 4.4 shows the co-ordinate system and Figure 4.5 shows the components (the plan from above and the cross-section). Assuming that the beam strikes the horizontal ground, θ_a is the difference between row azimuth (angle with respect to north-south direction) and solar azimuth ϕ (angle with respect to the south), θ_b is the angle of the radiation within the plane of a cross-section through the hedgerow perpendicular to the direction of the rows, and θ_c is the angle between a vertical plane through the zenith and the beam and a vertical plane through the zenith and the hedgerow cross-section. The relationships among angles are as follows:

$$\cos\psi = \cos\theta_b \cos\theta_c \tag{4.11}$$
$$\sin\theta_c = \cos\theta_a \sin\psi \tag{4.12}$$

AC ($s_{\psi,\phi}$) is the length of the radiation path from the top to the bottom of the hedgerow, BC ($s_{\theta c}$) is the length of the component of AC in the hedgerow cross-section, and CD ($s_{\theta b}$) is the length of the horizontal component of BC. The relationships among lengths are as follows:

$$s_{\psi,\phi} = \frac{s_{\theta c}}{\cos\theta_c} = \frac{s_{\theta b}}{\cos\theta_c \sin\theta_b} \tag{4.13}$$

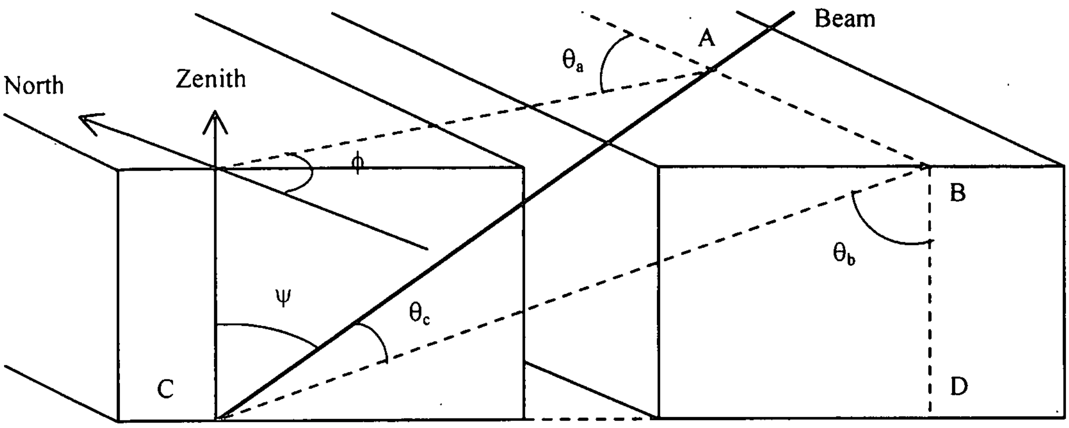


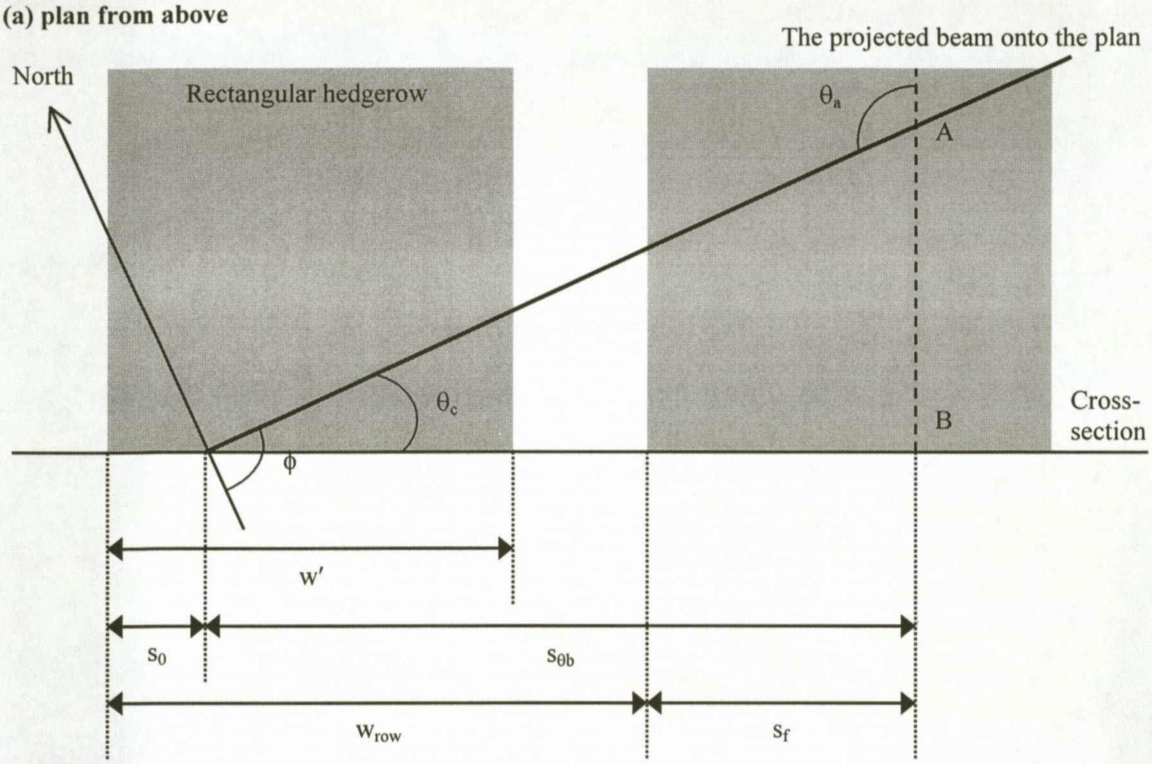
Figure 4.4. The coordinate system. θ_a: the difference between row azimuth and solar azimuth, θ_b: the angle of the radiation within the plane of a cross-section through the hedgerow perpendicular to the direction of the rows, θ_c: the angle between a vertical plane through the zenith and the beam and a vertical plane through the zenith and the hedgerow cross-section, AC ($s_{\psi,\phi}$): the length of the radiation path from the top to bottom of the hedgerow, BC ($s_{\theta c}$): the length of the component of AC in the hedgerow cross-section, and CD ($s_{\theta b}$): the length of the horizontal component of BC.

The radiation path length of the horizontal component in the hedgerow cross-section ($s_{\theta b}$) is calculated by:

$$s_{\theta b} = h \tan \theta_b \qquad (4.14)$$

When radiation traverses from the right-side of the hedgerow cross-section, s_0 is defined as a given distance from the left-side of the last unit row (the range is from the hedgerow to the next hedgerow, $0 \leq s_0 < w_{row}$) traversed by radiation. The total path length of the horizontal component in the hedgerow cross-section only for the hedgerow ($s_{\theta b}'$) with the hedgerow width (w') is calculated by:

(a) plan from above



(b) cross-section

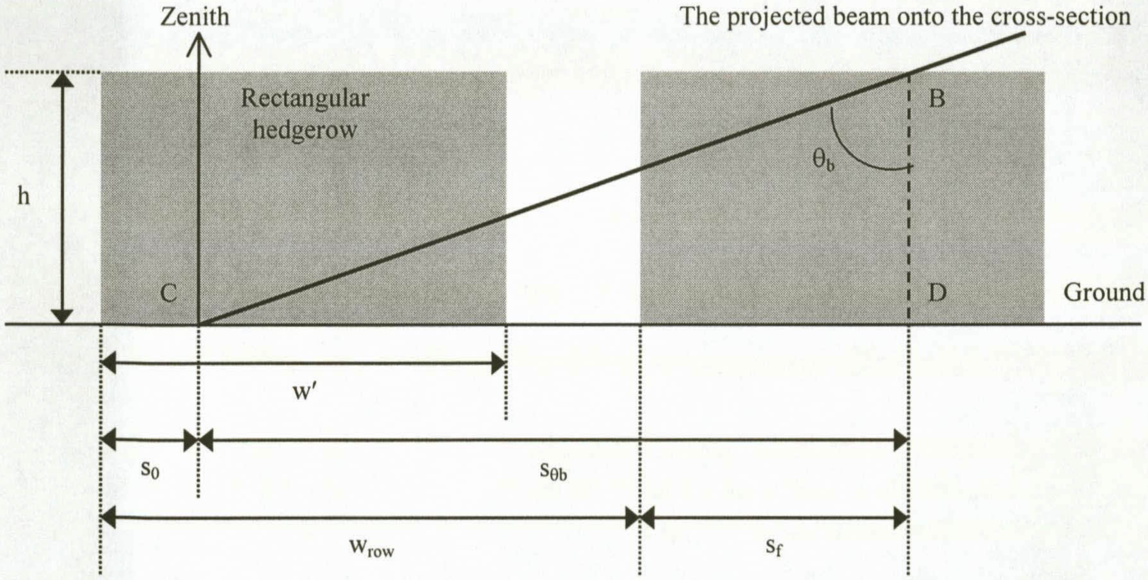


Figure 4.5. Diagrams of components of the coordinate system. θ_a: the difference between row azimuth and solar azimuth, θ_b: the angle of the radiation within the plane of a cross-section through the hedgerow perpendicular to the direction of the rows, θ_c: the angle between a vertical plane through the zenith and the beam and a vertical plane through the zenith and the hedgerow cross-section.

$$s_{\theta b}' = \begin{cases} (N-1)w' + (w' - s_0) + s_f & s_0 \le w', s_f \le w' \quad (4.15a) \\ (N-1)w' + s_f & s_0 > w', s_f \le w' \quad (4.15b) \\ Nw' + (w' - s_0) & s_0 \le w', s_f > w' \quad (4.15c) \\ Nw' & s_0 > w', s_f > w' \quad (4.15d) \end{cases}$$

where N is the integer number of units of inter-row spacing (w_{row}) traversed by radiation and s_f is a distance from the left-side of the first unit row traversed by radiation ($0 \le s_f < w_{row}$), which are calculated by:

$$N \le \frac{(s_{\theta b} + s_0)}{w_{row}} \qquad (4.16)$$

$$s_f = (s_{\theta b} + s_0) - Nw_{row} \qquad (4.17)$$

A numerical integration is used to compute the radiation transmission per unit intercrop hedgerow. For the direct radiation transmission, the computation is made with class intervals of 0.1 m in the hedgerow cross-section, and then a simple average of them is computed. For the diffuse radiation transmission, the computation is made with class intervals of 10° for both zenith and azimuth angles at each class interval for the direct radiation.

4.2.2. Description of the daily radiation transmission model

When both canopy surfaces of maize and beans in the intercrop are assumed to be horizontally homogeneous (Figure 4.2e), the total radiation interception is independent of crop height (Wallace *et al.*, 1991). The daily radiation transmission is simply given by:

$$I = I_0 \exp(-K_M LAI_M - K_B LAI_B) \qquad (4.18)$$

where K_M and K_B are canopy extinction coefficients for maize and beans on a daily basis and LAI_M and LAI_B are LAI for maize and beans respectively. K_M is 0.43 and K_B is 0.64, which were determined during the 1998/1999 growing season.

4.2.3. Estimation of the daily radiation interception and use

The first turbid layer only includes maize turbid medium while the second turbid layer consists of maize and bean turbid mediums (also see Figure 4.2e). The fraction of radiation intercepted by maize in the first turbid layer, F_{M1}, is given by:

$$F_{M1} = 1 - \exp\left(-K_M LAI_{M1}\right) \tag{4.19}$$

where LAI_{M1} is maize LAI in the first turbid layer. Using the equation described by Keating and Carberry (1993), the fraction of radiation intercepted by maize and beans in the second turbid layer is given by:

$$F_{M2} = \frac{K_M LAI_{M2}}{K_M LAI_{M2} + K_B LAI_B}\left[1 - \exp\left(-K_M LAI_{M2} - K_B LAI_B\right)\right] \tag{4.20}$$

$$F_B = \frac{K_B LAI_B}{K_M LAI_{M2} + K_B LAI_B}\left[1 - \exp\left(-K_M LAI_{M2} - K_B LAI_B\right)\right] \tag{4.21}$$

where LAI_{M2} and LAI_B are maize and bean LAI in the second turbid layer. Assuming that leaves are randomly distributed in the hedgerows, LAI_{M1} and LAI_{M2} can be calculated as follows:

$$LAI_{M1} = \frac{h_M - h_B}{h_M} LAI_M \tag{4.22}$$

$$LAI_{M2} = \frac{h_B}{h_M} LAI_M \tag{4.23}$$

where h_M and h_B are the height of maize and bean canopies.

Radiation use efficiency of maize and beans (RUE_M and RUE_B, respectively) is calculated by:

$$RUE_M = \frac{DM_M}{I_0(F_{M1} + F_{M2})} \tag{4.24}$$

$$RUE_B = \frac{DM_M}{I_0 F_B} \tag{4.25}$$

where DM_M and DM_B are dry matter for maize and beans, respectively.

4.2.4. Data collection

A field experiment was carried out on a fine sandy soil at the Soil Science experimental site of the University of the Orange Free State (latitude 29°01′S, longitude 26°09′E, altitude 1354 m above sea level) during the 1999/2000 growing season. Alternate intercrops of maize and beans were planted on 12 January 2000. The seedling establishment was estimated to be two weeks after sowing. Supplemental irrigation and fertiliser were applied. The experimental treatment had row orientations north-south (NS) and east-west (EW). The plot size was 18 m × 18 m. The inter- and intra-row spacing for each crop were 1.00 m and 0.15 m respectively, corresponding to 6.67 plants m^{-2}.

Above-ground plant samples were harvested weekly from 28 to 49 days after planting (DAP) and the harvest area was 3 m^2. Leaf area of the harvested samples was measured using the L-3100 leaf area meter (LI-COR, Inc., Lincoln, Nebraska, U.S.A.). The harvested samples were dried in an oven at 80 °C for 3 days. Canopy height and row cross-section width for maize and beans were measured on the same days.

Incident global and diffuse photosynthetically active radiation (PAR; the 0.4 to 0.7 μm wavelength) was measured above plant canopies using the LI-190SB quantum sensors (LI-COR Inc., Lincoln, Nebraska, U.S.A.). For the diffuse component a shade ring 15 mm in width and 70 mm in radius was mounted above the sensor. Transmitted PAR through the crop canopy was measured beneath the crop canopy using the LI-191SA line quantum sensors (LI-COR Inc., Lincoln, Nebraska, U.S.A.). The linear quantum sensor was set perpendicularly to the crop row orientation at the soil surface. All PAR's were recorded at intervals of ten seconds. The readings were averaged hourly and stored in the CR10X datalogger (Campbell Scientific Inc., Logan, Utah, U.S.A.). This radiation data was collected from 14 to 49 DAP.

4.2.5. Model evaluation

For comparison of the calculated value with the measured value, the correlation-based analysis, including the coefficient of determination (r^2) and F-test, and the deviation-based analysis, including mean bias error (MBE), root mean square error (RMSE) and the index of agreement (d), were used. MBE, RMSE and d are given by:

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(y_i - x_i) \tag{4.26}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - x_i)^2} \tag{4.27}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(y_i - x_i)^2}{\sum_{i=1}^{n}\left(|y_i'| + |x_i'|\right)^2} \tag{4.28}$$

where x_i and y_i are the measured and calculated values, n is the number of the paired set data, $x_i' = x_i - \bar{x}$ and $y_i' = y_i - \bar{x}$, and $\bar{x}$ is the measured mean (Willmott, 1981, 1982).

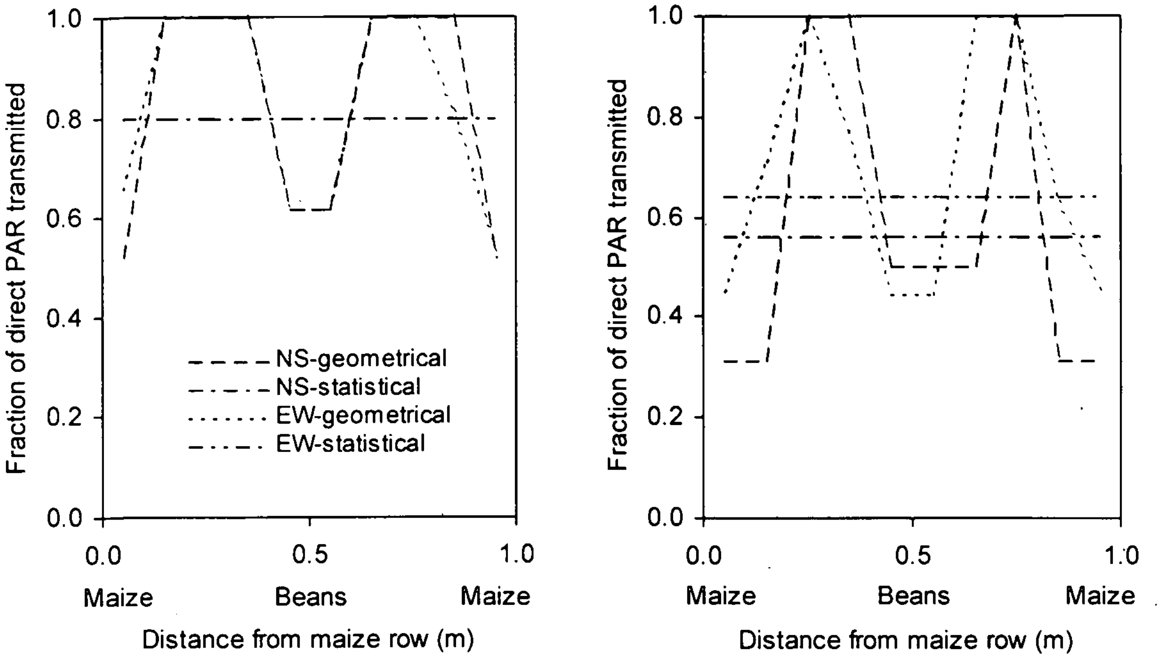
4.3. Results and Discussion

4.3.1. The instantaneous radiation transmission

The geometrical method was compared with the statistical method. For example, the PAR transmission was computed near solar noon (12:30 South African Standard Time) on 28, 35, 42 and 49 DAP. Figure 4.6 presents horizontal profiles of the fraction of direct PAR transmitted through the intercrop canopy. Distances from maize row 0.0, 0.5 and 1.0 m are the centres of maize, bean and maize hedgerows respectively. Positions of 0.0 and 1.0 m are regarded as the west-side and the east-side, respectively, of a unit row on NS row orientation treatment and the south-side and the north-side, respectively, on EW row orientation treatment. On all days, of course, the fraction of the transmitted PAR was constant in the statistical method, but the geometrical method depicted a fluctuation of the fraction of the transmitted PAR. In the geometrical method, on 28 and 35 DAP, NS and EW row directions were found to be similar. On 42 and 49 DAP, NS row treatment had a similar tendency to fluctuate between rows while the fraction of the transmitted PAR in the north-side (between 0.5 and 1.0 m from maize row) of EW row orientation tended to change more constantly. This may be explained by the relationship between the zenith and azimuth angles of sun and the direction of row. Near solar noon, the sun zenith angle was not zero, i.e., 14.03° on 28 DAP, 16.35° on 35 DAP, 18.83° on 42 DAP and 21.44° on 49 DAP. NS row was almost parallel to the azimuth of the sun, so that the lowest radiation transmission was computed near the hedgerow centres. Because EW row is perpendicular to the sun azimuth, on 42 and 49 DAP, the maize row situated at 1.0 m was projected on the south-side and lowered the radiation transmission of the next bean row while on 28 and 35 DAP the crop rows did not affect each other. For average PAR transmitted through the intercrop canopies per unit row, however, the geometrical method was not different from the statistical method.

The instantaneous radiation transmission was evaluated for 28, 35, 42 and 49 DAP. Figure 4.7 shows diurnal changes in the model output based on the geometrical method and the actual measurement. Reduction of the PAR transmission was observed from 28 DAP to 49 DAP. The PAR transmission was greater at midday than in the early morning and late afternoon on all four days. Overall, the model harmonised with the measurement. For example, on 28 DAP (Figure 4.7a), the model estimated the transmitted PAR well from sunrise to sunset in both NS and EW row orientations. However, on 35 and 42 DAP (Figures 4.7b and 4.7c), the transmitted PAR was underestimated at midday by 15 % on average, and on 49 DAP (Figure 4.7d) it was also underestimated in NS row direction.

(a) 28 DAP (b) 35 DAP



(c) 42 DAP (d) 49 DAP

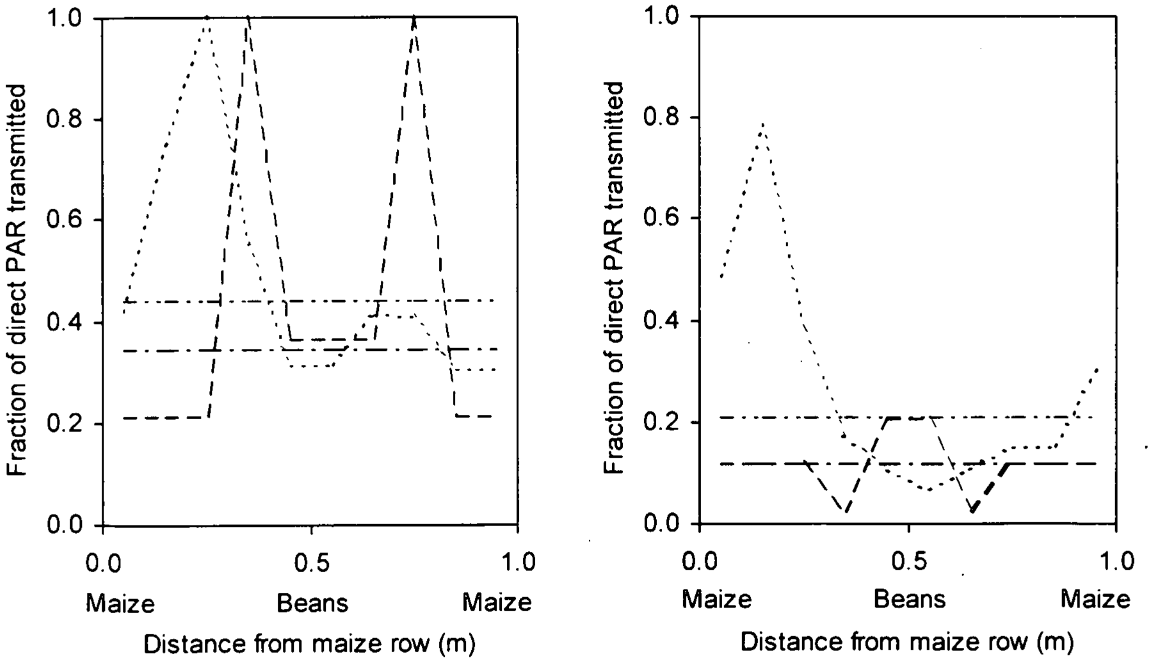
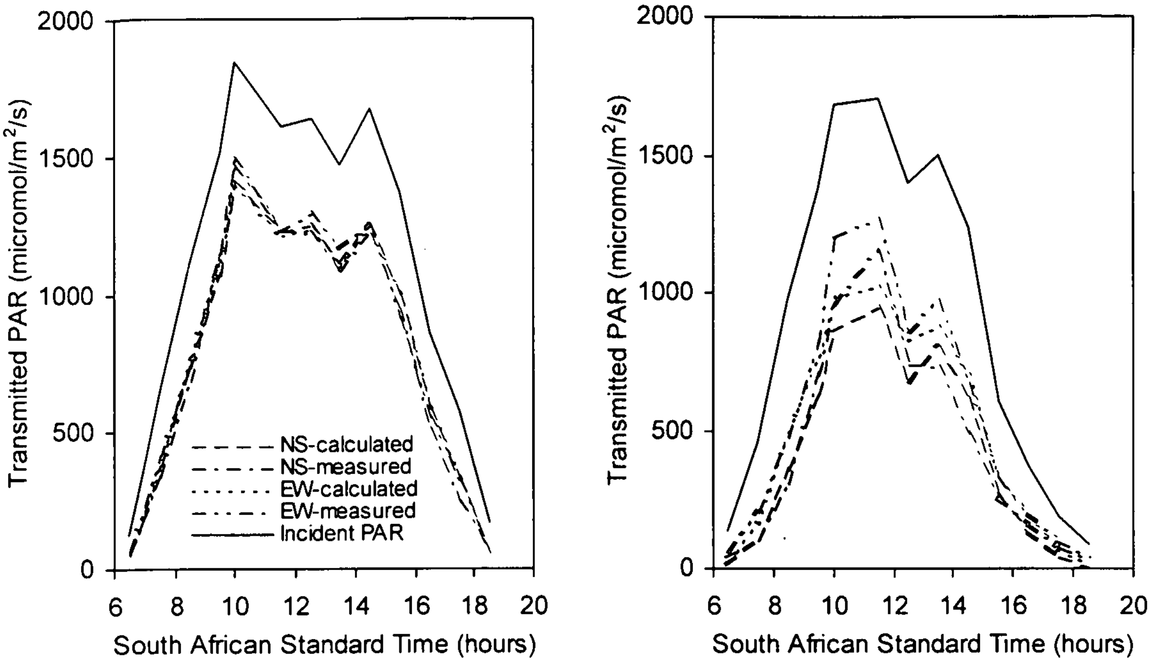
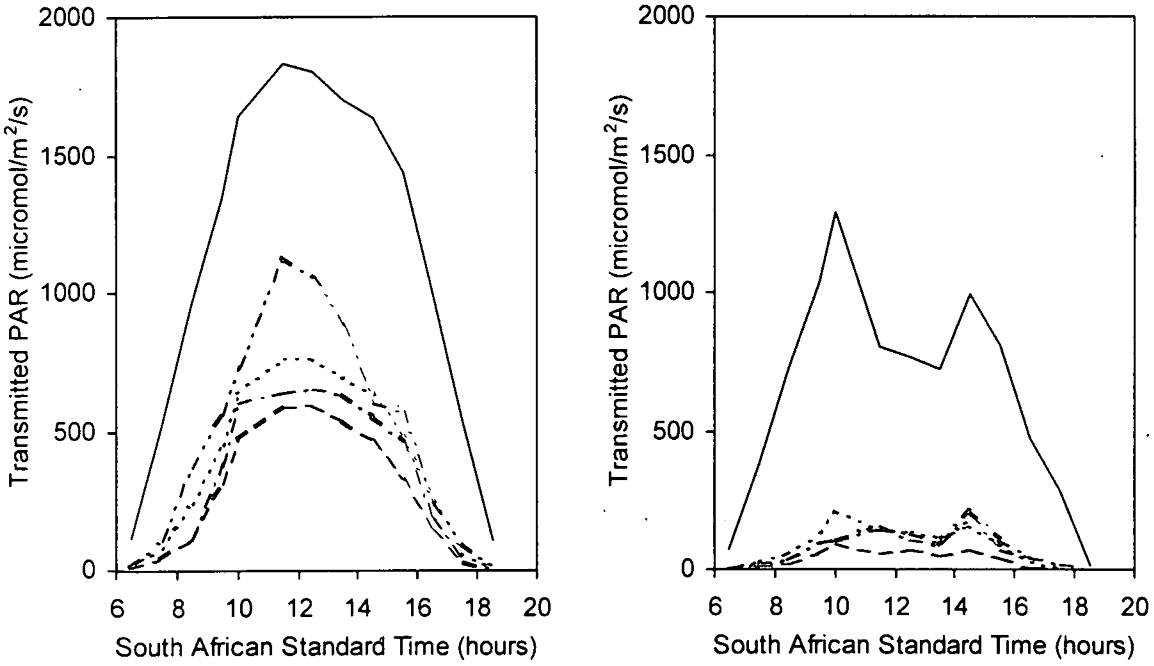


Figure 4.6. Horizontal profiles of direct PAR transmission through the maize-bean alternate intercrop canopy at 12:30 South African Standard Time.


(a) 28 DAP

(b) 35 DAP


(c) 42 DAP

(d) 49 DAP

Figure 4.7. Diurnal changes in the calculated and measured values of transmitted PAR through the maize-bean alternate intercrop canopy.

The underestimation may have resulted from sunflecks (Ozier-Lafontaine *et al.*, 1997). Figure 4.8 shows the model output based on the geometrical method against the measurement of the instantaneous PAR transmission. With respect to the deviation-based analysis, MBE was – 30 micromol m^{-2} s^{-1}; RMSE was 81 micromol m^{-2} s^{-1} and the index of agreement (d) was 0.99. With reference to the correlation-based analysis, the slope (= 0.94 micromol $micromol^{-1}$) and the intercept (= 2.59 micromol m^{-2} s^{-1}) were not significantly different from 1 and 0 respectively, at P-value = 0.01 ($r^2 = 0.97$). From these statistics it appears that the geometrical model accurately predicted the transmitted PAR as measured.

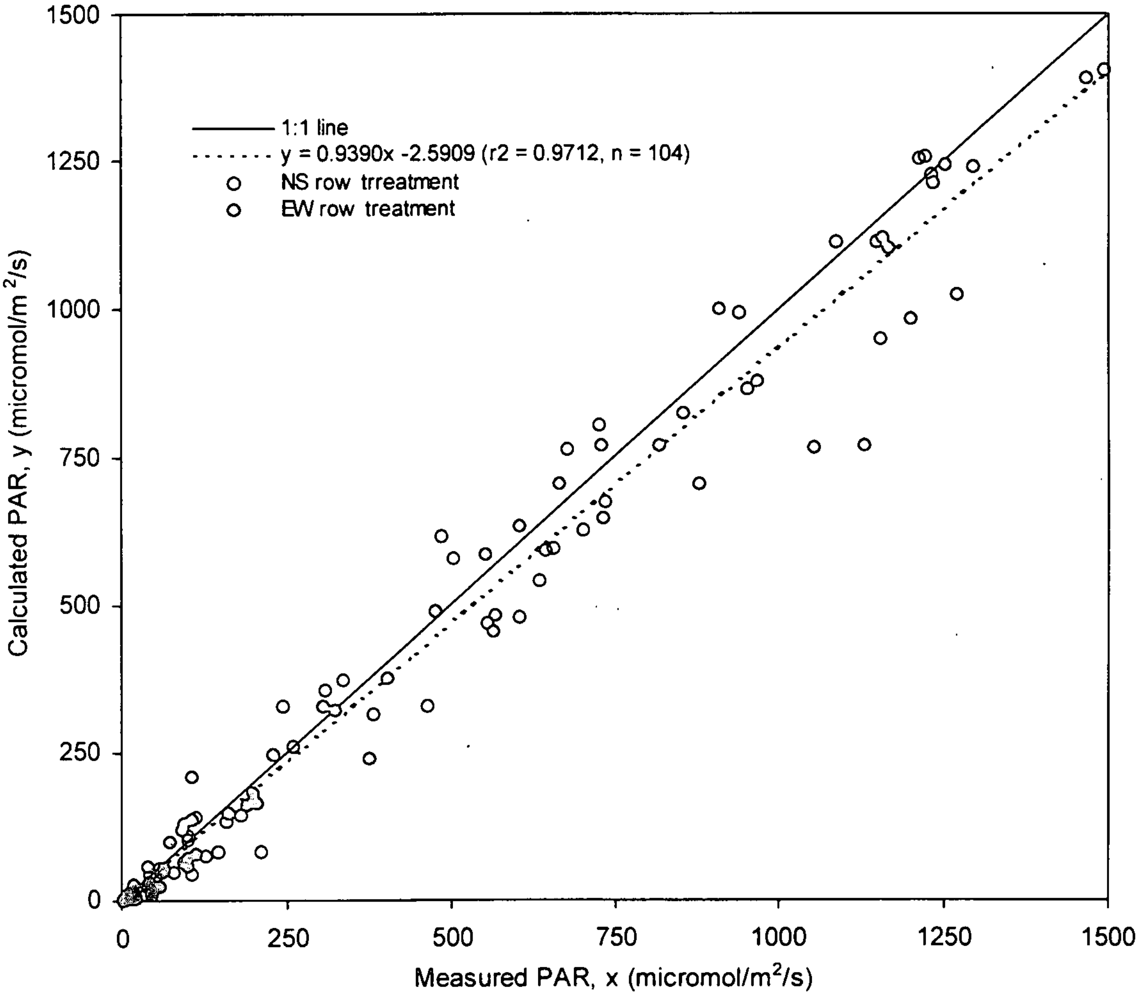


Figure 4.8. Plots of the measured against calculated values of the instantaneous transmitted PAR in the maize-bean alternate intercropping.

4.3.2. The daily radiation transmission

The daily radiation model was studied between 28 and 49 DAP. Because LAI was measured at 28, 35, 42 and 49, unknown LAI was estimated by extrapolating from the daily rate of LAI increase between two consecutive harvests. Seasonal courses of the daily radiation transmission are depicted in Figure 4.9. Corresponding with the instantaneous model, the model outputs followed the measured values and the PAR transmission decreased during the period. The fraction of the transmitted PAR was on average 0.72 on 28 DAP, 0.55 on 35 DAP, 0.37 on 42 DAP and 0.12 on 49 DAP. Figure 4.10 shows the graph of the calculated versus measured values of the daily radiation transmission. The model was made in the 1998/1999 growing season and validated in the 1999/2000 growing season. Concerning the deviation-based statistics, MBE and RMSE were – 0.16 mol m^{-2} s^{-1} and 2.32 mol m^{-2} s^{-1} respectively, and the index of agreement (d) was 0.99. In the correlation-based statistics, the slope (= 0.96 mol mol^{-1}) and the intercept (= 0.61 mol m^{-2} s^{-1}) were not significantly different from 1 and 0 respectively, at P-value = 0.01 (r^2 = 0.94). From these statistics it appears that model results were resonable.

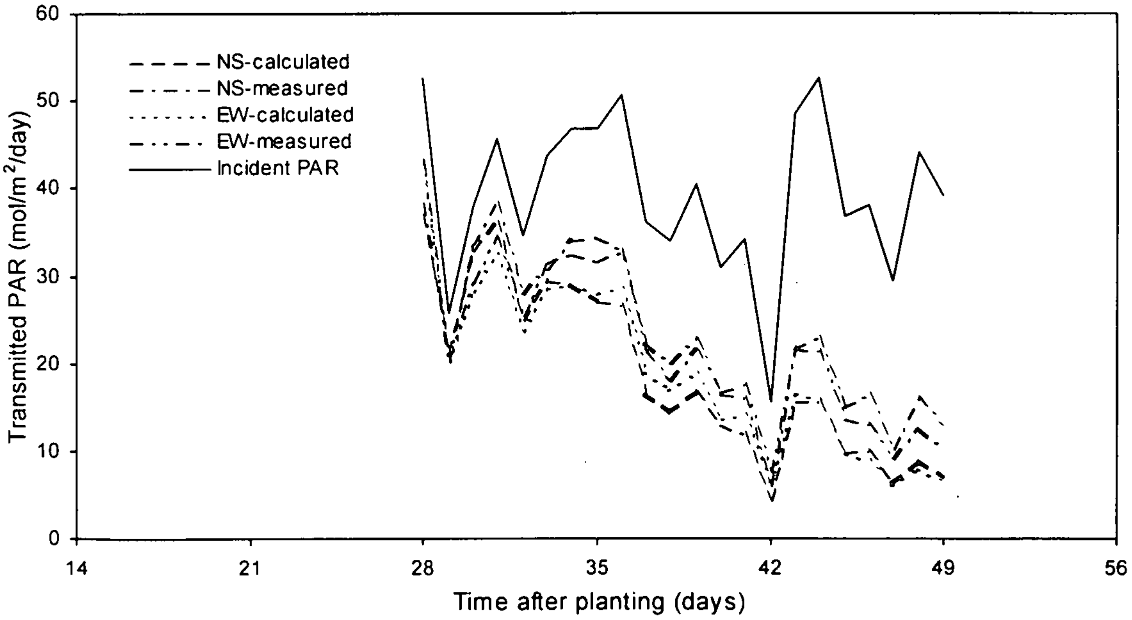


Figure 4.9. Seasonal changes in the calculated and measured (1999/2000) values of transmitted PAR through the maize-bean alternate intercrop canopy.

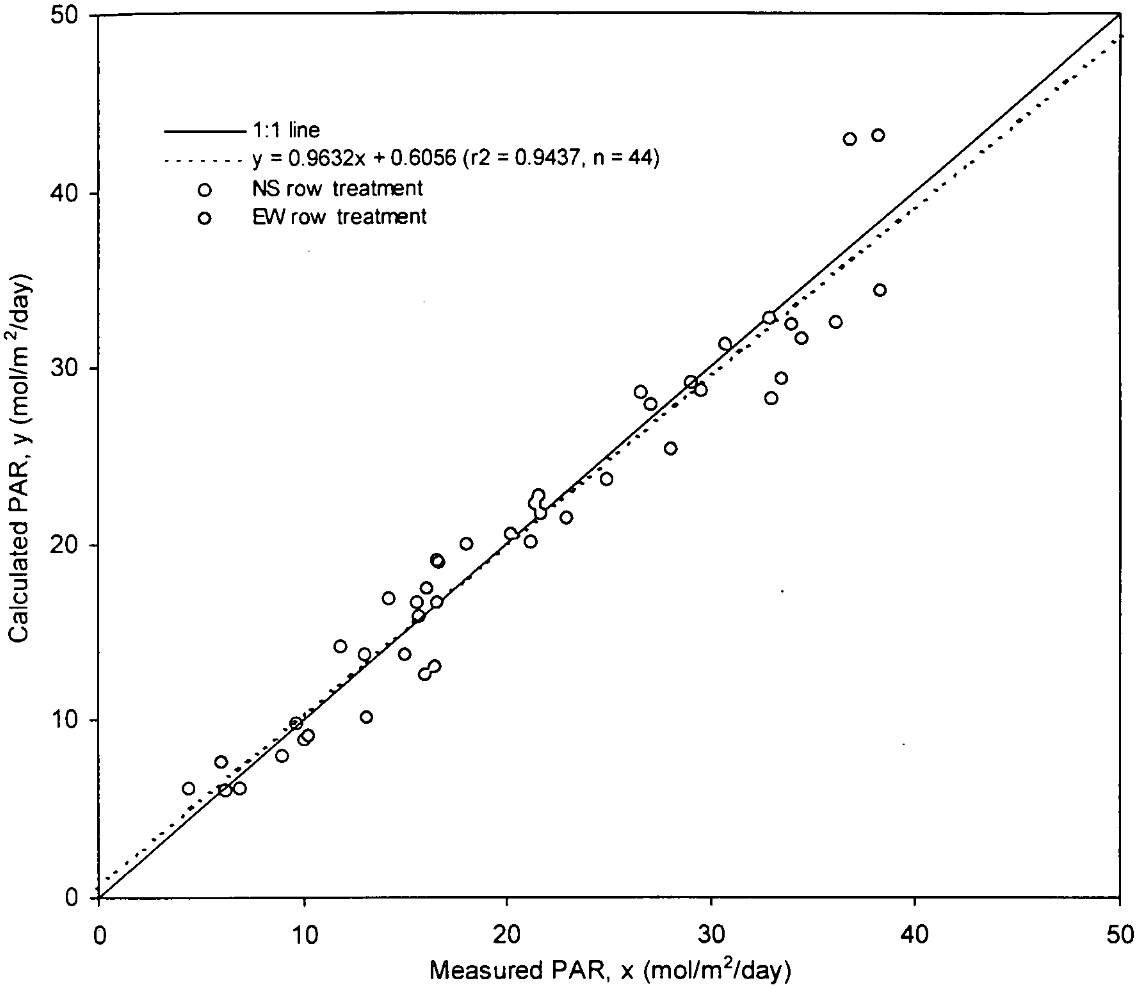


Figure 4.10. Plots of the measured against calculated values of the daily transmitted PAR in the maize-bean alternate intercropping.

4.3.3. Daily radiation interception and use

Figure 4.11 shows the changes in the fraction of PAR intercepted by maize and beans during the early vegetative growth stage. Estimated PAR interception by maize dramatically increased during the period whereas estimated PAR interception by beans gradually increased. This reflects the role of maize as the dominant crop in the maize-bean intercropping and that canopy growth reflects crop radiation interception. Difference in the PAR interception between maize and beans was greater in the NS row than in the EW row at 35, 42 and 49 DAP. This may be explained by the relationship of

LAI and radiation interception. The NS row oriented maize intercepted more PAR at the upper canopy (only maize vegetation) than the EW maize because the NS maize had greater LAI than the EW maize. In other words, the upper maize canopy in the EW row transmitted more PAR than that in the NS row. More PAR reached the lower canopy (both maize and bean forage) in the EW row than in the NS row, and the NS-oriented bean crop was equivalent in LAI to the EW-oriented beans. So, the amount of PAR intercepted by the EW beans was higher than that by the NS beans.

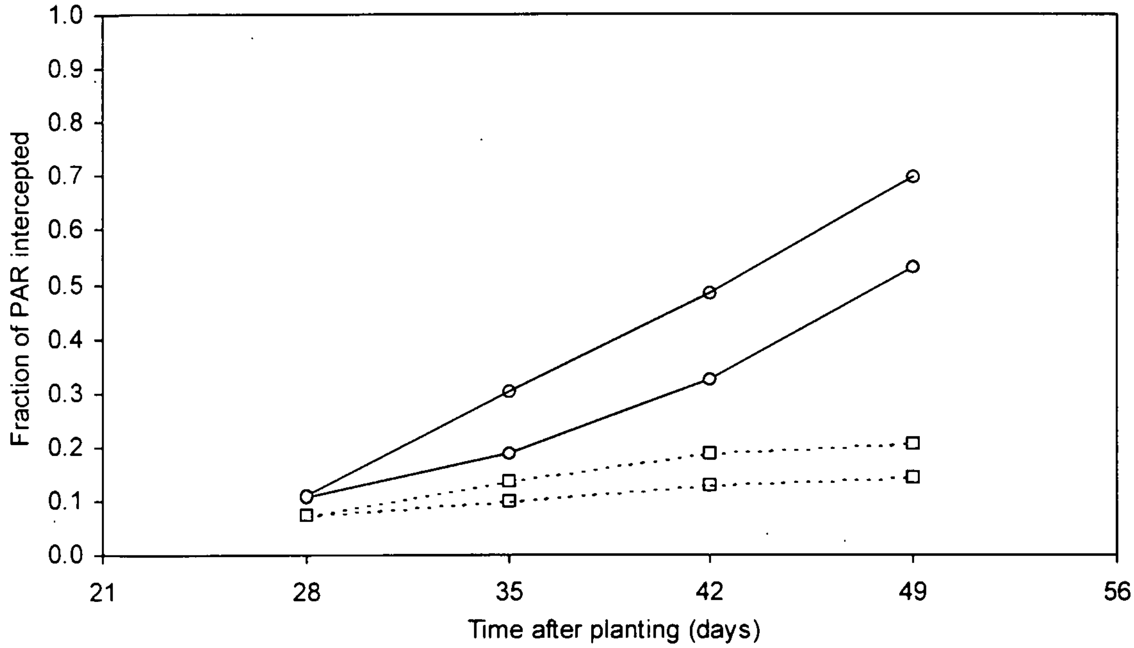


Figure 4.11 PAR interception of each component crop in the maize-bean intercropping during the 1999/2000 growing season (circle - maize; square - beans; open - NS; closed - EW).

Figure 4.12 presents PAR use efficiency of each component crop. RUE was 0.58 g mol^{-1} for maize and 0.33 g mol^{-1} for beans. This was equivalent to 4.7 % and 2.7 % of incident PAR for maize and beans respectively, using the conversion factors of 17.5 kJ g^{-1} and 4.6 micromol J^{-1} (Sivakumar and Virmani, 1980). Comparing the present growth efficiency with the growth efficiency 4.7 % for sole maize and 2.4 % for sole beans (see Chapter 3), the intercropping was equivalent in growth efficiency of maize sole cropped, whereas beans had 12.5 % greater RUE in the intercrop system than as a sole crop. This could lead to a yield advantage of the intercrop, compared to mono-culture, in this region (see Chapter 2). A similar result was reported by Marshall and Willey (1983) in millet-groundnut intercropping. In their study, intercropped millet had a similar RUE to sole cropped millet, but groundnut had 45 % greater RUE in intercropping than sole cropping. This explained that the intercrop yield advantage resulted from the increased RUE of groundnut (Keating and Carberry, 1993). In the study of Harris *et al.* (1987) on sorghum-groundnut intercropping, intercropped sorghum had 20 % lower RUE than sole cropped sorghum, though by contrast intercropped groundnut had about 20 % higher RUE than sole cropped groundnut. The decreased RUE of sorghum and the increased RUE of groundnut resulted in no intercrop yield advantage under that situation (Keating and Carberry, 1993).

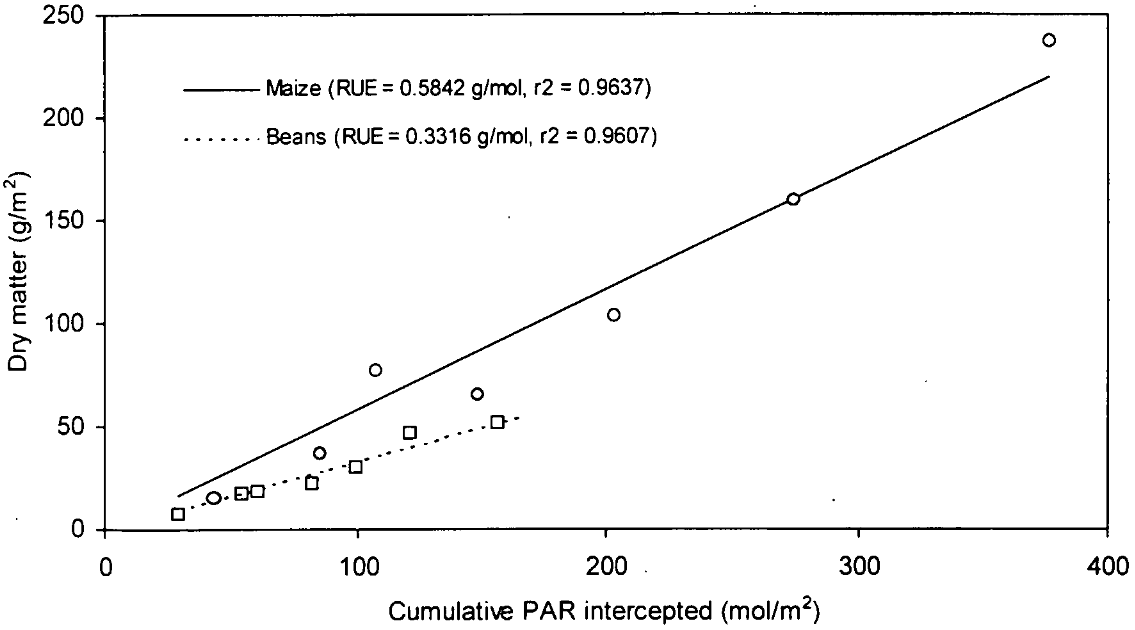


Figure 4.12. PAR use of each component crop in the maize-bean intercropping during the 1999/2000 growing season (circle - maize; square - beans; open - NS; closed - EW).

4.4. Conclusions

Both instantaneous and daily models for radiation transmission through the alternate intercrop canopy were built and tested. Both models accurately predicted the transmitted radiation throughout the vegetative stage. For the instantaneous model, two methods were compared, namely, the geometrical method versus the statistical method. In the geometrical method, the different instantaneous radiation transmission was computed at different locations between rows, however, the method was similar in the transmitted radiation per unit area to the statistical method. (see Figures 4.7, 4.8, 4.9 and 4.10). The daily amount of radiation intercepted and used by each component crop was estimated. F and RUE of each component crop in the intercropping were determined assuming that the canopy included two crop turbid layers. The estimated PAR intercepted by maize was greater than that by beans because maize was the dominant crop. Concerning RUE, no difference between intercropping and sole cropping was found on RUE of maize, whereas the intercropped beans had greater RUE than the sole cropped beans. Probably, the increased RUE of beans results in the intercrop yield advantage.

Chapter 5

Relationship between Solar Radiation and Photosynthetically Active Radiation

5.1. Introduction

All energy harnessed on earth is directly or indirectly derived from solar radiation (SR). Plants capture and store solar radiant energy through their photosynthetic systems. Radiation of wavelength between 0.4 and 0.7 μm is most efficiently utilised in photosynthesis, and therefore it is called photosynthetically active radiation (PAR). The maximum energy intercepted at the earth's surface depends on the solar angle, which is determined by the daily rotation of the earth and the orbit of the earth around the sun (Sinclair and Gardner, 1998). Radiation attenuation in the atmosphere is modified by molecular and aerosol scattering and by ozone, atmospheric gases and water vapour absorption (Monteith and Unsworth, 1990). Thus, the irradiance of solar radiation at the earth's surface is influenced by the sun-earth geometry and atmospheric transmissivity.

The PAR input is usually required in the radiation-based crop growth model, but PAR is not routinely measured although SR is observed in weather stations. Moon (1940) computed the spectral distribution of direct sunlight for sea level and suggested that the ratio of PAR to SR (PAR/SR) was 0.44 for places near sea level. Williams (1976) conducted the simulation for a wide variety of climatic conditions and concluded that the ratio of PAR to SR was constant. PAR/SR has been investigated worldwide to predict PAR from routine measured SR, and on the basis of the previous studies in several locations, PAR/SR basically falls between 0.45 and 0.50 (see Tables 5.1 and 5.2). Howell *et al.* (1983) and Meek *et al.* (1984) estimated PAR to be 45 % of SR whereas Szeicz (1974) and Stanhill and Fuchs (1977) recommended 50 % of SR. The latter has been observed within the wavelength 0.3 to 0.7 μm although at present, PAR is defined as a constant response to equal energy or quantum fluxes in wavelengths between 0.4 and 0.7 μm (McCree, 1972). In both studies it was concluded that PAR/SR was a constant ratio.

Recently, Udo and Aro (1999) reassessed PAR/SR across locations (latitudes from 7 to 70 degrees) and reported that PAR/SR should be regarded as a region-dependent value, as stated by Stigter and Musabilha (1982). However, Pinker and Laszlo (1992) mentioned that the use of constant PAR/SR could lead to errors in radiation-based plant growth model. In fact, PAR/SR increases as sky conditions change from clear to overcast (McCree, 1966; Rao, 1984; Papaioannou *et al.*, 1993, 1996) and as irradiance intensity decreases (Britton and Dodd, 1976).

Table 5.1. The ratio of PAR defined as wavebands between 0.3 and 0.7 μm to SR.

Location	Latitude	Altitude	Months	PAR/SR*		Reference
				Range	Mean	
Dar es Salaan Tanzania	7°S	58 m	Oct – Jan	–	0.51	Stigter and Musabilha (1982)
Jerusalem Israel	31°47′N	736 m	Jan – Dec	0.45 – 0.48	0.48	Stanhill and Fuchs (1977)
Athens Greece	37°58′N	107 m	Jan – Dec	0.43 – 0.50	0.47	Papaioannou *et al.* (1993)
Washinton DC USA	38°54′N	22 m	Jan – Dec	0.46 – 0.51	0.49	Stanhill and Fuchs (1977)
Rockeville MD USA	39°05′N	90 m	Jan – Dec	0.48 – 0.50	0.49	Stanhill and Fuchs (1977)
Guelph Canada	43°33′N	–	Nov – Jun	–	0.47	Blackburn and Proctor (1983)
Cambridge UK	52°N	25 m	Jan – Dec	0.47 – 0.51	0.49	Szeicz (1974)
Copenhagen Denmark	55.7°N	30 m	May – Oct	0.53 – 0.56	0.54	Kvifte *et al.* (1983)
Aas Norway	59.7°N	95 m	May – Oct	0.50 – 0.57	0.53	
			Mar – Aug	0.47 – 0.49	0.48	Hansen (1984)
Ultuna Sweden	59.8°N	17 m	May – Oct	0.50 – 0.53	0.52	Kvifte *et al.* (1983)
Reykjavik Iceland	64.1°N	62 m	May – Oct	0.49 – 0.53	0.51	
Sodankylä Finland	67.4°N	180 m	May – Oct	0.51 – 0.55	0.53	
Tromsø Norway	69.7°N	100 m	May – Oct	0.49 – 0.53	0.51	

*: pyranometer used for PAR measurement Only Dar es Salaam in the southern hemisphere

Table 5.2. The ratio of PAR defined as wavebands between 0.4 and 0.7 μm to SR.

Location	Latitude	Altitude	Months	PAR/SR*		Reference
				Range	Mean	
Ilorin Nigeria	8°32′N	375 m	Jan – Dec	0.42 – 0.47	0.46 (q)	Udo and Aro (1999)
Lhasa Tibet	29°41′N	3688 m	Apr – Oct	0.43 – 0.45	0.44 (p)	Zhang *et al.* (2000)
College Station TX, USA	30°35′N	97 m	Jan – Dec	0.46 – 0.48	0.47 (q)	Britton and Dodd (1976)
Jerusalem Israel	31°47′N	736 m	Jan – Dec	–	0.45 (p)	Goldberg and Klein (1977)
Fresno, CA USA	36°20′N	87 m	Jan – Dec	0.44 – 0.46	0.45 (q)	Howell *et al.* (1983)
Fresno, CA USA	36°40′N	104 m		0.44 – 0.46	0.44 (q)	
Athens Greece	37°58′N	107 m	Jan – Dec	0.41 – 0.45	0.43 (p)	Papaioannou *et al.* (1996)
Rockeville, MD USA	39°05′N	90 m	Jan – Dec	–	0.45 (p)	Goldberg and Klein (1977)
Lower Hutt New Zealand	41°18′S	–	–	–	0.48 (p)	McCree (1966)
Scottsbluff, NE USA	41°57′N	1225 m	Sep	–	0.46 (q)	Weiss and Norman (1985)
Ithaca, NY USA	42°26′N	–	Aug	–	0.47 (p)	Yocum *et al.* (1964)
Corvallis, OR USA	44°34′N	66 m	Jan – Dec	0.44 – 0.46	0.46 (p)	Rao (1984)
Copenhagen Denmark	55.7°N	30 m	May – Oct	0.47 – 0.50	0.49 (p)	Kvifte *et al.* (1983)
Aas Norway	59.7°N	95 m	May – Oct	0.46 – 0.52	0.48 (p)	
			Mar – Aug	0.43 – 0.45	0.44 (p)	Hansen (1984)
Ultuna Sweden	59.8°N	17 m	May – Oct	0.43 – 0.47	0.46 (q)	Rodskjer (1983)
				0.45 – 0.47	0.46 (p)	Kvifte *et al.* (1983)
Reykjavik Iceland	64.1°N	62 m	May – Oct	0.45 – 0.48	0.46 (p)	
Sodankylä Finland	67.4°N	180 m	May – Oct	0.47 – 0.49	0.48 (p)	
Tromsø Norway	69.7°N	100 m	May – Oct	0.44 – 0.47	0.45 (p)	

*: q – quantum sensor and p - pyranometer used for PAR measurement
None in the southern hemisphere

Moreover, the radiation-based crop growth model probably requires direct and diffuse components of radiation. The method to estimate a component of global radiation at the earth's surface is divided broadly into two models: the Beer's (Bouguer-Lambert's) Law model and the Liu and Jordan (regression) model. The former estimates direct radiation while the latter predicts diffuse radiation. The Beer's Law model explains the attenuation of monochromatic radiation through the atmosphere (Monteith and Unsworth, 1990). The model of direct radiation transmittance from the top of the atmosphere to the surface of the earth is described as an exponential equation of the product of the atmospheric extinction coefficient and air mass (Gates, 1966; Bird *et al.*, 1982; Weiss and Norman, 1985; Gueymard, 1989a, b; Alados *et al.*, 2000; Alados-Arboledas *et al.*, 2000).

The atmospheric extinction coefficient is subdivided into scattering (Rayleigh scattering, Mie scattering) coefficients and absorption (ozone, water vapour and other gaseous absorption) coefficients. Thus, the atmospheric extinction coefficient is complex. In contrast, the Liu and Jordan model is a simple equation. As proposed by Liu and Jordan (1960), the ratio of diffuse to global SR (K_{SR}) can be estimated from the clearness index, defined as the ratio of global to extraterrestrial SR (K_T). Many authors have found relationships between K_{SR} and K_T in several locations on an hourly basis (e.g., Orgill and Hollands, 1977; Erbs *et al.*, 1982), on a daily basis (e.g., Stanhill, 1966; Choudhury, 1963; Ruth and Chant, 1976; Tuller, 1976; Collares-Pereira and Rabl, 1979; Erbs *et al.*, 1982; Spitters *et al.*, 1986; Gopinathan and Soler, 1995; Roderick, 1999) or on an average monthly basis (e.g., Tuller, 1976; Collares-Pereira and Rabl, 1979; Erbs *et al.*, 1982; Gopinathan and Soler, 1995; Roderick, 1999).

In a radiation-based crop growth model, it is essential to estimate PAR and its components. However, little information concerning them is available for southern Africa and the southern hemisphere. The objective in this study was, therefore, to investigate global PAR/SR and the ratio of diffuse to global PAR (K_{PAR}) on the bases of daily and hourly data.

5.2. Materials and Methods

5.2.1. Data for global photosynthetically active and solar radiation

Global SR (0.3 to 2.8 μm in wavelength) and PAR (0.4 to 0.7 μm in wavelength) were measured at the Soil Science experimental site of the University of the Orange Free State (latitude 29°01′S, longitude 26°09′E, altitude 1354 m above sea level) at intervals of ten seconds, using the LI-200SZ pyranometer sensor and the LI-190SB quantum sensor (LI-COR Inc., Lincoln, Nebraska, U.S.A). The readings were averaged hourly and stored in a CR10X datalogger (Campbell Scientific Inc., Logan, Utah, U.S.A.). The data was collected from the middle of January 2000 to the middle of April 2000, giving 86 daily data sets including 1051 hourly data that were valid. Since the energy in PAR is not directly measured, the PAR quantum flux (μmol) was converted into its energy flux (J) using 4.6 μmol J^{-1} (McCree, 1972; McCartney, 1978).

5.2.2. Data for diffuse and global solar radiation

Data for global and diffuse SR (0.3 to 2.8 μm in wavelength) for 8 southern African weather stations was provided by the South African Weather Bureau. The radiation was measured using the Kipp solarimeter. The latitude, longitude, altitude, climate and period of the weather stations are summarised in Table 5.3. It covers latitudes from 22 to 34 degrees south and altitudes from 0 to 1725 m, representing various climates. The analysis was made year by year on an hourly basis whereas the whole data set of the period was used for the analysis on a daily basis.

5.2.3. Calculation of extraterrestrial solar radiation

Assuming that that solar radiation arrives in parallel beams from a point source and that the sun-earth distance does not vary seasonally, extraterrestrial SR on a horizontal surface (SR_0) is estimated by the Lambert's Cosine Law and the solar constant (SC):

$$SR_0 = SC \cos\psi \qquad (5.1)$$

where ψ is the angle of solar zenith. The solar zenith angle is calculated by the relationship among latitude (φ), solar declination (δ) and the hour angle from solar noon (θ):

$$\cos\psi = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\theta \qquad (5.2)$$

and in this study, 1373 W m^{-2} was taken as the solar constant (Monteith and Unsworth, 1990).

Table 5.3. The eight southern African weather stations for which global and diffuse solar radiation data is available.

Station	Latitude	Longitude	Altitude	Climate[a]	Period[b]
Windhoek	22°34′S	17°06′E	1725 m	Bsh	1957–1983 (27)
Pretoria	25°44′S	28°11′E	1330 m	Cwb	1957–1997 (41)
Keetmanshoop	26°34′S	18°07′E	1066 m	Bwk	1957–1985 (29)
Bloemfontein	29°06′S	26°18′E	1351 m	Bsk	1957–1993 (37)
Durban	29°58′S	30°57′E	8 m	Cfa	1957–1991 (35)
Middelburg	31°29′S	25°02′E	1270 m	Bsk	1968–1991 (24)
Cape Town	33°58′S	18°36′E	44 m	Csb	1957–1995 (39)
Port Elizabeth	33°59′S	25°36′E	60 m	Cfb	1957–1991 (35)

a: The Köppen classification. B-arid zones (s-steppe climate; w-desert climate; h-dry hot, mean annual temperature over 18°C; k-dry hot, mean annual temperature below 18°C); C-warm temperate climates with coldest month 18°C to –3°C (s-summer dry season; w-winter dry season; f-sufficient precipitation during all months; a-warmest month over 22°C; b-warmest month below 22°C, but at least 4 months above 10°C).

b: the number of years in parentheses

5.3. Results and Discussion

5.3.1. Ratio of photosynthetically active to solar radiation

The mean and standard deviation of PAR/SR on a daily basis were 0.48 and 0.06. The mean PAR/SR fell between 0.45 and 0.50, so PAR/SR in the region was not an exception to other reported data sets. Energy of PAR in wavebands between 0.4 and 0.7 μm above the atmosphere is 40 % of radiation emitted by the sun whereas that of PAR in wavebands between 0.3 and 0.7 μm PAR is 48 % (Monteith and Unsworth, 1990). From the literature (see Tables 5.1 and 5.2), a similar tendency is found on terrestrial PAR/SR. Figure 5.1 presents a plot of PAR/SR against latitude. PAR/SR on the basis of PAR in wavebands between 0.3 and 0.7 μm is higher than that of PAR in wavebands between 0.4 and 0.7 μm across latitudes. This suggests that the definition of PAR can be important for this kind of study, as reported by Udo and Aro (1999).

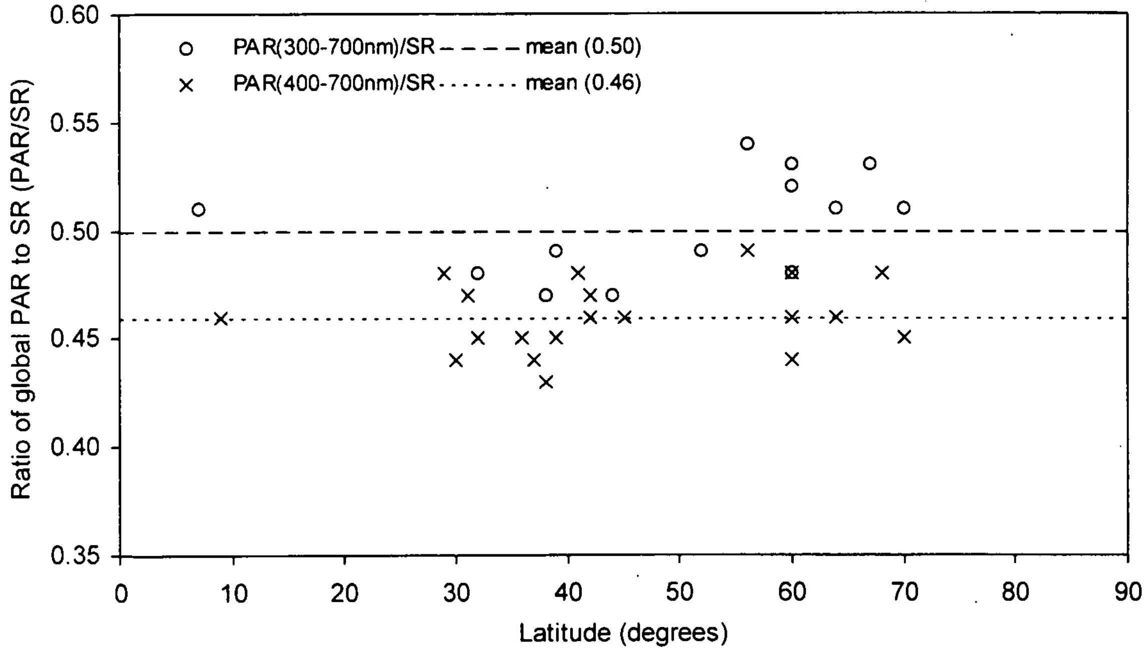


Figure 5.1. The plot of PAR/SR against latitude .

The standard deviation (± 12.5 %) implied that sky conditions changed from clear to overcast. To find the effects of sky conditions on PAR/SR, the clearness index (K_T) was evenly divided into three classes. PAR/SR on a daily basis was 0.53 for the range $0.00 \le K_T < 0.33$, 0.47 for the range $0.33 \le K_T \le 0.67$ and 0.42 for the range $0.67 < K_T \le 1.00$. Thus, PAR/SR decreased as K_T increased. Similarly, Britton and Dodd (1976) sorted daily total SR and found that PAR/SR decreased with increased daily total SR. Howell *et al.* (1983), however, reported that the effects of diurnal variations in the clearness index on PAR/SR was negligible on a daily basis for Fresno, California, U.S.A (36 degrees north).

Similar results were found for PAR/SR on an hourly basis. The mean and standard deviation of PAR/SR on an hourly basis were 0.49 and 0.08. PAR/SR was 0.55 for the range $0.00 \leq K_T < 0.33$, 0.48 for the range $0.33 \leq K_T \leq 0.67$ and 0.43 for the range $0.67 < K_T \leq 1.00$. No clear relationship between PAR/SR and K_{SR} on a daily basis was reported by Stanhill and Fuchs (1977) and the others above, however Stigter and Musabilha (1982) found that on a half-hourly basis PAR/SR increased with the increased K_{SR}. Their finding is analogous to the present result. On a daily basis, more than 75 % of the data was distributed in the range $0.33 \leq K_T \leq 0.67$, however, the data on the hourly basis was distributed more widely throughout the clearness index classes than on a daily basis. This indicates that PAR/SR on an hourly basis is more variable than that on a daily basis.

Recently, Alados *et al.*, (1996) and Alados and Alados-Arboledas (1999) found that PAR/SR on an hourly basis could be estimated using a multiple linear regression equation of the sky's clearness (the ratio of global to diffuse SR) and the sky's brightness (the ratio of diffuse to extraterrestrial SR). The sky's clearness and brightness carry a quantity of information equivalent to the clearness index (Perez *et al.*, 1990). Thus, PAR/SR can be a simple function of the clearness index. To develop an equation for Bloemfontein, South Africa for estimating PAR/SR from K_T, a method developed by Orgill and Hollands (1977) using hourly data was used. PAR/SR for each interval in K_T of 0.1 was averaged and the average values plotted against the values of PAR/SR for the mid-point of that interval (Figures 5.2 and 5.3). Polynomial equations were found as follows:

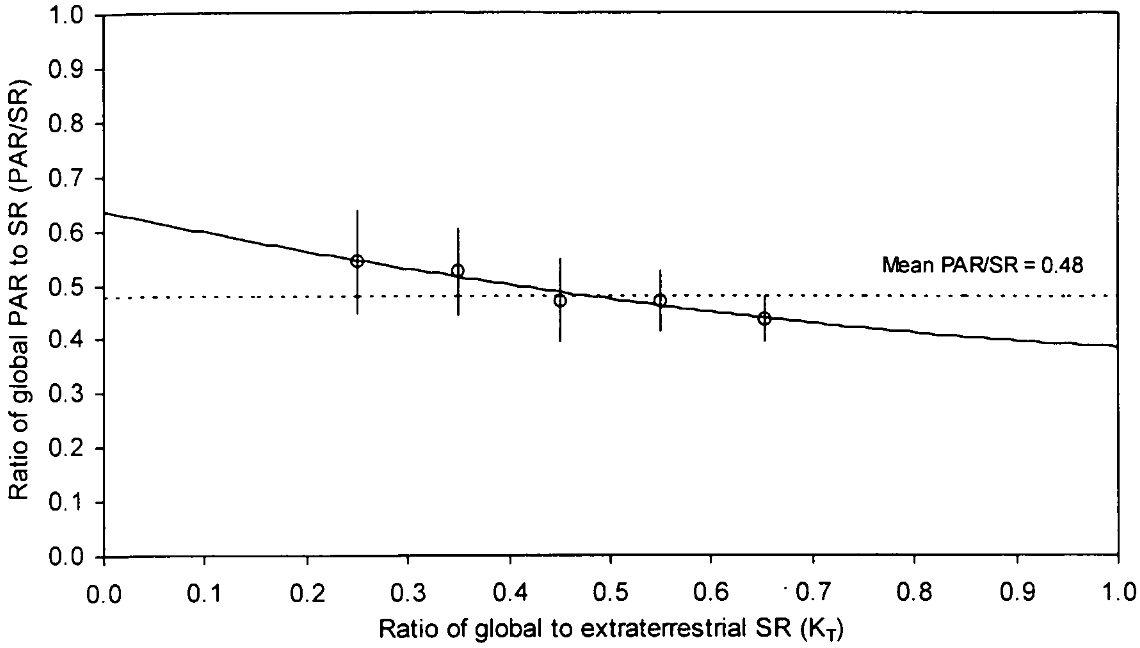


Figure 5.2 The relationship between PAR/SR and K_T on a daily basis for Bloemfontein, South Africa.

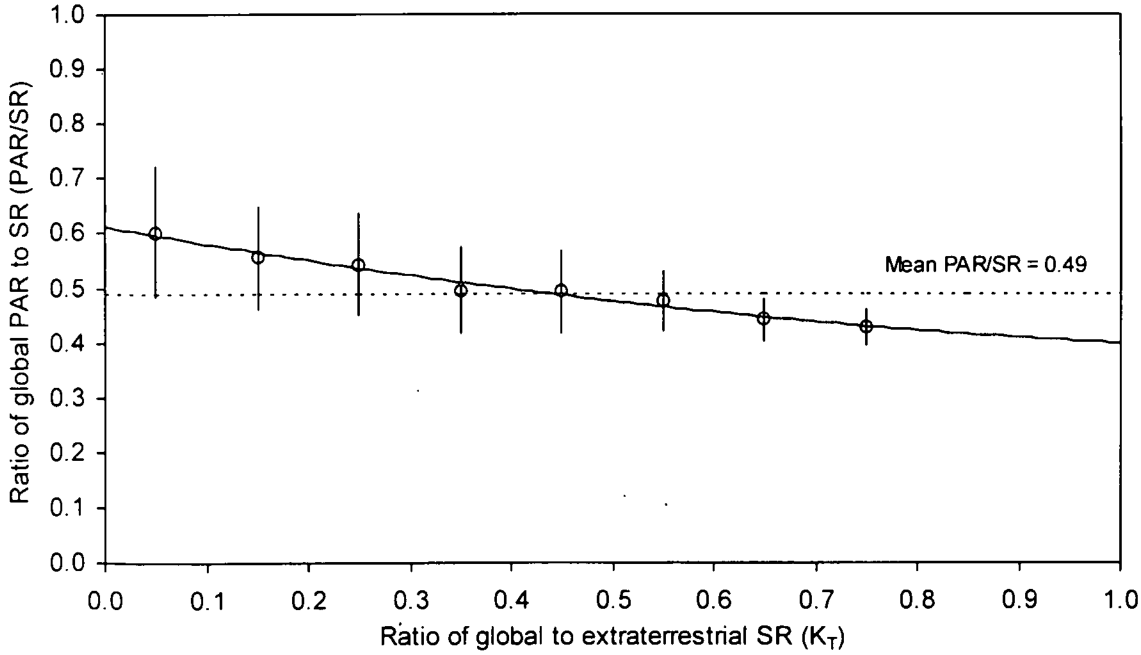


Figure 5.3 The relationship between PAR/SR and K_T on an hourly basis for Bloemfontein, South Africa.

on a daily basis:

$$\frac{PAR}{SR} = 0.1503 - 0.4008K_T + 0.6347{K_T}^2 \qquad r^2 = 0.9457 \qquad (5.3)$$

and on an hourly basis:

$$\frac{PAR}{SR} = 0.1208 - 0.3344K_T + 0.6127{K_T}^2 \qquad r^2 = 0.9773 \qquad (5.4)$$

There was a similarity between the quadratic equations. When K_T equals 1.0, theoretically PAR/SR is 0.4 because energy in the wavebands between 0.4 and 0.7 μm is 40 % of the Solar Constant (Moon, 1940; Monteith and Unsworth, 1990). Substituting $SR/SR_0 = 1$ into the equations gave 0.38 and 0.40 in PAR/SR on the basis of daily and hourly, respectively. These agree with the theoretical PAR/SR ratio of 40 %. McCree (1966) and Stigter and Musabilha (1982) reported that PAR/SR was greater than 0.6 under very cloudy skies. In this study, PAR/SR calculated from the equations also showed higher values up to 0.6 when K_T had extremely low values.

5.3.2. Ratio of diffuse to global radiation

Previous studies on the diffuse SR models imply that K_{SR} is classified into several range K_T in order to develop the models (Orgill and Hollands, 1977; Erbs *et al.*, 1982; Spitters *et al.*, 1986; Roderick, 1999). In this study, K_{SR} was grouped into three range K_T: (i) the low K_T class, (ii) the middle K_T class and (iii) the high K_T class. In general, there is only a small value of the diffuse fraction of radiation in the high K_T class. By contrast, a greater value of the diffuse fraction of radiation is observed in the low K_T class. The ratio classes explain sky conditions and solar angles. The high K_T class means clear sky and/or high solar elevation whereas the low K_T class describes overcast sky and/or low solar elevation. There are some factors affecting the relationship between K_{SR} and K_T. The maximum clearness index in the southern hemisphere (0.77 to 0.82 for Australia) is higher than that in the northern hemisphere (0.70 to 0.75) (Roderick, 1999). This may be explained by a higher loading of aerosols in the atmosphere in the northern hemisphere due to the greater land area and higher population (Roderick, 1999). Also, Ruth and Chant (1976) found that the relationship is dependent on latitude. The variation between locations results from differences in atmospheric conditions, especially water content of the atmosphere and cloud type (Spitters *et al.*, 1986).

Most of the data is distributed over the middle K_T class of the clearness index. In this range, there is a correlation between K_{SR} and K_T. The other ranges (the low and high K_T classes) represent a lower percentage of the data. In these ranges, a constant value of the diffuse fraction of radiation is recommended (Roderick, 1999). In this study, for the low K_T class, a maximum value of the diffuse fraction was chosen and a minimum value was used for the high K_T class. For the middle K_T class, a linear correlation was made in the range $0.2 \leq K_T \leq 0.8$ (which represented most of the data used in this study). Following the method of Orgill and Hollands (1977), K_{SR} for each interval in K_T of 0.05 was averaged, the average values plotted against the values of K_{SR} for the mid-point of that interval, and linear equations were fitted. For estimating K_{PAR}, as described by Spitters *et al.* (1986), K_{PAR} is 1.3 times greater than K_{SR} under clear sky conditions (the high K_T class) while K_{PAR} is equivalent to K_{SR} under overcast sky conditions (the low K_T class).

Figure 5.4 shows the relationship between K_{SR} and K_T for all the southern African weather stations used in this study. The mean maximum K_{SR} was 0.92 and 0.94 on the bases of daily and hourly, respectively, while the mean minimum K_{SR} was 0.10 and 0.16. In the middle K_T classes, the regression lines crossed at K_T of 0.55. Basically there was a similarity between the bases of daily and hourly. The simple linear threshold equations were derived as follows:

on a daily basis:

$$K_{SR} = \begin{cases} 0.9176 & 0.0000 \le K_T < 0.2138 \quad (5.5a) \\ 1.2253 - 1.4391K_T & 0.2138 \le K_T \le 0.7842 \quad (5.5b) \\ 0.0967 & 0.7842 < K_T \le 1.0000 \quad (5.5c) \end{cases}$$

and on an hourly basis:

$$K_{SR} = \begin{cases} 0.9378 & 0.0000 \le K_T < 0.1687 \quad (5.5d) \\ 1.1608 - 1.3221K_T & 0.1687 \le K_T \le 0.7572 \quad (5.5e) \\ 0.1597 & 0.7572 < K_T \le 1.0000 \quad (5.5f) \end{cases}$$

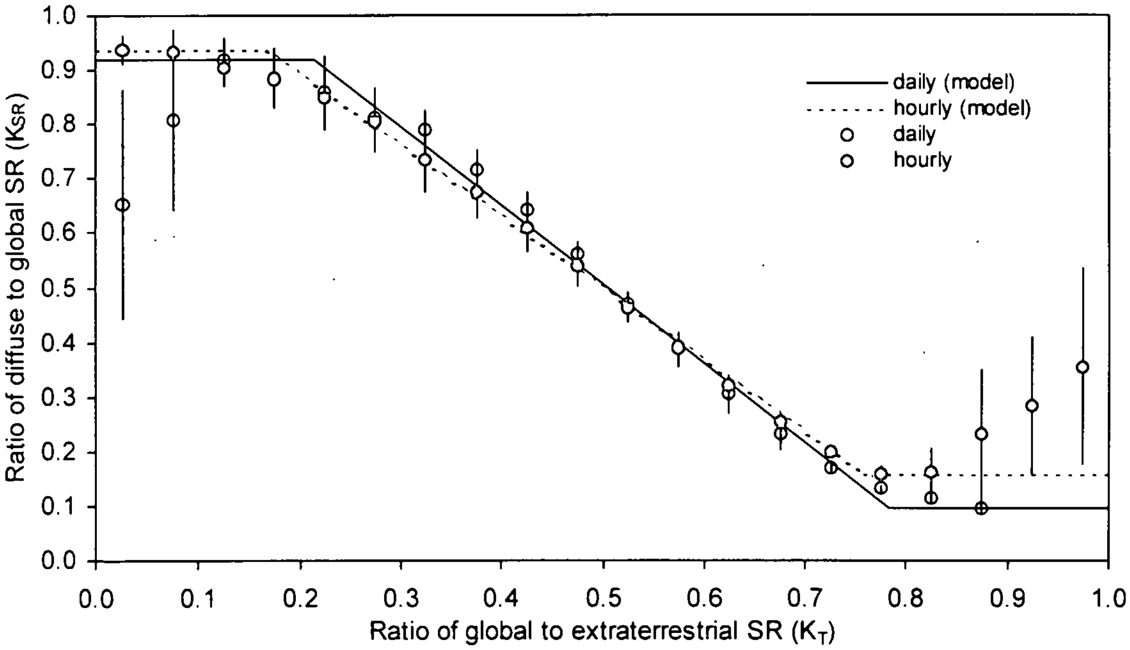


Figure 5.4. The relationships between K_{SR} and K_T for all weather stations.

At the transition from the low K_T class to the middle K_T class, the above equations overestimated because the actual values of K_{SR} around the transition point showed a curvilinear tendency. Even though the polynomials have been used by several authors (e.g., Erbs *et al.*, 1982; Spitters *et al.*, 1986), in this study, the linear model was chosen because r-square was greater than 0.99 in the linear regression analysis above for the middle K_T class and the model fell within the standard deviations. The above equations were enough to explain the relationship between K_{SR} and K_T for the middle K_T class. Tables 5.4 and 5.5 present the diffuse radiation models for the 8 weather stations on the basis of daily and hourly respectively. Likewise, in both of the low and high K_T classes, K_{SR} on an hourly basis was equivalent to or slightly higher than that on a daily basis within stations. In the middle K_T class, the regression analysis for all weather stations also showed high values of r-square ($r^2 > 0.93$).

Although Roderick (1999) reported that the diffuse radiation model tended to be latitude-dependent, in this study the model could rather be divided into climate zones than latitude. Figures 5.5 and 5.6 show the relationship between K_{SR} and K_T on a daily basis and on an hourly basis respectively. Within climate zones, a similar trend was found for the diffuse radiation model. In general, K_{SR} at each K_T for the semi-arid/arid climate zones (Middelburg, Bloemfontein, Keetmanshoop, Windhoek) was lower than that for the warm temperate climate zones (Port Elizabeth, Cape Town, Durban, Pretoria).

This may be explained by a balance of water (water vapour and clouds) in the atmosphere in relation to temperature. In humid areas, more scattering by clouds may occur because of the higher potential cloudiness due to low temperature. By contrast, comparatively high temperatures can provide less cloudiness in arid areas. The middle K_T class range for the semi-arid/arid climate zones was wider than that for the warm temperate ones. The model for all semi-arid/arid climate zones was represented by:

Table 5.4. The diffuse radiation models on a daily basis for each of the 8 weather stations.

Climate	Station	SR	PAR	Range
Semi-arid /Arid	Middelburg	$K_{SR}=0.8666$	$K_{PAR}=0.8666$	$0.0000 \le K_T < 0.2176$
		$K_{SR}=1.1605-1.3506K_T$	$K_{PAR}=1.1502-1.3032K_T$	$0.2176 \le K_T \le 0.7921$
		$K_{SR}=0.0907$	$K_{PAR}=0.1179$	$0.7921 < K_T \le 1.0000$
	Bloemfontein	$K_{SR}=0.8916$	$K_{PAR}=0.8916$	$0.0000 \le K_T < 0.2176$
		$K_{SR}=1.1905-1.3736K_T$	$K_{PAR}=1.1796-1.3237K_T$	$0.2176 \le K_T \le 0.7965$
		$K_{SR}=0.0964$	$K_{PAR}=0.1253$	$0.7965 < K_T \le 1.0000$
	Keetmanshoop	$K_{SR}=0.9658$	$K_{PAR}=0.9658$	$0.0000 \le K_T < 0.1026$
		$K_{SR}=1.0887-1.1976K_T$	$K_{PAR}=1.0840-1.1519K_T$	$0.1026 \le K_T \le 0.8182$
		$K_{SR}=0.1088$	$K_{PAR}=0.1415$	$0.8182 < K_T \le 1.0000$
	Windhoek	$K_{SR}=0.8857$	$K_{PAR}=0.8857$	$0.0000 \le K_T < 0.2322$
		$K_{SR}=1.2127-1.4080K_T$	$K_{PAR}=1.2018-1.3614K_T$	$0.2322 \le K_T \le 0.7991$
		$K_{SR}=0.0876$	$K_{PAR}=0.1139$	$0.7991 < K_T \le 1.0000$
Warm Temperate	Port Elizabeth	$K_{SR}=0.9519$	$K_{PAR}=0.9519$	$0.0000 \le K_T < 0.2294$
		$K_{SR}=1.3128-1.5733K_T$	$K_{PAR}=1.2951-1.4962K_T$	$0.2294 \le K_T \le 0.7493$
		$K_{SR}=0.1339$	$K_{PAR}=0.1740$	$0.7493 < K_T \le 1.0000$
	Cape Town	$K_{SR}=0.9384$	$K_{PAR}=0.9384$	$0.0000 \le K_T < 0.2117$
		$K_{SR}=1.2541-1.4916K_T$	$K_{PAR}=1.2403-1.4263K_T$	$0.2117 \le K_T \le 0.7606$
		$K_{SR}=0.1196$	$K_{PAR}=0.1555$	$0.7606 < K_T \le 1.0000$
	Durban	$K_{SR}=0.9480$	$K_{PAR}=0.9480$	$0.0000 \le K_T < 0.2431$
		$K_{SR}=1.3499-1.6531K_T$	$K_{PAR}=1.3282-1.5641K_T$	$0.2431 \le K_T \le 0.7292$
		$K_{SR}=0.1444$	$K_{PAR}=0.1877$	$0.7292 < K_T \le 1.0000$
	Pretoria	$K_{SR}=0.9461$	$K_{PAR}=0.9461$	$0.0000 \le K_T < 0.1961$
		$K_{SR}=1.2334-1.4653K_T$	$K_{PAR}=1.2209-1.4013K_T$	$0.1961 \le K_T \le 0.7597$
		$K_{SR}=0.1202$	$K_{PAR}=0.1563$	$0.7597 < K_T \le 1.0000$

Table 5.5. The diffuse radiation models on an hourly basis for each of the 8 weather stations.

Climate	Station	SR	PAR	Range
Semi-arid /Arid	Middelburg	$K_{SR}=0.8964$	$K_{PAR}=0.8964$	$0.0000 \le K_T < 0.1213$
		$K_{SR}=1.0344-1.1374K_T$	$K_{PAR}=1.0277-1.0823K_T$	$0.1213 \le K_T \le 0.8002$
		$K_{SR}=0.1243$	$K_{PAR}=0.1616$	$0.8002 < K_T \le 1.0000$
	Bloemfontein	$K_{SR}=0.9071$	$K_{PAR}=0.9071$	$0.0000 \le K_T < 0.1400$
		$K_{SR}=1.0718-1.1768K_T$	$K_{PAR}=1.0630-1.1136K_T$	$0.1400 \le K_T \le 0.7934$
		$K_{SR}=0.1381$	$K_{PAR}=0.1795$	$0.7934 < K_T \le 1.0000$
	Keetmanshoop	$K_{SR}=0.9693$	$K_{PAR}=0.9693$	$0.0000 \le K_T < 0.1027$
		$K_{SR}=1.0994-1.2668K_T$	$K_{PAR}=1.0940-1.2146K_T$	$0.1027 \le K_T \le 0.7755$
		$K_{SR}=0.1170$	$K_{PAR}=0.1521$	$0.7755 < K_T \le 1.0000$
	Windhoek	$K_{SR}=0.9653$	$K_{PAR}=0.9653$	$0.0000 \le K_T < 0.1782$
		$K_{SR}=1.2144-1.3976K_T$	$K_{PAR}=1.2032-1.3348K_T$	$0.1782 \le K_T \le 0.7791$
		$K_{SR}=0.1255$	$K_{PAR}=0.1632$	$0.7791 < K_T \le 1.0000$
Warm Temperate	Port Elizabeth	$K_{SR}=0.9359$	$K_{PAR}=0.9359$	$0.0000 \le K_T < 0.2041$
		$K_{SR}=1.2133-1.3593K_T$	$K_{PAR}=1.1940-1.2646K_T$	$0.2041 \le K_T \le 0.7627$
		$K_{SR}=0.1765$	$K_{PAR}=0.2295$	$0.7627 < K_T \le 1.0000$
	Cape Town	$K_{SR}=0.9545$	$K_{PAR}=0.9545$	$0.0000 \le K_T < 0.1809$
		$K_{SR}=1.2060-1.3899K_T$	$K_{PAR}=1.1909-1.3069K_T$	$0.1809 \le K_T \le 0.7538$
		$K_{SR}=0.1583$	$K_{PAR}=0.2058$	$0.7538 < K_T \le 1.0000$
	Durban	$K_{SR}=0.9377$	$K_{PAR}=0.9377$	$0.0000 \le K_T < 0.2198$
		$K_{SR}=1.2656-1.4920K_T$	$K_{PAR}=1.2422-1.3855K_T$	$0.2198 \le K_T \le 0.7274$
		$K_{SR}=0.1803$	$K_{PAR}=0.2344$	$0.7274 < K_T \le 1.0000$
	Pretoria	$K_{SR}=0.9462$	$K_{PAR}=0.9462$	$0.0000 \le K_T < 0.1733$
		$K_{SR}=1.1814-1.3574K_T$	$K_{PAR}=1.1672-1.2752K_T$	$0.1733 \le K_T \le 0.7533$
		$K_{SR}=0.1589$	$K_{PAR}=0.2066$	$0.7533 < K_T \le 1.0000$

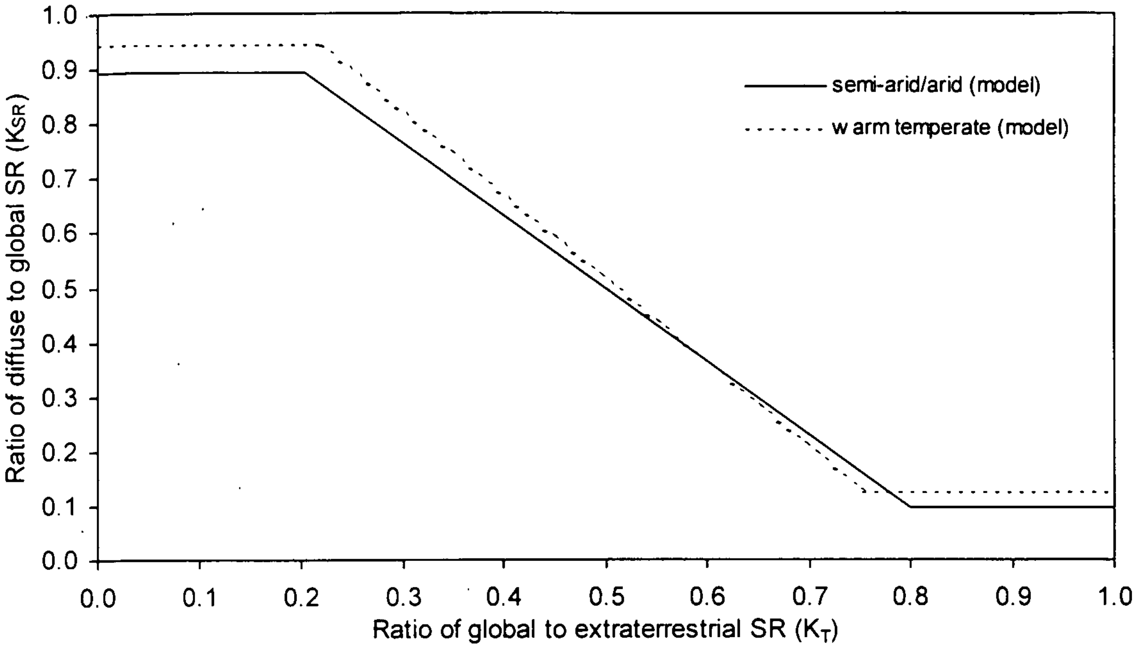


Figure 5.5. The relationships between K_{SR} and K_T on a daily basis for the semi-arid/arid and warm-temperate climates.

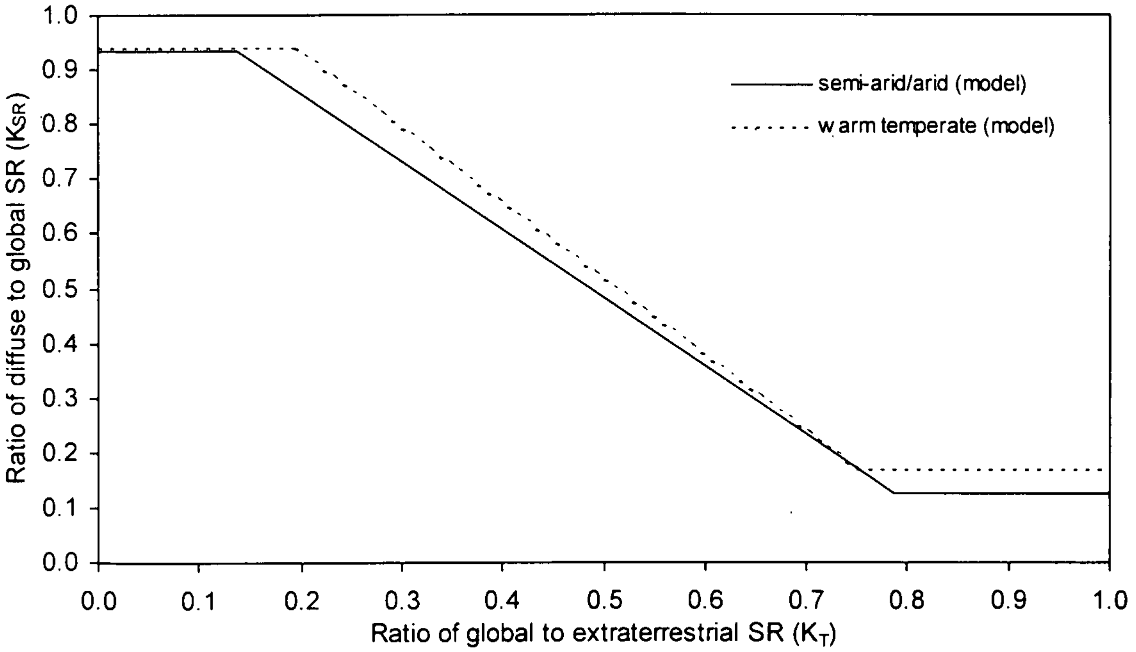


Figure 5.6. The relationships between K_{SR} and K_T on an hourly basis for the semi-arid/arid and warm temperate climates.

on a daily basis:

$$K_{SR} = \begin{cases} 0.8914 & 0.0000 \le K_T < 0.2039 \qquad (5.6a) \\ 1.1631 - 1.3323K_T & 0.2039 \le K_T \le 0.8004 \qquad (5.6b) \\ 0.0967 & 0.8004 < K_T \le 1.0000 \qquad (5.6c) \end{cases}$$

and on an hourly basis:

$$K_{SR} = \begin{cases} 0.9341 & 0.0000 \le K_T < 0.1373 \qquad (5.6d) \\ 1.1050 - 1.2447K_T & 0.1373 \le K_T \le 0.7864 \qquad (5.6e) \\ 0.1262 & 0.7864 < K_T \le 1.0000 \qquad (5.6f) \end{cases}$$

The model for all warm temperate climate zones was represented by:

on a daily basis:

$$K_{SR} = \begin{cases} 0.9439 & 0.0000 \le K_T < 0.2223 \qquad (5.7a) \\ 1.2875 - 1.5458K_T & 0.2223 \le K_T \le 0.7523 \qquad (5.7b) \\ 0.1246 & 0.7523 < K_T \le 1.0000 \qquad (5.7c) \end{cases}$$

and on an hourly basis:

$$K_{SR} = \begin{cases} 0.9414 & 0.0000 \le K_T < 0.1966 \qquad (5.7d) \\ 1.2166 - 1.3995K_T & 0.1966 \le K_T \le 0.7489 \qquad (5.7e) \\ 0.1685 & 0.7489 < K_T \le 1.0000 \qquad (5.7f) \end{cases}$$

5.4. Conclusions

In radiation-based crop growth modelling, it may be necessary to input PAR into the model. PAR is, however, not routinely measured in standard weather stations although SR is observed. This study was established in order to develop a model for estimates of direct and diffuse PAR. The global PAR model was developed using the global PAR and SR data which was measured and the extraterrestrial SR data. The clearness indices (K_T) were calculated: one on the estimates of the ratio of global PAR to SR (PAR/SR) and the other on the ratio of diffuse to global PAR (K_{PAR}). The quadratic function of the clearness index was fitted for estimating PAR/SR. The equation explained the theoretical PAR/SR when $K_T = 1$ and the PAR/SR measured previously by the several scientists when K_T had a low value. More than 20 year's data at each of eight weather stations was used for building the diffuse PAR model. The linear function of the clearness index, which had three K_T classes, fulfilled the estimation of K_{SR} and K_{PAR}. Using these models, subtracting diffuse PAR from global PAR gives the unknown component, namely direct PAR.

Chapter 6
General Conclusion

6.1. Concluding remarks

Overpopulation, natural disasters and food distribution are causes of food insecurity in Africa as well as other developing countries. Most African farmers are peasants or so-called small-scale farmers. In developed countries, agricultural scientists and extension officers timely and properly provide meteorological information to their farmers, but there is a lack of on-farm advisories in Africa (Stigter and Weiss, 1986). Such small-scale farmers have practised traditional cropping techniques, such as intercropping, in which they manipulate the crop microclimates (i.e., modifications on radiation, temperature, moisture and wind) without knowing it. Moreover, several studies indicate that the risk to the small-scale farmer in multiple cropping is lower than in sole cropping (Stigter and Weiss, 1986). The mechanisms of the microclimatic modification is, however, not scientifically clear. Therefore, this study has mainly been initiated to clarify one of the microclimatic modifications in a maize-bean intercropping system, namely, crop radiation interception and utilisation. Information that has been reported in this study may be valuable and helpful to agricultural scientists and extension officers with regard to on-farm advice for traditional cropping systems.

Many authors have reported that intercropping systems have higher productivity than sole cropping systems in various regions of Africa, including African semi-arid regions such as eastern Africa (e.g., Fisher, 1977a, b, 1979; Pilbeam *et al.*, 1994; Alemseged, *et al.*, 1996a, b) and southern Africa (e.g., Rees, 1986a, b, c; Austin and Marais, 1987; Lightfoot and Tayler, 1987a, b; Mukhala *et al.*, 1999) and African tropical regions, such as East Africa (e.g., Evans, 1960; Osiru and Willey, 1972; Willey and Osiru, 1972; Enyi, 1973) and West Africa (e.g., Agboola and Fayemi, 1971, 1972; Andrews, 1972; Mutsaers, 1978; Wahua *et al.*, 1981;Wanki *et al.*, 1982; Fawusi et al., 1982). Chapter 2 has presented the yield advantage of maize-bean intercropping in this semi-arid region which is in basic agreement with previous studies in the other African regions. However, the yield advantage was subject to the condition that both maize and beans were used; that is, the intercropping should be compared not only with sole maize, but also sole beans. In addition, there was no significant effect of row orientation on crop yields in this study although the effect was found in the previous studies on mono-culture cropping.

ICRISAT research centre (India) has reported several studies on radiation interception in cereal-legume intercropping. In general, the fraction of radiation intercepted increases in the vegetative stages while it is comparatively constant or slowly decreases during the reproductive stages (e.g., Natarajan and Willey, 1980b, 1985; Sivakumar and Virmani, 1980, 1984; Reddy and Willey, 1981; Marshall and Willey, 1983; Azam-Ali *et al.*, 1990). As presented in Chapter 3, a similar relationship in radiation interception in maize-bean intercropping was found in this region (Bloemfontein, South Africa). The increased radiation interception has been explained by the growth of leaf area during vegetative stages. From a radiation utilisation point of view, maize-bean intercropping is equal to or higher than maize sole cropping in the overall efficiency of radiation interception and use, and is higher than bean sole cropping. From those findings it follows that when farmers plan on cultivating both crops, planting maize associated with beans results in the higher conversion of radiant energy into plant mass than separate plantings. As a consequence, maize-bean intercropping is more advantages than maize sole cropping, and maize-bean intercropping can be recommended to small-scale farmers in this semi-arid region.

In Chapter 4, instantaneous and daily models of radiation transmission through the maize-bean intercrop canopy have been built and tested. Both models predict the radiation transmission with high accuracy. The daily model is utilised for estimating radiation interception and use by each component crop, and can be used to compute each plant mass per unit area. From this modelling study, it has been concluded that intercropping is equivalent in RUE to sole cropping for maize, but higher for beans. This additional RUE can explain the yield advantage. The conclusion made in this chapter supports the agronomic research, which has been reported in Chapters 2 and 3, and also confirms the validity of the crop modelling.

Chapter 5 has introduced an empirical model for estimating PAR (photosynthetically active radiation) from SR (solar radiation) above plant canopies. The model has not yet been tested, but the model should highly accurate due to the large data sets used in its development. The ratio of PAR to SR (PAR/SR) has been reported from many places in the northern hemisphere, but there were not many PAR/SR measurements documented in the southern hemisphere (including Bloemfontein, South Africa). In the relation between diffuse and global radiation, the model has been divided into climate zones in the middle latitudes, but does not cover the low and/or high latitudes. Therefore, since the model has to be refined, a further investigation into diffuse and global radiation of both PAR and SR is required at the other latitudes and/or climate zones, especially in various parts of the southern hemisphere.

Figure 6.1 shows the flow of energy of the crop model again, and the mathematical equation of the crop model is as follows:

$$Y = HI\int(F \times RUE \times PAR)dt \tag{6.1}$$

where Y is yield, HI is harvest index, F is the fraction of radiation intercepted, RUE is radiation use efficiency, PAR is photosynthetically active radiation and t is time during a growing season. K (canopy extinction coefficient) for the estimation of F, RUE and HI are summarised in Table 6.1. The method for the estimation of F is given in Section 4.2.3 (Chapter 4). There was no difference in RUE and HI between sole cropped and intercropped maize, therefore a given set of K, RUE and HI can satisfy the model for both sole and intercrop maize. However, different RUE and HI should be used for modelling bean growth between sole cropping and intercropping.

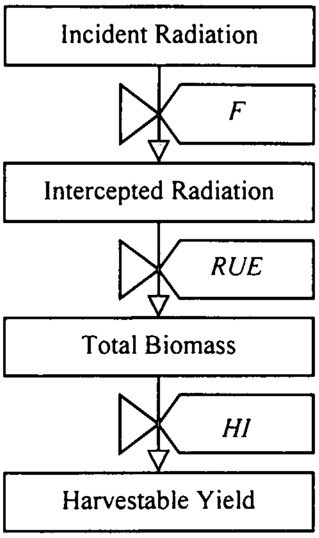


Figure 6.1. The energy flow diagram.

Table 6.1. A summary of K, RUE and HI for the crop model.

Crop	System	K	RUE	HI
Maize	Sole cropping	0.43	0.047	0.45
	Intercropping		0.047*	0.46
Beans	Sole cropping	0.64	0.024	0.41
	Intercropping		0.027*	0.31

*: figures were estimated using the radiation interception and use model in Chapter 4

6.2. Future study

In dryland crop production, the most limiting factor is water (rainfall and irrigation) availability, and it is thus necessary to improve crop water use efficiency. The key can be found in reduced soil temperature and retained soil moisture, and then the solution may lie in traditional cropping techniques, particularly mulching (Wilken, 1972; Baldy and Stigter, 1997). Mulching, often called shading, distinguishes between organic and inorganic mulches, and organic mulching is divided between natural and artificial mulches (Davies, 1975; Stigter, 1984a, b, c). Intercropping is one of the types of mulching, often referred to as live mulching. Mulch applications change soil temperature, soil moisture, soil physical properties, soil chemical properties, soil microbial activities, aerial physical properties, mechanical impact and weed growth (Davies, 1975; Stigter, 1984a, b, c). For understanding crop water use in the maize-bean intercropping, evapotranspiration from bean crop canopies needs to be measured or/and estimated.

Net radiation (overall incoming and outgoing radiant energy at a surface) is the major contributors to energy balance. Within plant canopies, net radiation is of importance in describing the fundamental quantity of energy available for plant growth; that is, net radiation drives the processes of photosynthesis, evaporation, transpiration, and air and soil heating (Rosenberg *et al.*, 1983). Net radiation comprises net short-wave (solar) radiation, which is utilised for assimilating carbon dioxide (CO_2) and net long-wave (thermal) radiation. With regard to crop water use, the most important phenomenon is that net radiation primarily provides the energy needed for evapotranspiration (Jensen *et al.*, 1989). Therefore, a study on a radiation balance of the maize-bean intercropping needs to be carried out.

Recently, Baldy and Stigter (1997) published a book titled 'Agrometeorology of multiple cropping in warm climates.' According to Baldy and Sigter (1997), many authors have studied energy balance in forestry and/or agroforestry, however there is insufficient data to formulate a complete energy balance for intercropping, especially at a canopy surface of associated crops. This project has helped to rectify that situation by providing information on the radiation, however, the task still remains to formulate a complete energy balance of the maize-bean intercropping. It is interesting that shade manipulation by associated crops in intercropping may increase crop water use of dominant crops because of a reduction in evaporation from soil (Stigter and Weiss, 1986). Consequently, further micro-climatic studies on intercropping are essential to understanding explaining its water use efficiency.

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Appendices

Table A.1. Dry matter measurements during the 1998/1999 and 1999/2000 growing seasons (g/plant).

(a) Maize - the 1998/1999 growing season

	DAP	Leaf	Stalk	Ear	Total
Sole cropped maize NS row	28	5.0 ± 0.6	2.2 ± 0.4	-	7.2 ± 0.8
	35	11.0 ± 1.1	7.2 ± 0.9	-	18.2 ± 1.9
	42	20.3 ± 1.4	17.9 ± 2.1	-	38.2 ± 3.3
	49	30.8 ± 1.5	29.6 ± 2.5	-	60.4 ± 3.9
	56	43.4 ± 2.9	44.2 ± 3.1	-	87.6 ± 3.3
	70	53.6 ± 2.9	98.0 ± 10.2	15.2 ± 2.6	166.8 ± 13.5
	84	53.6 ± 2.7	110.3 ± 11.1	36.9 ± 13.0	200.8 ± 26.3
	98	55.5 ± 4.5	111.1 ± 9.5	93.7 ± 15.2	260.3 ± 12.3
	112	60.3 ± 3.9	115.2 ± 7.8	167.5 ± 36.9	343.0 ± 41.4
	126	Cob 205.4 ± 27.2	Other 273.5 ± 22.9		478.9 ± 40.0
Sole cropped maize EW row	28	5.0 ± 1.0	2.5 ± 0.5	-	7.5 ± 1.4
	35	11.0 ± 2.0	6.8 ± 1.3	-	17.8 ± 3.4
	42	21.8 ± 4.7	19.2 ± 5.0	-	41.0 ± 9.6
	49	34.1 ± 2.2	30.6 ± 3.7	-	64.7 ± 5.5
	56	44.3 ± 2.4	49.5 ± 3.4	-	93.8 ± 5.1
	70	53.7 ± 4.7	102.7 ± 15.5	12.9 ± 1.7	169.3 ± 19.1
	84	51.8 ± 4.1	110.7 ± 9.1	24.7 ± 2.1	187.2 ± 5.4
	98	62.2 ± 7.5	125.3 ± 27.8	92.9 ± 29.9	280.4 ± 63.1
	112	57.0 ± 1.1	116.6 ± 8.9	161.6 ± 17.4	335.2 ± 23.0
	126	Cob 176.8 ± 32.3	Other 256.1 ± 30.2		432.9 ± 33.3
Inter-cropped maize NS row	28	4.7 ± 1.1	2.3 ± 0.4	-	7.0 ± 1.5
	35	10.8 ± 0.8	8.0 ± 0.8	-	18.8 ± 1.6
	42	21.4 ± 1.4	19.6 ± 1.4	-	41.0 ± 2.7
	49	33.1 ± 4.5	29.6 ± 4.7	-	62.7 ± 9.1
	56	42.8 ± 4.4	48.8 ± 8.7	-	91.6 ± 13.0
	70	50.8 ± 6.2	102.3 ± 12.6	16.3 ± 6.3	169.4 ± 24.1
	84	52.4 ± 4.6	113.6 ± 7.0	41.8 ± 10.8	207.8 ± 20.1
	98	53.8 ± 7.5	107.5 ± 18.6	95.0 ± 34.0	256.3 ± 57.0
	112	57.0 ± 5.8	110.4 ± 13.9	151.4 ± 21.9	318.8 ± 41.5
	126	Cob 189.8 ± 24.8	Other 240.2 ± 47.0		430.0 ± 65.6
Inter-cropped maize EW row	28	4.4 ± 0.7	2.1 ± 0.4	-	6.5 ± 1.2
	35	10.7 ± 0.1	7.3 ± 0.6	-	18.0 ± 0.5
	42	20.3 ± 2.8	18.0 ± 3.1	-	38.3 ± 5.9
	49	31.4 ± 3.5	30.5 ± 5.9	-	61.9 ± 9.2
	56	40.3 ± 4.8	43.4 ± 11.1	-	83.7 ± 15.6
	70	50.4 ± 2.3	96.9 ± 10.1	10.9 ± 1.2	158.2 ± 12.6
	84	51.6 ± 2.9	108.9 ± 3.5	43.0 ± 5.2	203.5 ± 9.7
	98	52.8 ± 6.4	103.4 ± 15.3	90.3 ± 11.6	246.5 ± 19.3
	112	55.2 ± 3.6	104.3 ± 14.3	148.2 ± 24.7	307.7 ± 42.4
	126	Cob 170.8 ± 14.0	Other 207.0 ± 52.1		377.8 ± 61.0

(mean ± standard error)

Table A.1. cont.

(b) Beans - during the 1998/1999 growing season

	DAP	Leaf	Stem	Pod	Total
Sole cropped beans NS row	28	1.2 ± 0.1	0.3 ± 0.0	-	1.5 ± 0.1
	35	2.5 ± 0.3	0.7 ± 0.1	-	3.2 ± 0.4
	42	6.5 ± 2.2	1.8 ± 0.6	-	8.3 ± 2.8
	49	11.4 ± 2.1	4.2 ± 0.6	-	15.6 ± 2.7
	56	12.8 ± 4.0	5.4 ± 1.6	-	18.2 ± 5.5
	70	21.5 ± 2.7	14.6 ± 1.9	4.6 ± 2.6	40.7 ± 6.4
	84	20.8 ± 2.2	17.1 ± 1.0	22.0 ± 4.4	59.9 ± 6.5
	98	18.0 ± 3.8	15.3 ± 2.1	46.2 ± 10.0	79.5 ± 15.7
	112	19.4 ± 2.8	19.9 ± 5.9	51.9 ± 16.4	91.2 ± 23.4
	126	Seed 40.4 ± 4.5	Other 61.8 ± 18.5		102.2 ± 21.8
Sole cropped beans EW row	28	1.1 ± 0.1	0.3 ± 0.0	-	1.4 ± 0.1
	35	2.5 ± 0.3	0.7 ± 0.1	-	3.2 ± 0.4
	42	6.9 ± 1.0	1.8 ± 0.3	-	8.7 ± 1.2
	49	10.6 ± 2.2	3.8 ± 0.9	-	14.4 ± 3.0
	56	11.7 ± 2.7	5.2 ± 1.5	-	16.9 ± 4.1
	70	20.1 ± 3.9	14.3 ± 2.1	5.0 ± 2.9	39.4 ± 6.6
	84	18.0 ± 1.9	14.8 ± 1.5	20.1 ± 7.9	52.9 ± 7.9
	98	16.5 ± 3.9	15.1 ± 4.8	35.4 ± 10.7	67.0 ± 17.6
	112	18.9 ± 1.7	18.4 ± 2.4	46.0 ± 10.2	83.3 ± 11.4
	126	Seed 36.8 ± 8.3	Other 63.6 ± 11.2		100.4 ± 17.8
Inter-cropped beans NS row	28	1.1 ± 0.2	0.3 ± 0.0	-	1.4 ± 0.2
	35	2.2 ± 1.0	0.7 ± 0.1	-	2.9 ± 1.1
	42	3.4 ± 0.4	1.1 ± 0.2	-	4.5 ± 0.5
	49	4.4 ± 1.4	1.9 ± 0.6	-	6.3 ± 2.0
	56	4.8 ± 1.0	2.3 ± 0.7	-	7.1 ± 1.7
	70	10.3 ± 3.3	7.1 ± 1.7	0.3 ± 0.3	17.4 ± 5.1
	84	10.7 ± 1.9	7.8 ± 1.7	1.9 ± 1.4	20.4 ± 3.7
	98	7.4 ± 2.4	5.8 ± 1.1	6.4 ± 4.1	19.6 ± 6.4
	112	7.6 ± 1.2	7.1 ± 1.7	8.4 ± 4.2	23.1 ± 5.5
	126	Seed 9.1 ± 2.1	Other 23.9 ± 3.0		33.1 ± 4.5
Inter-cropped beans EW row	28	1.1 ± 0.2	0.3 ± 0.1	-	1.4 ± 0.3
	35	2.9 ± 0.7	0.6 ± 0.1	-	3.5 ± 0.9
	42	3.4 ± 0.6	1.2 ± 0.3	-	4.6 ± 0.9
	49	4.9 ± 1.2	2.3 ± 0.9	-	7.2 ± 2.1
	56	4.4 ± 1.6	2.4 ± 1.7	-	6.8 ± 3.2
	70	9.5 ± 2.7	7.0 ± 2.0	0.8 ± 1.7	17.3 ± 5.2
	84	8.4 ± 0.8	7.8 ± 1.9	3.1 ± 3.0	19.3 ± 4.1
	98	7.9 ± 0.6	8.3 ± 1.8	7.1 ± 3.8	23.3 ± 5.3
	112	7.8 ± 2.3	8.0 ± 2.1	7.5 ± 2.8	23.3 ± 1.8
	126	Seed 9.7 ± 2.0	Other 24.2 ± 3.8		33.9 ± 5.2

(mean ± standard error)

Table A.1. cont.

(c) Maize - the 1999/2000 growing season

<table>
<tr><th>DAP</th><th colspan="2">Leaf</th><th colspan="2">Stalk</th><th colspan="2">Ear</th><th>Total</th></tr>
<tr><td></td><td colspan="7">Sole cropped maize & NS row</td></tr>
<tr><td>42</td><td colspan="2">18.7 ± 1.9</td><td colspan="2">13.3 ± 1.0</td><td colspan="2">-</td><td>32.0 ± 2.5</td></tr>
<tr><td>56</td><td colspan="2">47.3 ± 6.0</td><td colspan="2">58.5 ± 9.6</td><td colspan="2">-</td><td>105.8 ± 15.5</td></tr>
<tr><td>70</td><td colspan="2">50.2 ± 2.3</td><td colspan="2">113.5 ± 3.6</td><td colspan="2">11.7 ± 3.8</td><td>175.4 ± 5.8</td></tr>
<tr><td>84</td><td colspan="2">56.2 ± 6.3</td><td colspan="2">142.2 ± 3.5</td><td colspan="2">63.5 ± 5.3</td><td>261.9 ± 10.8</td></tr>
<tr><td>105</td><td colspan="2">49.8 ± 3.7</td><td colspan="2">115.7 ± 10.3</td><td colspan="2">168.0 ± 10.8</td><td>333.5 ± 21.7</td></tr>
<tr><td>126</td><td>Cob</td><td colspan="2">225.7 ± 24.1</td><td colspan="2">Other</td><td>284.7 ± 46.0</td><td>510.4 ± 23.0</td></tr>
<tr><td></td><td colspan="7">Sole cropped maize & EW row</td></tr>
<tr><td>42</td><td colspan="2">18.3 ± 2.8</td><td colspan="2">13.3 ± 2.5</td><td colspan="2">-</td><td>31.6 ± 4.6</td></tr>
<tr><td>56</td><td colspan="2">41.8 ± 8.5</td><td colspan="2">47.8 ± 10.1</td><td colspan="2">-</td><td>89.6 ± 18.6</td></tr>
<tr><td>70</td><td colspan="2">55.3 ± 4.0</td><td colspan="2">120.2 ± 10.3</td><td colspan="2">6.2 ± 0.8</td><td>181.7 ± 12.6</td></tr>
<tr><td>84</td><td colspan="2">58.2 ± 5.5</td><td colspan="2">132.5 ± 11.0</td><td colspan="2">56.3 ± 1.6</td><td>247.0 ± 17.7</td></tr>
<tr><td>105</td><td colspan="2">50.7 ± 6.7</td><td colspan="2">112.7 ± 14.4</td><td colspan="2">153.7 ± 27.9</td><td>317.1 ± 45.4</td></tr>
<tr><td>126</td><td>Cob</td><td colspan="2">221.0 ± 23.8</td><td colspan="2">Other</td><td>311.0 ± 25.9</td><td>532.0 ± 47.5</td></tr>
<tr><td></td><td colspan="7">Intercropped maize & NS row</td></tr>
<tr><td>42</td><td colspan="2">18.8 ± 1.3</td><td colspan="2">16.0 ± 2.2</td><td colspan="2">-</td><td>34.8 ± 3.4</td></tr>
<tr><td>56</td><td colspan="2">38.7 ± 3.5</td><td colspan="2">44.3 ± 10.6</td><td colspan="2">-</td><td>83.0 ± 14.1</td></tr>
<tr><td>70</td><td colspan="2">42.8 ± 5.4</td><td colspan="2">99.2 ± 22.5</td><td colspan="2">7.8 ± 5.3</td><td>149.8 ± 29.3</td></tr>
<tr><td>84</td><td colspan="2">50.0 ± 3.0</td><td colspan="2">124.2 ± 4.8</td><td colspan="2">53.8 ± 12.0</td><td>228.0 ± 19.8</td></tr>
<tr><td>105</td><td colspan="2">42.5 ± 7.8</td><td colspan="2">98.2 ± 12.6</td><td colspan="2">162.5 ± 33.1</td><td>303.2 ± 52.6</td></tr>
<tr><td>126</td><td>Cob</td><td colspan="2">199.0 ± 35.4</td><td colspan="2">Other</td><td>297.3 ± 81.0</td><td>496.3 ± 89.1</td></tr>
<tr><td></td><td colspan="7">Intercropped maize & EW row</td></tr>
<tr><td>42</td><td colspan="2">17.2 ± 2.6</td><td colspan="2">11.2 ± 2.0</td><td colspan="2">-</td><td>28.4 ± 4.5</td></tr>
<tr><td>56</td><td colspan="2">40.8 ± 4.6</td><td colspan="2">51.2 ± 2.0</td><td colspan="2">-</td><td>92.0 ± 5.0</td></tr>
<tr><td>70</td><td colspan="2">46.2 ± 3.2</td><td colspan="2">103.5 ± 17.8</td><td colspan="2">5.8 ± 3.8</td><td>155.5 ± 24.1</td></tr>
<tr><td>84</td><td colspan="2">51.7 ± 4.0</td><td colspan="2">130.0 ± 6.7</td><td colspan="2">51.3 ± 8.5</td><td>233.0 ± 7.4</td></tr>
<tr><td>105</td><td colspan="2">39.5 ± 7.8</td><td colspan="2">100.2 ± 3.8</td><td colspan="2">128.2 ± 31.3</td><td>267.9 ± 35.4</td></tr>
<tr><td>126</td><td>Cob</td><td colspan="2">223.5 ± 31.7</td><td colspan="2">Other</td><td>282.7 ± 11.6</td><td>506.2 ± 29.6</td></tr>
</table>

(mean ± standard error)

Table A.1. cont.

(d) Beans - the 1999/2000 growing season

<table>
<tr><th>DAP</th><th colspan="2">Leaf</th><th colspan="2">Stem</th><th colspan="2">Pod</th><th>Total</th></tr>
<tr><td></td><td colspan="7">Sole cropped beans & NS row</td></tr>
<tr><td>42</td><td colspan="2">12.7 ± 3.1</td><td colspan="2">5.8 ± 0.8</td><td colspan="2">-</td><td>18.5 ± 3.8</td></tr>
<tr><td>56</td><td colspan="2">16.3 ± 2.5</td><td colspan="2">12.8 ± 0.8</td><td colspan="2">-</td><td>29.1 ± 3.2</td></tr>
<tr><td>70</td><td colspan="2">14.2 ± 0.6</td><td colspan="2">13.7 ± 2.0</td><td colspan="2">13.5 ± 2.6</td><td>41.4 ± 4.9</td></tr>
<tr><td>84</td><td colspan="2">11.5 ± 4.0</td><td colspan="2">10.5 ± 3.8</td><td colspan="2">36.5 ± 14.1</td><td>58.5 ± 21.6</td></tr>
<tr><td>105</td><td colspan="2">13.0 ± 7.1</td><td colspan="2">14.5 ± 6.2</td><td colspan="2">54.3 ± 17.9</td><td>81.8 ± 29.6</td></tr>
<tr><td>126</td><td>Seed</td><td colspan="2">33.5 ± 13.4</td><td colspan="2">Other</td><td>47.3 ± 11.3</td><td>80.8 ± 24.0</td></tr>
<tr><td></td><td colspan="7">Sole cropped beans & EW row</td></tr>
<tr><td>42</td><td colspan="2">11.0 ± 3.0</td><td colspan="2">4.8 ± 0.8</td><td colspan="2">-</td><td>15.8 ± 3.8</td></tr>
<tr><td>56</td><td colspan="2">19.5 ± 2.5</td><td colspan="2">13.0 ± 1.3</td><td colspan="2">-</td><td>32.5 ± 3.6</td></tr>
<tr><td>70</td><td colspan="2">15.0 ± 6.6</td><td colspan="2">13.2 ± 5.1</td><td colspan="2">13.2 ± 5.0</td><td>41.4 ± 15.8</td></tr>
<tr><td>84</td><td colspan="2">10.3 ± 2.6</td><td colspan="2">9.0 ± 2.2</td><td colspan="2">33.3 ± 9.6</td><td>52.6 ± 14.0</td></tr>
<tr><td>105</td><td colspan="2">16.5 ± 8.7</td><td colspan="2">14.8 ± 7.2</td><td colspan="2">53.2 ± 22.4</td><td>84.5 ± 38.1</td></tr>
<tr><td>126</td><td>Seed</td><td colspan="2">32.2 ± 0.3</td><td colspan="2">Other</td><td>49.7 ± 12.3</td><td>81.9 ± 12.4</td></tr>
<tr><td></td><td colspan="7">Intercropped beans & NS row</td></tr>
<tr><td>42</td><td colspan="2">5.5 ± 0.5</td><td colspan="2">2.7 ± 0.3</td><td colspan="2">-</td><td>8.2 ± 0.8</td></tr>
<tr><td>56</td><td colspan="2">10.3 ± 1.3</td><td colspan="2">7.5 ± 2.0</td><td colspan="2">-</td><td>17.8 ± 3.3</td></tr>
<tr><td>70</td><td colspan="2">9.3 ± 1.8</td><td colspan="2">8.5 ± 1.8</td><td colspan="2">6.2 ± 4.4</td><td>24.0 ± 7.8</td></tr>
<tr><td>84</td><td colspan="2">8.0 ± 3.6</td><td colspan="2">8.5 ± 2.5</td><td colspan="2">11.5 ± 4.1</td><td>28.0 ± 10.0</td></tr>
<tr><td>105</td><td colspan="2">7.2 ± 0.8</td><td colspan="2">6.7 ± 0.6</td><td colspan="2">16.5 ± 4.8</td><td>30.4 ± 5.8</td></tr>
<tr><td>126</td><td>Seed</td><td colspan="2">9.3 ± 5.4</td><td colspan="2">Other</td><td>21.7 ± 5.3</td><td>31.0 ± 7.5</td></tr>
<tr><td></td><td colspan="7">Intercropped beans & EW row</td></tr>
<tr><td>42</td><td colspan="2">7.0 ± 1.5</td><td colspan="2">3.2 ± 0.6</td><td colspan="2">-</td><td>10.2 ± 2.0</td></tr>
<tr><td>56</td><td colspan="2">10.5 ± 2.2</td><td colspan="2">8.0 ± 1.7</td><td colspan="2">-</td><td>18.5 ± 3.9</td></tr>
<tr><td>70</td><td colspan="2">8.7 ± 2.3</td><td colspan="2">8.2 ± 1.8</td><td colspan="2">2.3 ± 1.3</td><td>19.2 ± 5.3</td></tr>
<tr><td>84</td><td colspan="2">7.2 ± 0.3</td><td colspan="2">7.5 ± 0.5</td><td colspan="2">10.8 ± 4.0</td><td>25.5 ± 4.8</td></tr>
<tr><td>105</td><td colspan="2">4.5 ± 1.8</td><td colspan="2">5.7 ± 1.3</td><td colspan="2">13.3 ± 2.1</td><td>23.5 ± 4.4</td></tr>
<tr><td>126</td><td>Seed</td><td colspan="2">12.2 ± 4.5</td><td colspan="2">Other</td><td>26.5 ± 10.4</td><td>38.7 ± 11.0</td></tr>
</table>

(mean ± standard error)

Table A.2. Leaf area measurements during the 1998/1999 growing season (cm^2/plant).

(a) **Maize**

	Sole cropping		Intercropping	
DAP	NS row	EW row	NS row	EW row
28	911 ± 97	974 ± 179	962 ± 188	966 ± 167
35	2079 ± 171	1959 ± 264	2036 ± 169	2013 ± 132
42	3839 ± 164	3840 ± 653	3869 ± 373	3799 ± 553
49	5589 ± 308	5962 ± 458	5774 ± 735	5514 ± 624
56	7627 ± 276	7741 ± 598	7372 ± 548	7281 ± 666
70	8907 ± 439	8727 ± 552	8051 ± 589	8215 ± 730

(mean ± standard error)

(b) Beans

	Sole cropping		Intercropping	
DAP	NS row	EW row	NS row	EW row
28	173 ± 23	158 ± 18	174 ± 16	178 ± 30
35	365 ± 65	392 ± 38	368 ± 72	375 ± 69
42	946 ± 277	947 ± 163	643 ± 74	617 ± 138
49	1928 ± 309	1825 ± 449	993 ± 313	1082 ± 301
56	2006 ± 513	2059 ± 502	1242 ± 223	1204 ± 398
70	4376 ± 484	4346 ± 470	2680 ± 659	2734 ± 595

(mean ± standard error)

Table A.3. The fraction of PAR intercepted during the 1998/1999 and 1999/2000 growing seasons.

(a) **9:00 – the 1998/1999 growing season**

	Sole maize cropping		Sole bean cropping		Intercropping	
DAP	NS row	EW row	NS row	EW row	NS row	EW row
28	0.207	0.189	0.067	0.166	0.382	0.352
35	0.443	0.433	0.294	0.346	0.580	0.539
42	0.723	0.612	0.519	0.541	0.759	0.686
49	0.841	0.891	0.770	0.789	0.879	0.772
56	0.963	0.938	0.835	0.908	0.951	0.914
63	0.938	0.959	0.977	0.941	0.965	0.977
70	0.978	0.988	0.979	0.984	0.991	0.991
77	0.970	0.972	0.984	0.987	0.986	0.989
84	0.957	0.966	0.980	0.983	0.990	0.989
91	0.967	0.969	0.971	0.928	0.980	0.988
98	0.964	0.963	0.971	0.932	0.990	0.988
105	0.968	0.946	0.960	0.930	0.986	0.982
112	0.947	0.923	0.876	0.825	0.945	0.983
119	0.964	0.887	0.870	0.836	0.984	0.968
126	0.959	0.825	0.891	0.896	0.967	0.954

Table A.3. cont.

(b) 12:00 - the 1998/1999 growing season

	Sole maize cropping		Sole bean cropping		Intercropping	
DAP	NS row	EW row	NS row	EW row	NS row	EW row
28	0.162	0.190	0.026	0.052	0.270	0.272
35	0.317	0.366	0.245	0.299	0.456	0.418
42	0.460	0.590	0.408	0.470	0.612	0.606
49	0.634	0.689	0.570	0.671	0.679	0.719
56	0.732	0.763	0.776	0.847	0.796	0.801
63	0.711	0.847	0.884	0.937	0.922	0.856
70	0.788	0.853	0.956	0.965	0.946	0.886
77	0.783	0.810	0.940	0.940	0.854	0.942
84	0.766	0.737	0.909	0.896	0.907	0.837
91	0.782	0.835	0.899	0.897	0.931	0.916
98	0.868	0.804	0.914	0.883	0.921	0.890
105	0.844	0.762	0.837	0.809	0.929	0.873
112	0.824	0.797	0.756	0.783	0.883	0.884
119	0.873	0.880	0.731	0.836	0.938	0.917
126	0.875	0.876	0.783	0.813	0.911	0.928

(c) 15:00 - the 1998/1999 growing season

	Sole maize cropping		Sole bean cropping		Intercropping	
DAP	NS row	EW row	NS row	EW row	NS row	EW row
28	0.211	0.226	0.082	0.153	0.239	0.284
35	0.390	0.428	0.248	0.339	0.476	0.478
42	0.680	0.676	0.437	0.538	0.740	0.678
49	0.794	0.739	0.642	0.717	0.820	0.857
56	0.873	0.859	0.798	0.863	0.916	0.906
63	0.881	0.944	0.888	0.915	0.919	0.943
70	0.938	0.913	0.974	0.979	0.968	0.972
77	0.857	0.939	0.926	0.940	0.942	0.970
84	0.908	0.922	0.964	0.966	0.961	0.987
91	0.918	0.922	0.943	0.922	0.969	0.982
98	0.922	0.923	0.917	0.896	0.963	0.978
105	0.934	0.918	0.916	0.867	0.926	0.978
112	0.943	0.924	0.857	0.898	0.937	0.971
119	0.895	0.899	0.821	0.823	0.904	0.963
126	0.929	0.914	0.792	0.874	0.924	0.972

(d) between 10:00 and 14:00 - the 1999/2000 growing season

	Sole maize cropping		Sole bean cropping		Intercropping	
DAP	NS row	EW row	NS row	EW row	NS row	EW row
42	0.600	0.617	0.761	0.732	0.711	0.752
56	0.858	0.854	0.923	0.926	0.922	0.933
70	0.958	0.951	0.965	0.975	0.981	0.954
84	0.933	0.907	0.906	0.951	0.962	0.964
105	0.950	0.857	0.819	0.861	0.960	0.949
126	0.912	0.868	0.747	0.753	0.908	0.844

Table A.4. Cumulative incident PAR during the 1998/1999 and 1999/2000 growing seasons (MJ/m^2).

DAP	1998/1999	1999/2000	DAP	1998/1999	1999/2000	DAP	1998/1999	1999/2000
7	85	78	49	605	474	91	1099	890
14	165	154	56	696	530	98	1178	947
21	252	220	63	785	605	105	1246	1000
28	346	269	70	869	688	112	1311	1054
35	434	319	77	956	770	119	1357	1100
42	524	402	84	1032	831	126	1421	1141

Table A.5. Model inputs (LAI, hedgerow height and hedgerow width, LAD and Biomass).

	DAP	NS-maize	EW-maize	NS-beans	EW-beans
LAI (m^2/m^2)	28	0.28	0.27	0.13	0.13
	35	0.86	0.51	0.23	0.27
	42	1.59	0.98	0.40	0.46
	49	3.03	1.93	0.84	0.81
Hedgerow height (m)	28	0.30	0.30	0.15	0.15
	35	0.60	0.40	0.20	0.25
	42	0.80	0.60	0.25	0.30
	49	1.10	1.00	0.35	0.35
Hedgerow width (m)	28	0.20	0.20	0.20	0.20
	35	0.35	0.30	0.25	0.25
	42	0.50	0.40	0.30	0.30
	49	0.70	0.50	0.40	0.40
LAD (m^2/m^3)	28	4.67	4.50	4.33	4.33
	35	4.10	4.25	4.60	4.32
	42	3.98	4.08	5.33	5.11
	49	3.94	3.86	6.00	5.79
Biomass (g/m^2)	28	16	16	8	8
	35	77	37	17	19
	42	104	65	23	31
	49	237	160	47	52

Table A.6. The ratio of PAR to SR during the 1999/2000 growing season.

	PAR/SR	
K_T	Daily	Hourly
0.05	–	0.6019 ± 0.1201
0.15	–	0.5570 ± 0.0940
0.25	0.5414 ± 0.0750	0.5429 ± 0.0940
0.35	0.5226 ± 0.0535	0.4960 ± 0.0793
0.45	0.4702 ± 0.0478	0.4932 ± 0.0754
0.55	0.4693 ± 0.0532	0.4770 ± 0.0555
0.65	0.4349 ± 0.0327	0.4410 ± 0.0404
0.75	–	0.4281 ± 0.0325
0.85	–	–
0.95	–	–

(mean ± standard error)

Table A.7. The ratio of diffuse to global SR on a daily basis (average).

K_T	WHK	PTA	KMS	BFN	DBN	MDB	CT	PE
0.025	0.4368	0.8184	0.2878	0.5736	0.8441	0.6992	0.7420	0.8176
0.075	0.7464	0.9263	0.4460	0.8241	0.9480	0.7855	0.8737	0.9071
0.125	0.8417	0.9461	0.9658	0.8916	0.9390	0.8666	0.9384	0.9519
0.175	0.8386	0.9244	0.7977	0.8682	0.9460	0.8531	0.9228	0.9367
0.225	0.8857	0.8680	0.7106	0.8460	0.9097	0.8263	0.8972	0.9216
0.275	0.8232	0.8159	0.6932	0.8105	0.8695	0.7861	0.8356	0.8638
0.325	0.7650	0.7888	0.7691	0.7529	0.8675	0.7579	0.7729	0.8296
0.375	0.6910	0.7099	0.7074	0.6892	0.8073	0.6525	0.7142	0.7484
0.425	0.6303	0.6267	0.6253	0.6340	0.7152	0.5952	0.6423	0.6784
0.475	0.5394	0.5528	0.5660	0.5436	0.6141	0.5110	0.5648	0.5824
0.525	0.4538	0.4676	0.4861	0.4778	0.4310	0.4639	0.4824	0.4936
0.575	0.4022	0.3828	0.4062	0.4055	0.3152	0.3869	0.3906	0.3985
0.625	0.3364	0.2961	0.3433	0.3289	0.2396	0.3149	0.2920	0.2845
0.675	0.2684	0.2092	0.2658	0.2443	0.1983	0.2415	0.2087	0.2088
0.725	0.1817	0.1598	0.1780	0.1764	0.1680	0.1634	0.1624	0.1692
0.775	0.1273	0.1312	0.1281	0.1348	0.1444	0.1232	0.1359	0.1349
0.825	0.0999	0.1202	0.1088	0.1063	–	0.1059	0.1196	0.1339
0.875	0.0876	–	0.1120	0.0964	–	0.0907	–	–
0.925	–	–	–	–	–	–	–	–
0.975	–	–	–	–	–	–	–	–

WHK – Windhoek; PTA – Pretoria; KMS – Keetmanshoop; BFN – Bloemfontein;
DBN – Durban; MDB – Middelburg; CT – Cape Town; PE – Port Elizabeth

Table A.8. The ratio of diffuse to global SR on an hourly basis.

(a) Windhoek

	Year									
K_T	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
0.025	0.952	0.895	0.954	1.000	1.000	0.831	0.921	0.975	0.944	1.000
0.075	0.963	0.895	0.941	0.991	0.961	0.957	0.976	0.944	0.947	0.994
0.125	0.940	0.861	0.914	0.946	0.913	0.971	0.967	0.942	0.871	0.966
0.175	0.902	0.852	0.914	0.902	0.846	0.943	0.944	0.881	0.905	0.942
0.225	0.873	0.908	0.892	0.885	0.906	0.946	0.928	0.886	0.897	0.866
0.275	0.818	0.843	0.894	0.872	0.925	0.834	0.884	0.880	0.897	0.909
0.325	0.817	0.769	0.790	0.787	0.826	0.775	0.849	0.782	0.842	0.825
0.375	0.730	0.706	0.687	0.694	0.727	0.719	0.775	0.720	0.721	0.768
0.425	0.656	0.647	0.654	0.609	0.676	0.556	0.691	0.604	0.709	0.679
0.475	0.580	0.563	0.557	0.560	0.610	0.498	0.646	0.560	0.580	0.620
0.525	0.493	0.464	0.510	0.525	0.510	0.453	0.539	0.507	0.467	0.528
0.575	0.418	0.389	0.428	0.433	0.435	0.362	0.477	0.450	0.439	0.441
0.625	0.349	0.355	0.328	0.326	0.359	0.322	0.430	0.397	0.342	0.345
0.675	0.289	0.280	0.279	0.277	0.304	0.230	0.356	0.329	0.283	0.294
0.725	0.207	0.209	0.200	0.191	0.228	0.174	0.275	0.255	0.216	0.201
0.775	0.141	0.148	0.140	0.133	0.171	0.129	0.212	0.188	0.159	0.143
0.825	0.113	0.124	0.122	0.137	0.128	0.117	0.195	0.177	0.142	0.129
0.875	0.120	0.134	0.130	0.143	0.131	0.302	0.277	0.199	0.179	0.175
0.925	0.153	0.179	0.196	0.187	0.223	0.408	0.412	0.241	0.218	0.241
0.975	0.183	0.234	0.332	0.309	0.365	0.355	0.486	0.299	0.224	0.270

	Year									
K_T	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
0.025	1.000	0.966	1.000	1.000	1.000	0.966	0.976	0.977	0.966	0.983
0.075	0.981	0.987	0.962	0.989	0.978	0.974	0.984	0.957	0.988	1.000
0.125	0.959	0.952	0.932	0.853	0.933	0.916	0.906	0.896	0.936	0.921
0.175	0.974	0.928	0.888	0.889	0.906	0.921	0.811	0.943	0.935	0.941
0.225	0.872	0.835	0.895	0.878	0.824	0.834	0.802	0.846	0.828	0.829
0.275	0.862	0.867	0.770	0.831	0.856	0.870	0.809	0.846	0.852	0.818
0.325	0.783	0.762	0.781	0.800	0.795	0.791	0.803	0.782	0.776	0.745
0.375	0.689	0.685	0.683	0.656	0.659	0.744	0.675	0.699	0.699	0.708
0.425	0.631	0.546	0.606	0.618	0.615	0.673	0.537	0.685	0.641	0.575
0.475	0.541	0.524	0.554	0.523	0.522	0.566	0.532	0.582	0.560	0.526
0.525	0.460	0.431	0.432	0.483	0.465	0.501	0.440	0.470	0.475	0.402
0.575	0.377	0.372	0.375	0.416	0.392	0.411	0.377	0.419	0.386	0.359
0.625	0.346	0.314	0.324	0.344	0.347	0.342	0.314	0.357	0.339	0.278
0.675	0.239	0.229	0.235	0.269	0.258	0.302	0.245	0.268	0.285	0.209
0.725	0.191	0.180	0.178	0.210	0.208	0.225	0.202	0.210	0.213	0.155
0.775	0.132	0.142	0.138	0.154	0.154	0.159	0.140	0.151	0.159	0.117
0.825	0.121	0.110	0.115	0.117	0.116	0.117	0.104	0.112	0.119	0.112
0.875	0.161	0.161	0.150	0.122	0.122	0.129	0.127	0.153	0.135	0.138
0.925	0.216	0.195	0.164	0.183	0.187	0.210	0.156	0.190	0.244	0.255
0.975	0.251	0.204	0.324	0.185	0.224	0.237	0.196	0.209	0.273	0.289

Table A.8. cont.

	Year						
K_T	1977	1978	1979	1980	1981	1982	1983
0.025	0.992	0.972	0.971	0.865	0.951	1.000	0.964
0.075	0.991	0.977	0.975	0.830	0.952	0.982	0.987
0.125	0.938	0.983	0.931	0.936	0.864	0.944	0.961
0.175	0.936	0.917	0.917	0.953	0.815	0.924	0.963
0.225	0.873	0.887	0.838	0.939	0.726	0.855	0.878
0.275	0.858	0.826	0.815	0.901	0.722	0.840	0.819
0.325	0.785	0.756	0.758	0.863	0.671	0.727	0.753
0.375	0.700	0.587	0.742	0.793	0.610	0.659	0.666
0.425	0.637	0.555	0.647	0.629	0.527	0.577	0.581
0.475	0.549	0.517	0.571	0.560	0.441	0.518	0.514
0.525	0.436	0.473	0.498	0.537	0.350	0.433	0.398
0.575	0.361	0.400	0.380	0.432	0.329	0.342	0.384
0.625	0.300	0.292	0.324	0.352	0.267	0.298	0.323
0.675	0.223	0.254	0.252	0.300	0.200	0.235	0.234
0.725	0.153	0.184	0.179	0.224	0.148	0.168	0.181
0.775	0.117	0.153	0.148	0.169	0.122	0.129	0.140
0.825	0.128	0.118	0.105	0.143	0.107	0.122	0.138
0.875	0.191	0.114	0.128	0.217	0.114	0.165	0.195
0.925	0.329	0.186	0.199	0.367	0.174	0.232	0.314
0.975	0.315	0.178	0.321	0.327	0.244	0.425	0.424

(b) Pretoria

	Year									
K_T	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
0.025	0.955	0.942	0.958	0.959	0.893	0.981	0.954	0.881	0.981	0.928
0.075	0.980	0.956	0.956	0.978	0.966	0.960	0.974	0.965	0.978	0.958
0.125	0.953	0.923	0.954	0.950	0.934	0.912	0.920	0.946	0.940	0.966
0.175	0.944	0.910	0.934	0.895	0.908	0.906	0.953	0.957	0.932	0.947
0.225	0.886	0.880	0.883	0.862	0.865	0.831	0.905	0.885	0.858	0.911
0.275	0.867	0.833	0.839	0.819	0.836	0.777	0.875	0.840	0.832	0.865
0.325	0.787	0.779	0.722	0.767	0.756	0.709	0.791	0.786	0.686	0.818
0.375	0.696	0.687	0.671	0.701	0.743	0.614	0.734	0.706	0.683	0.742
0.425	0.614	0.622	0.604	0.573	0.607	0.582	0.674	0.670	0.572	0.646
0.475	0.542	0.533	0.519	0.516	0.581	0.483	0.567	0.580	0.534	0.555
0.525	0.426	0.469	0.440	0.433	0.447	0.434	0.515	0.519	0.479	0.514
0.575	0.403	0.370	0.369	0.386	0.407	0.363	0.448	0.432	0.375	0.431
0.625	0.330	0.328	0.299	0.314	0.328	0.292	0.380	0.368	0.337	0.362
0.675	0.248	0.243	0.238	0.247	0.257	0.230	0.317	0.294	0.259	0.296
0.725	0.193	0.187	0.176	0.170	0.186	0.173	0.257	0.229	0.205	0.230
0.775	0.146	0.152	0.134	0.134	0.138	0.133	0.212	0.203	0.168	0.178
0.825	0.139	0.145	0.131	0.138	0.130	0.142	0.155	0.229	0.159	0.162
0.875	0.271	0.268	0.189	0.186	0.220	0.219	0.233	0.439	0.289	0.241
0.925	0.369	0.397	0.270	0.213	0.209	0.221	0.367	0.558	0.396	0.330
0.975	0.430	0.526	0.256	0.393	0.365	0.335	0.282	0.515	0.386	0.434

Table A.8. cont.

	Year									
K_T	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
0.025	0.952	0.941	0.906	0.970	0.849	0.969	1.000	0.964	1.000	1.000
0.075	0.972	0.955	0.904	0.953	0.922	0.936	0.939	0.961	0.990	0.992
0.125	0.942	0.946	0.974	0.937	0.945	0.922	0.963	0.957	0.960	0.961
0.175	0.986	0.961	0.943	0.923	0.922	0.900	0.949	0.944	0.953	0.942
0.225	0.921	0.917	0.869	0.881	0.853	0.859	0.891	0.833	0.885	0.857
0.275	0.912	0.893	0.856	0.826	0.826	0.839	0.862	0.818	0.865	0.864
0.325	0.848	0.818	0.798	0.797	0.763	0.783	0.812	0.808	0.782	0.789
0.375	0.786	0.737	0.723	0.673	0.686	0.686	0.713	0.684	0.687	0.679
0.425	0.698	0.641	0.638	0.570	0.625	0.612	0.647	0.602	0.594	0.606
0.475	0.595	0.609	0.594	0.530	0.548	0.554	0.555	0.545	0.559	0.519
0.525	0.535	0.520	0.492	0.450	0.466	0.468	0.486	0.459	0.462	0.476
0.575	0.464	0.448	0.401	0.397	0.397	0.383	0.446	0.389	0.401	0.393
0.625	0.409	0.383	0.352	0.318	0.331	0.336	0.364	0.325	0.302	0.323
0.675	0.343	0.322	0.263	0.252	0.258	0.269	0.281	0.257	0.242	0.247
0.725	0.262	0.249	0.208	0.190	0.203	0.200	0.226	0.189	0.184	0.194
0.775	0.215	0.194	0.174	0.160	0.171	0.165	0.171	0.160	0.151	0.173
0.825	0.176	0.159	0.175	0.182	0.173	0.136	0.161	0.214	0.201	0.137
0.875	0.203	0.191	0.208	0.362	0.254	0.245	0.222	0.288	0.235	0.214
0.925	0.254	0.308	0.311	0.394	0.414	0.397	0.536	0.380	0.368	0.267
0.975	0.438	0.345	0.407	0.618	0.476	0.478	0.688	0.342	0.361	0.288

	Year									
K_T	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
0.025	0.971	0.945	0.983	1.000	0.955	0.874	0.910	0.923	1.000	0.993
0.075	0.966	0.966	0.966	0.984	0.975	0.911	0.904	0.969	0.985	0.993
0.125	0.977	0.959	0.925	0.916	0.964	0.870	0.861	0.943	0.963	0.977
0.175	0.936	0.925	0.923	0.924	0.943	0.893	0.885	0.927	0.923	0.930
0.225	0.887	0.856	0.832	0.848	0.901	0.805	0.840	0.840	0.869	0.880
0.275	0.807	0.816	0.796	0.815	0.855	0.733	0.788	0.836	0.822	0.856
0.325	0.774	0.783	0.741	0.800	0.748	0.686	0.726	0.785	0.780	0.751
0.375	0.704	0.702	0.654	0.688	0.700	0.628	0.646	0.691	0.687	0.652
0.425	0.570	0.603	0.598	0.586	0.595	0.572	0.551	0.625	0.585	0.581
0.475	0.537	0.508	0.534	0.522	0.526	0.496	0.485	0.519	0.549	0.522
0.525	0.463	0.445	0.459	0.429	0.467	0.434	0.442	0.471	0.440	0.456
0.575	0.391	0.391	0.375	0.372	0.400	0.371	0.368	0.366	0.377	0.375
0.625	0.330	0.314	0.297	0.310	0.313	0.289	0.304	0.298	0.306	0.297
0.675	0.252	0.254	0.250	0.242	0.245	0.233	0.235	0.231	0.240	0.237
0.725	0.203	0.180	0.182	0.183	0.194	0.183	0.180	0.174	0.175	0.178
0.775	0.157	0.149	0.154	0.145	0.167	0.151	0.145	0.148	0.150	0.158
0.825	0.175	0.186	0.148	0.156	0.185	0.244	0.208	0.170	0.191	0.211
0.875	0.217	0.285	0.217	0.220	0.283	0.417	0.347	0.332	0.256	0.336
0.925	0.371	0.385	0.280	0.307	0.487	0.470	0.391	0.376	0.454	0.421
0.975	0.507	0.312	0.240	0.234	0.305	0.431	0.374	0.404	0.250	0.484

Table A.8. cont.

	Year										
K_T	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997
0.025	0.994	1.000	0.998	0.812	0.814	0.940	0.870	0.830	0.887	0.882	0.884
0.075	0.990	0.967	0.967	0.777	0.780	0.888	0.955	0.897	0.939	0.920	0.901
0.125	0.971	0.951	0.972	0.765	0.781	0.850	0.901	0.908	0.913	0.860	0.886
0.175	0.951	0.934	0.931	0.752	0.753	0.873	0.881	0.867	0.849	0.844	0.867
0.225	0.867	0.893	0.858	0.706	0.705	0.847	0.821	0.805	0.845	0.815	0.802
0.275	0.837	0.886	0.834	0.648	0.660	0.802	0.797	0.812	0.808	0.775	0.830
0.325	0.794	0.822	0.748	0.580	0.632	0.714	0.769	0.764	0.712	0.777	0.761
0.375	0.678	0.714	0.687	0.542	0.536	0.654	0.691	0.661	0.673	0.680	0.674
0.425	0.603	0.634	0.603	0.483	0.466	0.580	0.622	0.541	0.580	0.641	0.614
0.475	0.532	0.576	0.539	0.425	0.405	0.524	0.550	0.501	0.510	0.552	0.537
0.525	0.435	0.474	0.460	0.372	0.366	0.438	0.487	0.438	0.451	0.472	0.474
0.575	0.374	0.388	0.404	0.292	0.314	0.401	0.398	0.392	0.385	0.399	0.370
0.625	0.312	0.322	0.320	0.247	0.251	0.320	0.333	0.296	0.314	0.328	0.304
0.675	0.237	0.249	0.245	0.189	0.199	0.265	0.256	0.234	0.245	0.249	0.235
0.725	0.176	0.181	0.176	0.135	0.151	0.203	0.186	0.169	0.179	0.187	0.173
0.775	0.158	0.156	0.139	0.118	0.123	0.171	0.173	0.153	0.149	0.154	0.165
0.825	0.277	0.198	0.207	0.158	0.153	0.227	0.249	0.274	0.160	0.208	0.210
0.875	0.341	0.314	0.346	0.344	0.280	0.424	0.396	0.382	0.311	0.322	0.467
0.925	0.384	0.363	0.416	0.270	0.346	0.450	0.496	0.328	0.274	0.440	0.528
0.975	0.517	0.353	0.413	0.431	0.243	0.650	0.379	0.582	0.426	0.436	0.782

Table A.8. cont.

(c) Keetmanshoop

	Year									
K_T	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
0.025	1.000	0.934	0.850	1.000	0.969	1.000	1.000	1.000	1.000	0.954
0.075	0.984	0.982	0.975	0.987	0.983	0.970	0.978	0.984	0.962	0.972
0.125	0.860	0.862	0.837	0.829	0.800	0.792	0.955	0.860	0.862	0.886
0.175	0.843	0.788	0.842	0.815	0.854	0.773	0.933	0.840	0.893	0.813
0.225	0.866	0.858	0.842	0.877	0.919	0.859	0.844	0.864	0.912	0.907
0.275	0.748	0.686	0.927	0.732	0.769	0.720	0.790	0.736	0.747	0.677
0.325	0.642	0.656	0.639	0.596	0.637	0.727	0.744	0.642	0.619	0.681
0.375	0.620	0.593	0.634	0.590	0.626	0.636	0.749	0.620	0.657	0.711
0.425	0.508	0.542	0.591	0.551	0.525	0.496	0.660	0.501	0.593	0.590
0.475	0.456	0.414	0.470	0.454	0.434	0.438	0.559	0.456	0.529	0.520
0.525	0.388	0.388	0.425	0.437	0.409	0.416	0.492	0.388	0.455	0.487
0.575	0.339	0.357	0.364	0.326	0.326	0.343	0.445	0.339	0.390	0.397
0.625	0.284	0.267	0.282	0.290	0.284	0.264	0.383	0.284	0.369	0.354
0.675	0.231	0.227	0.241	0.217	0.220	0.244	0.338	0.231	0.282	0.276
0.725	0.177	0.162	0.172	0.148	0.148	0.163	0.262	0.176	0.230	0.217
0.775	0.120	0.127	0.121	0.119	0.116	0.121	0.189	0.118	0.176	0.155
0.825	0.104	0.116	0.118	0.121	0.123	0.103	0.170	0.104	0.134	0.122
0.875	0.119	0.133	0.139	0.152	0.158	0.137	0.265	0.119	0.137	0.135
0.925	0.153	0.194	0.201	0.173	0.231	0.159	0.349	0.154	0.173	0.171
0.975	0.149	0.173	0.175	0.269	0.216	0.218	0.353	0.149	0.201	0.211

	Year									
K_T	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
0.025	1.000	1.000	1.000	1.000	0.826	0.950	1.000	0.854	0.888	1.000
0.075	0.955	0.968	0.943	0.942	0.943	0.988	0.992	0.920	0.913	1.000
0.125	0.836	0.733	0.955	0.939	0.851	0.839	0.825	0.879	0.875	0.869
0.175	0.882	0.845	0.806	0.817	0.854	0.741	0.852	0.859	0.826	0.861
0.225	0.854	0.853	0.775	0.905	0.896	0.826	0.867	0.869	0.837	0.877
0.275	0.662	0.674	0.665	0.840	0.841	0.752	0.719	0.839	0.774	0.588
0.325	0.658	0.615	0.637	0.659	0.731	0.677	0.702	0.690	0.715	0.637
0.375	0.651	0.589	0.562	0.605	0.652	0.614	0.632	0.693	0.557	0.566
0.425	0.547	0.477	0.501	0.567	0.626	0.512	0.576	0.597	0.523	0.488
0.475	0.507	0.487	0.442	0.488	0.517	0.486	0.441	0.514	0.448	0.527
0.525	0.393	0.418	0.410	0.444	0.458	0.403	0.408	0.458	0.399	0.496
0.575	0.361	0.336	0.336	0.341	0.378	0.363	0.369	0.420	0.412	0.358
0.625	0.308	0.278	0.286	0.325	0.315	0.305	0.307	0.356	0.325	0.337
0.675	0.248	0.226	0.217	0.233	0.247	0.217	0.238	0.271	0.273	0.272
0.725	0.183	0.162	0.164	0.184	0.175	0.158	0.167	0.191	0.206	0.197
0.775	0.126	0.124	0.123	0.130	0.130	0.118	0.120	0.139	0.146	0.153
0.825	0.122	0.105	0.108	0.118	0.114	0.114	0.113	0.111	0.111	0.108
0.875	0.135	0.132	0.160	0.136	0.136	0.141	0.141	0.120	0.112	0.117
0.925	0.175	0.213	0.220	0.163	0.163	0.172	0.146	0.144	0.149	0.138
0.975	0.211	0.234	0.263	0.173	0.198	0.199	0.190	0.162	0.159	0.164

Table A.8. cont.

	Year								
K_T	1977	1978	1979	1980	1981	1982	1983	1984	1985
0.025	0.916	1.000	1.000	1.000	1.000	1.000	1.000	1.000	–
0.075	0.989	1.000	0.979	0.960	0.964	0.929	0.977	0.743	1.000
0.125	0.903	0.917	0.975	0.884	0.820	0.877	0.941	0.921	0.833
0.175	0.858	0.889	0.860	0.859	0.820	0.779	0.936	0.888	0.892
0.225	0.773	0.815	0.894	0.899	0.609	0.802	0.838	0.886	0.905
0.275	0.754	0.773	0.794	0.763	0.657	0.727	0.792	0.846	0.920
0.325	0.635	0.708	0.707	0.722	0.587	0.551	0.666	0.657	0.665
0.375	0.607	0.657	0.649	0.646	0.527	0.579	0.674	0.588	0.596
0.425	0.589	0.551	0.634	0.570	0.474	0.552	0.547	0.545	0.459
0.475	0.560	0.472	0.545	0.512	0.369	0.425	0.502	0.477	0.469
0.525	0.472	0.439	0.526	0.468	0.407	0.423	0.393	0.381	0.323
0.575	0.417	0.452	0.396	0.413	0.351	0.366	0.348	0.355	0.320
0.625	0.300	0.359	0.315	0.314	0.302	0.297	0.308	0.305	0.232
0.675	0.260	0.273	0.288	0.260	0.218	0.245	0.240	0.237	0.194
0.725	0.217	0.214	0.204	0.203	0.176	0.178	0.174	0.160	0.166
0.775	0.150	0.154	0.151	0.149	0.125	0.126	0.135	0.115	0.121
0.825	0.101	0.114	0.111	0.119	0.102	0.112	0.145	0.132	0.117
0.875	0.112	0.114	0.133	0.138	0.111	0.155	0.214	0.202	0.183
0.925	0.150	0.145	0.196	0.172	0.155	0.172	0.198	0.172	0.188
0.975	0.153	0.194	0.223	0.184	0.175	0.208	0.217	–	0.165

(d) Bloemfontein

	Year									
K_T	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
0.025	0.952	0.856	0.955	0.983	0.981	0.960	0.976	0.978	0.904	0.946
0.075	0.949	0.990	0.941	0.942	0.949	0.922	0.947	0.977	0.941	0.938
0.125	0.892	0.942	0.937	0.936	0.914	0.899	0.911	0.920	0.877	0.896
0.175	0.894	0.879	0.895	0.901	0.891	0.901	0.905	0.880	0.869	0.872
0.225	0.838	0.850	0.892	0.826	0.851	0.814	0.826	0.839	0.823	0.815
0.275	0.845	0.841	0.852	0.831	0.752	0.749	0.833	0.808	0.801	0.807
0.325	0.739	0.774	0.839	0.744	0.722	0.690	0.785	0.748	0.706	0.711
0.375	0.692	0.649	0.738	0.623	0.635	0.565	0.712	0.659	0.608	0.614
0.425	0.589	0.555	0.612	0.508	0.620	0.563	0.658	0.658	0.579	0.590
0.475	0.512	0.561	0.594	0.514	0.527	0.553	0.576	0.607	0.574	0.568
0.525	0.467	0.508	0.551	0.491	0.456	0.456	0.575	0.504	0.502	0.531
0.575	0.403	0.443	0.470	0.389	0.350	0.374	0.473	0.445	0.399	0.426
0.625	0.360	0.350	0.354	0.323	0.355	0.304	0.415	0.392	0.365	0.367
0.675	0.290	0.286	0.307	0.261	0.251	0.234	0.345	0.326	0.313	0.303
0.725	0.217	0.247	0.235	0.195	0.197	0.179	0.300	0.274	0.248	0.247
0.775	0.157	0.185	0.182	0.155	0.148	0.133	0.246	0.222	0.191	0.189
0.825	0.126	0.147	0.145	0.134	0.121	0.130	0.208	0.182	0.147	0.140
0.875	0.141	0.135	0.140	0.142	0.146	0.146	0.183	0.199	0.141	0.131
0.925	0.175	0.164	0.153	0.169	0.167	0.170	0.198	0.257	0.177	0.145
0.975	0.286	0.188	0.172	0.199	0.201	0.194	0.266	0.313	0.242	0.164

Table A.8. cont.

	Year									
K_T	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
0.025	0.954	0.980	0.902	0.942	0.947	0.961	0.929	0.988	0.920	0.966
0.075	0.959	0.984	0.903	0.964	0.873	0.927	0.953	0.959	0.934	0.984
0.125	0.929	0.905	0.828	0.883	0.917	0.913	0.928	0.930	0.932	0.960
0.175	0.897	0.905	0.789	0.881	0.858	0.838	0.889	0.913	0.861	0.879
0.225	0.834	0.838	0.754	0.840	0.838	0.815	0.799	0.833	0.851	0.843
0.275	0.808	0.746	0.722	0.764	0.779	0.783	0.749	0.818	0.810	0.779
0.325	0.680	0.659	0.659	0.670	0.675	0.709	0.700	0.679	0.692	0.721
0.375	0.606	0.635	0.609	0.576	0.597	0.626	0.626	0.652	0.656	0.678
0.425	0.625	0.595	0.561	0.558	0.582	0.537	0.591	0.605	0.588	0.612
0.475	0.604	0.527	0.511	0.490	0.489	0.520	0.505	0.546	0.517	0.545
0.525	0.527	0.457	0.423	0.459	0.439	0.460	0.450	0.503	0.455	0.487
0.575	0.443	0.402	0.375	0.396	0.386	0.410	0.391	0.394	0.395	0.404
0.625	0.362	0.338	0.327	0.341	0.320	0.323	0.318	0.333	0.326	0.354
0.675	0.324	0.282	0.277	0.258	0.260	0.258	0.272	0.261	0.264	0.285
0.725	0.260	0.229	0.221	0.223	0.208	0.197	0.228	0.220	0.197	0.227
0.775	0.201	0.188	0.179	0.169	0.159	0.152	0.158	0.156	0.147	0.158
0.825	0.139	0.138	0.136	0.132	0.121	0.111	0.118	0.124	0.121	0.131
0.875	0.125	0.121	0.129	0.116	0.116	0.121	0.114	0.128	0.148	0.145
0.925	0.146	0.133	0.152	0.148	0.143	0.154	0.155	0.232	0.191	0.221
0.975	0.187	0.187	0.202	0.170	0.201	0.218	0.191	0.303	0.249	0.250

	Year									
K_T	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
0.025	0.984	0.949	0.899	0.933	0.937	0.912	0.928	0.917	0.877	0.828
0.075	0.963	0.936	0.950	0.939	0.925	0.816	0.935	0.921	0.875	0.842
0.125	0.933	0.917	0.943	0.913	0.891	0.811	0.883	0.858	0.877	0.839
0.175	0.875	0.858	0.901	0.823	0.851	0.771	0.833	0.844	0.821	0.793
0.225	0.842	0.818	0.841	0.775	0.798	0.713	0.813	0.790	0.811	0.786
0.275	0.771	0.781	0.783	0.742	0.723	0.658	0.736	0.733	0.735	0.733
0.325	0.716	0.693	0.695	0.637	0.591	0.649	0.676	0.713	0.654	0.667
0.375	0.614	0.627	0.611	0.603	0.620	0.580	0.648	0.588	0.607	0.618
0.425	0.593	0.552	0.592	0.581	0.587	0.503	0.573	0.506	0.567	0.571
0.475	0.530	0.552	0.529	0.440	0.487	0.485	0.531	0.484	0.533	0.571
0.525	0.488	0.503	0.478	0.388	0.415	0.401	0.457	0.443	0.478	0.455
0.575	0.384	0.371	0.389	0.338	0.344	0.344	0.400	0.381	0.398	0.365
0.625	0.339	0.345	0.324	0.267	0.333	0.307	0.349	0.327	0.357	0.361
0.675	0.263	0.292	0.259	0.226	0.268	0.247	0.299	0.262	0.288	0.282
0.725	0.204	0.209	0.207	0.175	0.213	0.197	0.242	0.224	0.228	0.256
0.775	0.153	0.162	0.160	0.139	0.173	0.168	0.193	0.178	0.201	0.179
0.825	0.127	0.128	0.119	0.111	0.143	0.142	0.157	0.155	0.164	0.154
0.875	0.147	0.152	0.126	0.128	0.114	0.123	0.154	0.141	0.153	0.135
0.925	0.194	0.245	0.174	0.195	0.154	0.223	0.218	0.251	0.201	0.200
0.975	0.301	0.285	0.229	0.257	0.330	0.270	0.280	0.359	0.276	0.235

Table A.8. cont.

	Year						
K_T	1987	1988	1989	1990	1991	1992	1993
0.025	0.934	0.708	0.755	0.875	0.860	0.516	0.775
0.075	0.839	0.748	0.744	0.741	0.808	0.744	0.883
0.125	0.829	0.771	0.730	0.762	0.816	0.679	0.841
0.175	0.783	0.740	0.735	0.735	0.818	0.737	0.824
0.225	0.747	0.725	0.728	0.725	0.760	0.719	0.864
0.275	0.701	0.654	0.643	0.681	0.677	0.641	0.777
0.325	0.630	0.632	0.573	0.579	0.623	0.567	0.635
0.375	0.593	0.603	0.577	0.567	0.538	0.617	0.562
0.425	0.541	0.527	0.565	0.530	0.561	0.453	0.565
0.475	0.457	0.483	0.503	0.515	0.495	0.460	0.482
0.525	0.448	0.421	0.382	0.408	0.444	0.343	0.423
0.575	0.375	0.348	0.344	0.343	0.354	0.363	0.353
0.625	0.311	0.299	0.313	0.301	0.308	0.300	0.269
0.675	0.254	0.257	0.234	0.225	0.253	0.218	0.223
0.725	0.202	0.199	0.187	0.175	0.185	0.189	0.169
0.775	0.147	0.146	0.132	0.126	0.152	0.178	0.169
0.825	0.127	0.125	0.121	0.126	0.139	0.153	0.167
0.875	0.117	0.129	0.147	0.169	0.179	0.183	0.207
0.925	0.183	0.198	0.190	0.244	0.211	0.225	0.331
0.975	0.229	0.297	0.248	0.332	0.262	0.249	0.487

(e) Durban

	Year									
K_T	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
0.025	0.983	0.947	0.975	0.968	0.964	0.958	0.971	0.974	0.983	0.969
0.075	0.966	0.945	0.961	0.945	0.956	0.973	0.969	0.956	0.966	0.951
0.125	0.953	0.936	0.961	0.968	0.970	0.953	0.975	0.967	0.964	0.937
0.175	0.956	0.921	0.952	0.963	0.952	0.952	0.976	0.970	0.959	0.950
0.225	0.952	0.930	0.935	0.925	0.939	0.939	0.950	0.978	0.938	0.950
0.275	0.904	0.891	0.898	0.897	0.898	0.871	0.922	0.935	0.919	0.913
0.325	0.808	0.769	0.836	0.744	0.802	0.763	0.850	0.885	0.887	0.873
0.375	0.696	0.704	0.714	0.686	0.710	0.718	0.758	0.810	0.796	0.808
0.425	0.610	0.614	0.624	0.606	0.602	0.659	0.704	0.706	0.738	0.701
0.475	0.528	0.556	0.559	0.504	0.532	0.534	0.619	0.632	0.612	0.624
0.525	0.428	0.461	0.456	0.430	0.420	0.428	0.537	0.531	0.533	0.540
0.575	0.339	0.339	0.373	0.350	0.338	0.356	0.460	0.458	0.446	0.462
0.625	0.295	0.281	0.281	0.260	0.258	0.269	0.354	0.350	0.345	0.355
0.675	0.224	0.210	0.207	0.193	0.208	0.207	0.277	0.273	0.258	0.273
0.725	0.189	0.187	0.182	0.180	0.169	0.174	0.232	0.228	0.210	0.208
0.775	0.147	0.156	0.143	0.153	0.158	0.158	0.158	0.222	0.187	0.176
0.825	0.140	0.155	0.218	0.193	0.168	0.216	0.275	0.314	0.228	0.235
0.875	0.348	0.381	0.587	0.670	0.338	0.150	0.572	1.000	0.461	0.395
0.925	0.494	0.747	0.737	1.000	0.490	0.480	0.600	–	0.284	0.540
0.975	1.000	1.000	1.000	1.000	1.000	0.600	1.000	–	0.531	0.832

Table A.8. cont.

	Year									
K_T	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
0.025	0.965	0.964	0.968	0.960	0.956	0.927	0.945	0.921	0.896	0.902
0.075	0.945	0.921	0.958	0.960	0.940	0.936	0.936	0.904	0.931	0.924
0.125	0.930	0.881	0.959	0.947	0.943	0.925	0.946	0.915	0.915	0.902
0.175	0.924	0.803	0.953	0.958	0.930	0.925	0.944	0.905	0.914	0.902
0.225	0.935	0.812	0.939	0.942	0.931	0.929	0.934	0.892	0.914	0.909
0.275	0.909	0.841	0.894	0.877	0.903	0.867	0.909	0.844	0.874	0.859
0.325	0.835	0.684	0.821	0.807	0.792	0.774	0.798	0.756	0.761	0.780
0.375	0.754	0.643	0.715	0.700	0.717	0.682	0.678	0.689	0.700	0.688
0.425	0.658	0.535	0.610	0.612	0.614	0.606	0.642	0.600	0.641	0.625
0.475	0.555	0.435	0.538	0.558	0.533	0.525	0.526	0.526	0.562	0.550
0.525	0.488	0.354	0.462	0.451	0.426	0.442	0.477	0.267	0.455	0.460
0.575	0.386	0.424	0.358	0.357	0.333	0.355	0.353	0.328	0.376	0.365
0.625	0.298	0.388	0.272	0.270	0.256	0.255	0.287	0.269	0.279	0.284
0.675	0.227	0.328	0.204	0.217	0.199	0.202	0.227	0.225	0.233	0.226
0.725	0.191	0.335	0.176	0.175	0.177	0.175	0.193	0.210	0.214	0.200
0.775	0.164	0.304	0.186	0.175	0.201	0.173	0.164	0.170	0.194	0.167
0.825	0.275	0.320	0.296	0.331	0.577	0.229	0.161	0.173	0.153	0.174
0.875	0.426	0.309	0.526	1.000	0.283	0.680	0.477	0.496	0.204	0.343
0.925	0.412	0.223	0.372	–	0.888	0.631	0.400	0.097	0.788	
0.975	0.660	0.272	0.732	1.000	1.000	1.000	0.750	0.683	0.719	0.688

	Year									
K_T	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
0.025	0.952	0.969	0.903	0.931	0.912	0.894	0.861	0.858	0.923	0.811
0.075	0.915	0.924	0.888	0.915	0.944	0.923	0.906	0.893	0.921	0.842
0.125	0.942	0.927	0.909	0.879	0.947	0.930	0.902	0.908	0.905	0.858
0.175	0.946	0.939	0.924	0.858	0.947	0.942	0.908	0.922	0.919	0.862
0.225	0.914	0.919	0.925	0.875	0.948	0.927	0.918	0.933	0.884	0.890
0.275	0.897	0.893	0.878	0.816	0.893	0.896	0.901	0.877	0.852	0.842
0.325	0.819	0.833	0.800	0.740	0.842	0.844	0.846	0.849	0.743	0.806
0.375	0.723	0.752	0.738	0.667	0.777	0.737	0.764	0.759	0.637	0.713
0.425	0.648	0.640	0.628	0.589	0.686	0.653	0.652	0.684	0.575	0.666
0.475	0.559	0.551	0.551	0.541	0.598	0.569	0.543	0.554	0.464	0.560
0.525	0.437	0.472	0.474	0.429	0.518	0.484	0.474	0.456	0.420	0.481
0.575	0.326	0.363	0.349	0.331	0.425	0.398	0.381	0.353	0.351	0.377
0.625	0.262	0.259	0.283	0.271	0.344	0.308	0.301	0.280	0.295	0.317
0.675	0.225	0.202	0.214	0.198	0.250	0.246	0.246	0.231	0.251	0.269
0.725	0.206	0.184	0.197	0.180	0.213	0.217	0.215	0.218	0.223	0.263
0.775	0.193	0.171	0.169	0.163	0.186	0.182	0.180	0.197	0.203	0.212
0.825	0.241	0.361	0.226	0.162	0.178	0.191	0.256	0.163	0.174	0.186
0.875	0.484	0.457	0.694	0.663	0.342	0.512	0.448	0.532	0.448	0.437
0.925	0.573	–	0.500	0.549	0.563	0.488	0.500	0.501	0.464	0.328
0.975	0.832	0.750	0.466	0.501	0.660	0.750	0.800	0.667	0.708	0.583

Table A.8. cont.

	Year				
K_T	1987	1988	1989	1990	1991
0.025	0.968	0.998	0.940	0.964	0.838
0.075	0.974	0.995	0.968	0.921	0.829
0.125	0.968	0.989	0.962	0.926	0.891
0.175	0.966	0.964	0.953	0.929	0.886
0.225	0.948	0.966	0.911	0.894	0.837
0.275	0.907	0.906	0.858	0.838	0.828
0.325	0.814	0.821	0.767	0.770	0.776
0.375	0.724	0.695	0.688	0.708	0.682
0.425	0.651	0.638	0.626	0.639	0.597
0.475	0.549	0.567	0.563	0.540	0.561
0.525	0.441	0.425	0.415	0.456	0.413
0.575	0.326	0.335	0.343	0.328	0.321
0.625	0.276	0.268	0.266	0.262	0.251
0.675	0.230	0.223	0.213	0.219	0.200
0.725	0.195	0.212	0.179	0.199	0.194
0.775	0.186	0.167	0.151	0.161	0.232
0.825	0.278	0.229	0.231	0.193	0.610
0.875	0.397	0.450	–	0.524	–
0.925	–	0.750	–	0.577	0.230
0.975	0.500	0.419	0.919	0.489	–

(f) Middelburg

	Year									
K_T	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
0.025	0.933	0.928	0.950	0.993	0.965	0.983	0.965	0.962	0.926	0.966
0.075	0.927	0.905	0.968	0.973	0.975	0.966	0.924	0.943	0.935	0.932
0.125	0.860	0.901	0.902	0.911	0.898	0.911	0.944	0.885	0.898	0.870
0.175	0.815	0.867	0.898	0.884	0.896	0.884	0.866	0.873	0.898	0.832
0.225	0.824	0.769	0.745	0.821	0.852	0.804	0.845	0.811	0.867	0.820
0.275	0.775	0.739	0.759	0.724	0.773	0.706	0.763	0.768	0.776	0.779
0.325	0.657	0.615	0.610	0.661	0.711	0.696	0.712	0.691	0.714	0.723
0.375	0.623	0.596	0.598	0.659	0.587	0.692	0.683	0.643	0.672	0.639
0.425	0.593	0.583	0.570	0.647	0.657	0.650	0.651	0.551	0.619	0.596
0.475	0.503	0.503	0.566	0.553	0.582	0.571	0.551	0.519	0.552	0.500
0.525	0.503	0.454	0.487	0.472	0.473	0.476	0.504	0.458	0.473	0.440
0.575	0.391	0.364	0.383	0.419	0.402	0.419	0.398	0.355	0.384	0.406
0.625	0.360	0.326	0.348	0.370	0.358	0.353	0.347	0.310	0.323	0.284
0.675	0.277	0.281	0.267	0.285	0.280	0.276	0.273	0.245	0.274	0.259
0.725	0.213	0.226	0.222	0.232	0.220	0.222	0.220	0.200	0.209	0.177
0.775	0.171	0.161	0.163	0.169	0.162	0.160	0.142	0.133	0.150	0.123
0.825	0.125	0.128	0.125	0.134	0.128	0.116	0.119	0.114	0.109	0.109
0.875	0.133	0.131	0.133	0.128	0.143	0.134	0.124	0.129	0.136	0.150
0.925	0.160	0.154	0.153	0.147	0.162	0.142	0.162	0.150	0.175	0.158
0.975	0.252	0.191	0.194	0.151	0.222	0.161	0.218	0.158	0.200	0.158

Table A.8. cont.

	Year									
K_T	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
0.025	0.956	0.897	0.956	0.943	0.927	0.917	0.922	0.829	0.743	0.843
0.075	0.914	0.904	0.951	0.900	0.887	0.950	0.908	0.765	0.769	0.848
0.125	0.851	0.851	0.863	0.874	0.890	0.859	0.844	0.820	0.689	0.809
0.175	0.832	0.818	0.862	0.793	0.792	0.854	0.781	0.744	0.657	0.741
0.225	0.812	0.799	0.720	0.769	0.754	0.758	0.726	0.732	0.631	0.706
0.275	0.718	0.717	0.703	0.721	0.698	0.700	0.699	0.690	0.633	0.666
0.325	0.710	0.671	0.700	0.653	0.696	0.670	0.671	0.608	0.558	0.553
0.375	0.623	0.642	0.711	0.611	0.602	0.663	0.590	0.557	0.526	0.570
0.425	0.554	0.552	0.566	0.602	0.584	0.593	0.533	0.538	0.479	0.475
0.475	0.539	0.515	0.465	0.516	0.475	0.490	0.472	0.504	0.420	0.442
0.525	0.448	0.386	0.419	0.396	0.428	0.424	0.406	0.414	0.356	0.374
0.575	0.361	0.385	0.357	0.396	0.376	0.403	0.389	0.386	0.329	0.315
0.625	0.288	0.304	0.277	0.323	0.338	0.345	0.317	0.313	0.271	0.302
0.675	0.236	0.232	0.234	0.277	0.285	0.294	0.294	0.282	0.236	0.230
0.725	0.171	0.174	0.183	0.218	0.222	0.249	0.224	0.222	0.188	0.179
0.775	0.122	0.124	0.132	0.181	0.177	0.192	0.175	0.163	0.138	0.137
0.825	0.103	0.110	0.101	0.143	0.145	0.154	0.144	0.144	0.111	0.117
0.875	0.136	0.149	0.113	0.119	0.124	0.134	0.121	0.125	0.099	0.110
0.925	0.196	0.168	0.170	0.113	0.134	0.141	0.123	0.140	0.123	0.115
0.975	0.222	0.247	0.203	0.167	0.143	0.170	0.195	0.173	0.141	0.178

	Year			
K_T	1988	1989	1990	1991
0.025	0.774	0.664	0.792	0.780
0.075	0.760	0.758	0.794	0.731
0.125	0.794	0.801	0.713	0.751
0.175	0.804	0.750	0.676	0.721
0.225	0.761	0.765	0.713	0.645
0.275	0.718	0.685	0.610	0.706
0.325	0.605	0.637	0.668	0.527
0.375	0.593	0.606	0.583	0.533
0.425	0.557	0.586	0.452	0.506
0.475	0.520	0.517	0.391	0.512
0.525	0.420	0.404	0.474	0.362
0.575	0.385	0.370	0.309	0.310
0.625	0.331	0.306	0.282	0.296
0.675	0.276	0.238	0.277	0.250
0.725	0.234	0.179	0.181	0.148
0.775	0.171	0.146	0.160	0.120
0.825	0.130	0.130	0.125	0.120
0.875	0.118	0.131	0.100	0.187
0.925	0.111	0.147	0.122	0.171
0.975	0.135	0.138	0.201	0.739

Table A.8. cont.

(g) Cape Town

	Year									
K_T	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
0.025	1.000	1.000	0.891	1.000	1.000	0.978	0.894	1.000	1.000	1.000
0.075	0.968	0.954	0.962	0.971	0.960	0.951	0.902	0.973	0.942	0.976
0.125	0.958	0.923	0.886	0.946	0.930	0.902	0.900	0.941	0.949	0.951
0.175	0.932	0.916	0.910	0.934	0.940	0.921	0.865	0.915	0.970	0.932
0.225	0.925	0.900	0.864	0.925	0.895	0.863	0.837	0.893	0.886	0.922
0.275	0.891	0.867	0.861	0.857	0.844	0.811	0.788	0.826	0.867	0.866
0.325	0.811	0.797	0.757	0.798	0.759	0.709	0.739	0.793	0.793	0.755
0.375	0.744	0.692	0.752	0.735	0.717	0.656	0.657	0.752	0.710	0.733
0.425	0.663	0.631	0.611	0.675	0.618	0.618	0.609	0.650	0.710	0.662
0.475	0.590	0.588	0.575	0.597	0.558	0.565	0.569	0.618	0.611	0.581
0.525	0.502	0.527	0.512	0.522	0.503	0.475	0.473	0.535	0.511	0.518
0.575	0.446	0.418	0.402	0.417	0.431	0.438	0.399	0.469	0.441	0.437
0.625	0.373	0.346	0.330	0.343	0.326	0.345	0.319	0.397	0.357	0.340
0.675	0.283	0.270	0.245	0.259	0.266	0.267	0.276	0.320	0.287	0.275
0.725	0.208	0.197	0.184	0.185	0.185	0.195	0.194	0.232	0.208	0.202
0.775	0.161	0.152	0.139	0.137	0.148	0.139	0.138	0.201	0.171	0.155
0.825	0.151	0.151	0.154	0.138	0.165	0.127	0.167	0.222	0.180	0.161
0.875	0.189	0.200	0.197	0.206	0.164	0.175	0.328	0.273	0.190	0.174
0.925	0.213	0.218	0.188	0.246	0.228	0.232	0.770	0.333	0.202	0.219
0.975	0.292	0.249	0.254	0.251	0.284	0.427	0.615	0.400	0.247	0.263

	Year									
K_T	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
0.025	1.000	1.000	1.000	1.000	1.000	1.000	0.952	0.980	0.944	0.958
0.075	0.985	0.986	0.940	0.978	0.956	0.923	0.959	0.941	0.970	0.942
0.125	0.947	0.943	0.940	0.955	0.932	0.890	0.923	0.883	0.942	0.908
0.175	0.947	0.959	0.913	0.924	0.926	0.935	0.927	0.909	0.887	0.914
0.225	0.882	0.919	0.882	0.908	0.910	0.851	0.847	0.846	0.854	0.917
0.275	0.760	0.840	0.849	0.853	0.806	0.840	0.807	0.802	0.777	0.876
0.325	0.749	0.768	0.753	0.799	0.703	0.685	0.720	0.716	0.696	0.764
0.375	0.681	0.751	0.751	0.725	0.721	0.655	0.662	0.645	0.614	0.713
0.425	0.681	0.659	0.628	0.651	0.620	0.594	0.571	0.583	0.580	0.644
0.475	0.565	0.612	0.570	0.583	0.544	0.547	0.521	0.523	0.486	0.512
0.525	0.514	0.475	0.509	0.482	0.431	0.444	0.423	0.424	0.386	0.457
0.575	0.432	0.441	0.409	0.408	0.385	0.372	0.381	0.377	0.323	0.354
0.625	0.332	0.345	0.353	0.313	0.296	0.276	0.303	0.281	0.245	0.300
0.675	0.288	0.291	0.266	0.237	0.228	0.221	0.233	0.218	0.206	0.206
0.725	0.216	0.203	0.197	0.161	0.171	0.162	0.168	0.153	0.151	0.149
0.775	0.162	0.158	0.147	0.156	0.142	0.149	0.145	0.143	0.131	0.148
0.825	0.146	0.155	0.177	0.198	0.177	0.161	0.173	0.177	0.189	0.166
0.875	0.174	0.201	0.216	0.237	0.221	0.223	0.201	0.189	0.216	0.266
0.925	0.220	0.242	0.229	0.284	0.258	0.246	0.268	0.257	0.287	0.266
0.975	0.258	0.242	0.264	0.323	0.291	0.247	0.202	0.301	0.387	0.194

Table A.8. cont.

	Year									
K_T	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
0.025	0.758	0.941	0.860	0.916	0.979	0.972	1.000	1.000	1.000	1.000
0.075	0.865	0.867	0.875	0.938	0.956	0.981	0.995	1.000	0.995	0.996
0.125	0.881	0.862	0.908	0.926	0.924	0.984	0.982	0.977	0.971	0.973
0.175	0.901	0.857	0.932	0.911	0.907	0.919	0.955	0.945	0.943	0.950
0.225	0.864	0.801	0.903	0.909	0.828	0.917	0.923	0.887	0.896	0.913
0.275	0.845	0.750	0.800	0.858	0.797	0.822	0.871	0.839	0.887	0.875
0.325	0.799	0.724	0.734	0.816	0.777	0.745	0.798	0.793	0.798	0.772
0.375	0.706	0.700	0.723	0.769	0.679	0.746	0.738	0.709	0.738	0.716
0.425	0.674	0.606	0.688	0.617	0.614	0.655	0.672	0.690	0.641	0.654
0.475	0.570	0.514	0.596	0.586	0.454	0.564	0.622	0.601	0.584	0.530
0.525	0.465	0.434	0.467	0.462	0.431	0.496	0.505	0.524	0.499	0.468
0.575	0.391	0.337	0.381	0.392	0.377	0.423	0.440	0.438	0.403	0.351
0.625	0.324	0.268	0.342	0.343	0.290	0.340	0.356	0.363	0.319	0.304
0.675	0.227	0.215	0.239	0.289	0.246	0.279	0.277	0.272	0.264	0.230
0.725	0.168	0.173	0.173	0.207	0.184	0.213	0.215	0.226	0.185	0.181
0.775	0.138	0.154	0.147	0.150	0.150	0.170	0.179	0.177	0.168	0.144
0.825	0.165	0.138	0.147	0.139	0.153	0.147	0.179	0.146	0.168	0.147
0.875	0.192	0.171	0.215	0.216	0.134	0.193	0.203	0.207	0.266	0.250
0.925	0.237	0.226	0.228	0.300	0.159	0.319	0.316	0.272	0.396	0.281
0.975	0.312	0.272	0.191	0.467	0.292	0.409	0.433	0.352	0.179	0.326

	Year								
K_T	1987	1988	1989	1990	1991	1992	1993	1994	1995
0.025	1.000	1.000	0.891	1.000	1.000	0.978	0.894	1.000	1.000
0.075	0.968	0.954	0.962	0.971	0.960	0.951	0.902	0.973	0.942
0.125	0.958	0.923	0.886	0.946	0.930	0.902	0.900	0.941	0.949
0.175	0.932	0.916	0.910	0.934	0.940	0.921	0.865	0.915	0.970
0.225	0.925	0.900	0.864	0.925	0.895	0.863	0.837	0.893	0.886
0.275	0.891	0.867	0.861	0.857	0.844	0.811	0.788	0.826	0.867
0.325	0.811	0.797	0.757	0.798	0.759	0.709	0.739	0.793	0.793
0.375	0.744	0.692	0.752	0.735	0.717	0.656	0.657	0.752	0.710
0.425	0.663	0.631	0.611	0.675	0.618	0.618	0.609	0.650	0.710
0.475	0.590	0.588	0.575	0.597	0.558	0.565	0.569	0.618	0.611
0.525	0.502	0.527	0.512	0.522	0.503	0.475	0.473	0.535	0.511
0.575	0.446	0.418	0.402	0.417	0.431	0.438	0.399	0.469	0.441
0.625	0.373	0.346	0.330	0.343	0.326	0.345	0.319	0.397	0.357
0.675	0.283	0.270	0.245	0.259	0.266	0.267	0.276	0.320	0.287
0.725	0.208	0.197	0.184	0.185	0.185	0.195	0.194	0.232	0.208
0.775	0.161	0.152	0.139	0.137	0.148	0.139	0.138	0.201	0.171
0.825	0.151	0.151	0.154	0.138	0.165	0.127	0.167	0.222	0.180
0.875	0.189	0.200	0.197	0.206	0.164	0.175	0.328	0.273	0.190
0.925	0.213	0.218	0.188	0.246	0.228	0.232	0.770	0.333	0.202
0.975	0.292	0.249	0.254	0.251	0.284	0.427	0.615	0.400	0.247

Table A.8. cont.

(h) Port Elizabeth

	Year									
K_T	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966
0.025	0.948	1.000	0.964	0.985	0.976	1.000	0.965	0.982	0.848	0.962
0.075	0.973	0.970	0.975	0.927	0.962	0.969	0.976	1.000	0.933	0.944
0.125	0.949	0.947	0.934	0.889	0.955	0.945	0.968	0.968	0.898	0.951
0.175	0.925	0.936	0.899	0.901	0.928	0.945	0.956	0.945	0.865	0.915
0.225	0.916	0.903	0.871	0.887	0.924	0.944	0.924	0.932	0.879	0.866
0.275	0.854	0.809	0.811	0.843	0.861	0.886	0.863	0.866	0.842	0.828
0.325	0.793	0.820	0.734	0.767	0.789	0.794	0.878	0.840	0.783	0.783
0.375	0.790	0.813	0.707	0.789	0.766	0.746	0.865	0.830	0.789	0.764
0.425	0.695	0.736	0.648	0.733	0.755	0.737	0.756	0.755	0.754	0.741
0.475	0.604	0.625	0.556	0.646	0.702	0.693	0.710	0.656	0.638	0.592
0.525	0.510	0.535	0.502	0.508	0.561	0.567	0.608	0.598	0.560	0.571
0.575	0.447	0.467	0.443	0.456	0.477	0.487	0.504	0.497	0.453	0.451
0.625	0.350	0.373	0.338	0.383	0.364	0.367	0.409	0.421	0.362	0.360
0.675	0.250	0.281	0.279	0.291	0.271	0.268	0.352	0.350	0.271	0.267
0.725	0.219	0.219	0.213	0.206	0.222	0.206	0.278	0.296	0.241	0.206
0.775	0.182	0.185	0.165	0.160	0.167	0.180	0.230	0.238	0.202	0.179
0.825	0.179	0.182	0.166	0.183	0.205	0.232	0.245	0.293	0.233	0.234
0.875	0.303	0.248	0.212	0.230	0.252	0.298	0.332	0.447	0.402	0.344
0.925	0.313	0.327	0.310	0.289	0.282	0.312	0.399	0.581	0.500	0.374
0.975	0.585	0.306	0.367	0.530	0.303	0.399	0.689	0.623	0.461	0.452

	Year									
K_T	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976
0.025	0.958	0.960	0.966	0.957	0.939	0.944	0.883	0.918	0.942	0.978
0.075	0.926	0.938	0.909	0.921	0.943	0.900	0.935	0.910	0.942	0.983
0.125	0.931	0.888	0.923	0.942	0.942	0.916	0.916	0.913	0.911	0.925
0.175	0.911	0.866	0.907	0.928	0.925	0.866	0.898	0.901	0.901	0.921
0.225	0.870	0.835	0.855	0.882	0.904	0.862	0.882	0.886	0.869	0.864
0.275	0.765	0.769	0.827	0.786	0.845	0.797	0.858	0.828	0.829	0.757
0.325	0.750	0.740	0.743	0.791	0.772	0.770	0.750	0.741	0.766	0.730
0.375	0.719	0.739	0.776	0.759	0.716	0.739	0.732	0.757	0.742	0.690
0.425	0.633	0.682	0.660	0.700	0.713	0.663	0.684	0.714	0.689	0.673
0.475	0.561	0.577	0.582	0.629	0.667	0.563	0.671	0.585	0.580	0.496
0.525	0.469	0.502	0.481	0.550	0.481	0.496	0.532	0.516	0.494	0.461
0.575	0.394	0.438	0.411	0.422	0.418	0.388	0.478	0.425	0.419	0.428
0.625	0.298	0.349	0.316	0.340	0.337	0.297	0.378	0.331	0.328	0.282
0.675	0.219	0.270	0.255	0.268	0.269	0.246	0.299	0.264	0.261	0.215
0.725	0.186	0.207	0.191	0.205	0.201	0.197	0.226	0.205	0.197	0.193
0.775	0.158	0.170	0.167	0.175	0.188	0.163	0.179	0.167	0.164	0.172
0.825	0.244	0.192	0.194	0.187	0.189	0.191	0.157	0.149	0.177	0.164
0.875	0.306	0.237	0.234	0.281	0.213	0.215	0.219	0.198	0.206	0.200
0.925	0.319	0.267	0.382	0.307	0.317	0.255	0.287	0.257	0.322	0.296
0.975	0.350	0.424	0.318	0.444	0.376	0.330	0.380	0.306	0.397	0.338

Table A.8. cont.

	Year									
K_T	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986
0.025	0.956	0.970	1.000	0.958	0.969	0.933	0.906	0.924	0.874	0.917
0.075	0.925	0.895	0.978	0.936	0.931	0.901	0.896	0.929	0.864	0.913
0.125	0.900	0.936	0.925	0.935	0.893	0.915	0.908	0.892	0.835	0.878
0.175	0.864	0.900	0.873	0.873	0.842	0.860	0.873	0.839	0.855	0.885
0.225	0.863	0.871	0.826	0.792	0.852	0.809	0.826	0.811	0.775	0.867
0.275	0.791	0.823	0.814	0.787	0.833	0.811	0.826	0.787	0.737	0.786
0.325	0.763	0.820	0.804	0.773	0.806	0.740	0.799	0.770	0.738	0.751
0.375	0.716	0.743	0.754	0.700	0.747	0.727	0.752	0.773	0.713	0.747
0.425	0.653	0.701	0.616	0.643	0.649	0.681	0.659	0.698	0.621	0.674
0.475	0.571	0.612	0.548	0.524	0.598	0.563	0.589	0.556	0.507	0.622
0.525	0.466	0.517	0.509	0.477	0.520	0.515	0.524	0.493	0.482	0.443
0.575	0.408	0.426	0.402	0.397	0.415	0.413	0.412	0.401	0.386	0.411
0.625	0.322	0.323	0.304	0.332	0.357	0.313	0.331	0.316	0.314	0.312
0.675	0.260	0.294	0.250	0.253	0.292	0.256	0.246	0.230	0.230	0.243
0.725	0.187	0.171	0.207	0.181	0.214	0.204	0.204	0.187	0.196	0.177
0.775	0.161	0.145	0.162	0.162	0.186	0.177	0.197	0.151	0.174	0.151
0.825	0.165	0.183	0.145	0.154	0.141	0.175	0.203	0.194	0.186	0.173
0.875	0.210	0.288	0.237	0.184	0.178	0.235	0.278	0.304	0.297	0.346
0.925	0.365	0.274	0.271	0.337	0.281	0.357	0.234	0.405	0.341	0.342
0.975	0.352	0.652	0.608	0.344	0.436	0.471	0.426	0.434	0.407	0.372

	Year				
K_T	1987	1988	1989	1990	1991
0.025	0.917	1.000	0.748	0.877	0.735
0.075	0.938	0.986	0.773	0.845	0.876
0.125	0.881	0.978	0.811	0.847	0.857
0.175	0.890	0.970	0.790	0.823	0.832
0.225	0.827	0.905	0.811	0.799	0.748
0.275	0.764	0.833	0.778	0.756	0.767
0.325	0.718	0.806	0.724	0.756	0.780
0.375	0.714	0.794	0.725	0.733	0.725
0.425	0.658	0.745	0.588	0.629	0.604
0.475	0.592	0.606	0.540	0.516	0.527
0.525	0.444	0.552	0.474	0.472	0.461
0.575	0.417	0.448	0.412	0.402	0.366
0.625	0.315	0.381	0.314	0.335	0.307
0.675	0.262	0.269	0.243	0.270	0.246
0.725	0.201	0.209	0.184	0.229	0.202
0.775	0.181	0.180	0.171	0.205	0.184
0.825	0.216	0.214	0.212	0.175	0.185
0.875	0.321	0.454	0.290	0.291	0.250
0.925	0.354	0.414	0.299	0.315	0.345
0.975	0.292	0.456	0.374	0.406	0.439

Summary

RADIATION INTERCEPTION AND USE IN A MAIZE AND BEAN INTERCROPPING SYSTEM

BY

MITSURU TSUBO

Food shortage is known to have been caused by overpopulation, natural disasters and poor food distribution. In areas facing food insecurity, such as Africa, peasants or small-scale farmers have practised traditional cropping techniques since old times. One of the techniques is intercropping, and many intercropping studies have been reported since the 1960s. According to those studies, intercropping has higher productivity and also higher resource use than sole cropping, however, the contribution of crop radiation utilisation to that higher productivity is unclear. From this background, a quest as to whether intercropping was suitable to small-scale farming in a semi-arid region (Free State, South Africa) has started. The main aim of this study was to analyse and model radiation interception and employment in a maize-bean intercropping system with alternate (north-south and east-west) row directions (Chapters 3 and 4). Also, the intercrop yield advantage was assessed in terms of intensity of land use, accumulation of energy and return of cash increment (Chapter 2); and photosynthetically active radiation (PAR) above plant canopies was investigated (Chapter 5).

In Chapter 2 it was shown that the maize-bean intercropping had a yield advantage, compared with the sole cropping, under the set conditions used for both maize and beans planting. In other words, maize-bean intercropping was equivalent in yield to sole maize, and gave a higher yield than sole beans. This was explained by crop radiation interception and use in Chapter 3. The intercropping was analogous to maize sole cropping in the overall efficiency of radiation interception and use, and had greater radiation interception and use than bean sole cropping. In addition, no difference in crop productivity and efficiency was found between row direction treatments. In the modelling study (Chapter 4), the intercropped maize had the same growth efficiency as the sole cropped maize, but beans had greater radiation utilisation in intercropping than in sole cropping. This resulted in an intercropping yield advantage. In Chapter 5, an empirical equation for estimating PAR from solar radiation has been introduced because PAR is not routinely measured at weather stations. The equation may be accurate enough to compute PAR from the large data sets available across southern Africa.

This study has shown that planting maize in association with beans is advantageous compared with separate planting, in both crop productivity and efficiency. Normally, small-scale farmers cultivate not one crop but a staple crop and supplement crops. From this point of view, the conclusion is drawn that intercropping is suitable for use in the small-scale farming sector.

Keywords: semi-arid, small-scale farming, land equivalent ratio (LER), energy value (EV), radiation intercepted, radiation use efficiency (RUE), harvest index (HI), radiation transmission model, row orientation, photosynthetically active radiation (PAR).

Opsomming

STRALINGSONDERSKEPPING EN -VERBRUIK IN ‘n MIELIE-EN-BONE TUSSENVERBOUINGSISTEEM

DEUR

MITSURU TSUBO

Dit is bekend dat oorbevolking, natuurrampe en gebrekkige voedselverspreiding grotendeels die oorsaak van voedseltekorte is. In gebiede soos Afrika, waar voedselonsekerheid die arm bevolking of kleinskaalboere dikwels in die gesig staar, is boere goed vertroud met die tradisionele verbouingstegnieke van toeka se dae. Een van die tegnieke is tussen- of kruisverbouing wat die studieveld al in die 1960s betree het. Volgens bewese resultate lewer tussenverbouing hoër opbrengste en veral hoër gewashulpbronverbruik as enkelverbouing. Na aanleiding van hierdie agtergrond is daar gepoog om die gepastheid van kruisverbouing op kleinskaalboerdery in die semi-ariede area (Bloemfontein, Vrystaat, Suid Afrika) na te vors en is ‘n studie uitgevoer om gewasstralingsonderskepping en verbruik van gewasstraling te ondersoek. Die hoofdoel van die studie is die analise en modellering van stralingsonderskepping en verbruik in die mielie/bone tussenverbouing met twee verskillende (noord-suid en oos-wes) ryrigtings (Hoofstukke 3 en 4). Verder is die kruisverbouingsopbrengsvoordeel bereken in terme van intensitiet van landsverbruik, akkumerlering van energie en geldverdienste (Hoofstuk 2) en is ondersoek ingestel na fotosintetiese aktiewe sraling (FAS), wat die primêre faktor is in plantegroei bokant plantgewasdakke (Hoofstuk 5).

In Hoofstuk 2 is bewys dat tussenverbouing ‘n opbrengsvoordeel teenoor monoverbouing toon, met die veronderstelling dat beide mielies en bone geplant word. Met ander woorde, mielie-bone tussenverbouing is ekwivalent in opbrengs aan slegs mielies en toon ‘n hoër opbrengs as slegs bone. Hierdie verskynsel word deur gewasstralingsonderskepping en -

verbruik in Hoofstuk 3 behandel. Die tussenverbouing het ooreengekom met slegs mielieverbouing in die algehele doeltreffendheid van stralingsonderskepping en verbruik en wys hoër stralingsonderskepping en verbruik as die geval by slegs boneverbouing. Verder, geen verskil is tussen ryrigting behandelings op opbrengste en doeltreffendheid gevind nie. In Hoofstuk 4 (modelleringstudie) is gevind dat die tussenverboude mielies dieselfde groeidoeltreffendheid as slegs verboude mielies het, maar dat bone groter stralingsverbruik by tussenverbouing as by monoverbouing toon. Dit kan lei tot die tussenverboude opbrengsvoordeel. In Hoofstuk 5 word 'n empiriese vergelyking vir berekening van FAS vanaf straling voorgestel, omdat FAS nie normaalweg gemeet word deur weerstasies nie. Die vergelyking mag akkuraat genoeg wees om FAS by groot datastelle te bereken.

Hierdie studie het bewys dat die gesamentlike aanplanting van mielies en bone voordelig is vir gewasproduktiwiteit en doeltreffendheid, in vergelyking met afsonderlike aanplanting. Gewoonlik sal kleinboere nie 'n enkele gewas nie, maar 'n hoofvoedselgewas plus supplementêre gewasse kweek. Die gevolgtrekking is dus gemaak dat tussenverbouing gepas is vir kleinskaalboerdery.