RADIATION and WATER UTILISATION EFFICIENCY by MONO-CULTURE and INTER-CROP TO SUIT SMALL-SCALE IRRIGATION FARMING

By

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DECLARATION

I declare that the thesis hereby submitted by me for the Doctor of Philosophy degree 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 further cede copy right of the thesis in favour of the University of the Orange Free State.

Elijah Mukhala

Signature ....

Date: December, 1998

Place: Bloemfontein, South Africa.

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Organisation

This thesis is organised in form of eight chapters. Chapter one comprises the introduction and outlines the main aims of this research. Chapter two comprises all the materials and methods used in this research work. Chapter three deals with the findings of the social economic survey which were later used to develop the field experimentation. Chapter three has been accepted for publication in the South African Journal of Agricultural extension with the title: Experiences and perceptions of Black small-scale irrigation farmers in the Free State. Mukhala, E. & Groenewald, D.C., 1998, 27:1-18. Chapter four deals with grain yield, total nutrient yield, water use and water use efficiencies (WUE) of inter-crop and mono-crop production systems. Chapter five deals with influence of photosynthetic active radiation on dry matter production and also radiation use efficiency (RUE). Chapter six deals with nutrient content of inter-crops and mono-crops. Part of Chapter six has been accepted for publication in the Journal of Nutrition Science, Canada with the title: Dietary nutrient deficiency in small-scale farming communities in South Africa: Benefits of inter-cropping maize (*Zea mays*) and Beans (*Phaseolus vulgaris*) Mukhala, E., De Jager, J.M., Van Rensburg, L.D. & Walker, S. (*in press*). Chapter seven deals with crop simulation using Putu-IDSS and BEWAB Models both developed at the University of the Orange Free State. The last chapter comprises the summary of the findings and recommendations.

CHAPTER 1

INTRODUCTION

1.1 Motivation

The question of how agricultural output in African countries can be increased has become more important as populations multiply while resources are continually dwindling (Pearce, 1993). The benefits of large scale irrigation schemes in developing countries have long been questioned and there is an increasing tendency to promote small-scale irrigation farming (Pearce, 1993; Turner, 1994). While support for this kind of farming is increasing, some planners have chosen to criticise small-scale/informal irrigation farming on grounds that it is ill-planned and therefore economically unviable, gives disappointing results, or is a downright failure (Underhill, 1993). Underhill (1993) further points out that what these planners fail to appreciate is the fact that it is not the size of the scheme or the informal approach that cause such failures, and goes on to stress that the basic factors influencing the success or failure of a scheme (social and economic factors, technology level, water resources, land suitability, etc.) are the same for large or small-scale schemes. The solution to the aforementioned criticisms is not, therefore, to discourage the small-scale approach, but to provide small-scale farmers with guidelines for development and sustainability. In many developing countries, small-scale farmers have made a major contribution to the total agricultural production of the country. In South Africa, planners and politicians are aware of the contribution small and micro-scale irrigation makes to household food security (de Lange, 1994). Garden community plots which grow vegetables make a significant contribution to incomes of housewives and pensioners who have taxing responsibilities to feed massive families (de Lange, 1994). Hence, the potential exists in small-scale irrigation farming to improve the food security of the rural poor people and raise the general standard of life.

Inter-cropping is a widespread practice which is generally accepted to have some advantages over mono-cropping systems in the tropics. Research aimed at improving small-scale farming practices has contributed to the welfare of farmers, particularly subsistence farmers. Formal and informal surveys of representative farmers, and review of secondary data provide the essential setting against which the unknown and theorised benefits of a new inter-cropping system can be compared. Specific enquiries into farmers perceptions of benefits and disadvantages of inter-cropping can provide an even more focused assessment of the research issues to be addressed (Rhoades & Bebbington, 1990). An assessment of the constraints (biophysical and socio-economic) from the farmers perspective, enables the researcher to develop technologies with a greater probability of success than through traditional research at the experiment station (Fukai & Midmore, 1993). Fukai & Midmore (1993) further point out that major consideration should be given to adaptive inter-cropping research when determining whether limited resources are used more efficiently by inter-crops than by mono-crops.

Several natural resources contribute to the development of crops. Among these are solar radiation, water and nutrients. Limited studies in which water use has been measured have been reported. Water is often the most limiting factor in crop growth, and thus the ability of roots to explore a large soil volume and extract water is critical (Etherington, 1976 in Francis, 1989). Inter-crops hold promise of being more efficient in exploring a larger total soil volume especially if the component crops have different rooting habits, for example rooting depth (Willey, 1979a).

1.2 Literature review

1.2.1. Classification of small-scale irrigation farming

Small-scale farming is practised in many countries and many different classes exist varying from country to country. Guijt and Thompson in Turner (1994) pointed out that irrigation systems can be classified according to size, source of water, management style, degree of water control, source of innovation, landscape niche or type of technology. Ambler in Turner (1994) as well pointed out that number of farmers, cost of scheme, or revenue generated may also be used as criteria. In South Africa, the source of irrigation water has in some cases been used as a basis for categorising small-scale irrigation farmers. The categories are:

i Farmers on irrigation schemes (communal water supply infra-structure)

ii Vegetable gardeners (communal water supply infra-structure) and

iii Independent farmers (each with a "private" water supply)

Statistics on irrigation schemes in South Africa are not well documented although the Development Bank of Southern Africa (DBSA) estimates that there are 150 000 farmers on irrigation schemes. The lack of data on the location and areas of small-scale irrigation schemes also applies to many other countries (de Lange, 1994; Turner, 1994).

1.2.2 Management systems of small-scale irrigation farming

Interest in the advancement of small-scale or farmer-managed irrigation systems (FMIS), as opposed to large, government-managed systems, has grown rapidly in the last decade (Carter, 1993; Turner, 1994). Management systems play a major role in the acceptability and success of irrigation schemes. Centrally managed schemes have often created dissatisfaction amongst participants as they have expressed negative views on being deprived of decision making power. Most independent farmers have succeeded as they have only themselves to blame for any poor management decisions (de Lange, 1994). In South Africa, two systems of management exist on these irrigation schemes categorised as:

i Schemes which are centrally (or externally) managed, where farmers receive most of the instructions

ii Schemes where farmers themselves make decisions

Vegetable gardening makes up a significant and important sector of irrigation farming in rural and urban areas of South Africa. The number of independent farmers, i.e. those involved in vegetable gardening, are probably the largest. Statistics are, however, not available as they are not financed or managed by formal institutions (de Lange, 1994). However, there are approximately 150 000 farmers participating in community gardening projects (de Lange, 1994).

1.2.3 Crop combinations in inter-cropping systems

Inter-cropping is the growing of two or more crop species concurrently on a given piece of land (Willey & Osiru, 1972; Ofori & Stern, 1987). Studies have shown that grain yields of component crops are reduced compared to grain yields when grown alone, although the resultant combined grain yield may be higher than either (Enyi, 1973; Dalal, 1974; Fisher, 1977; Remison, 1978). Inter-cropping is practised in many African countries, including South Africa, with different crop combinations *inter alia* maize and groundnuts (Liphazi *et al.*, 1997), maize and beans (Siame *et al.*, 1997; Ayisi & Poswall, 1997), maize and cowpea (Watiki *et al.*, 1993), pearl millet and groundnut (Reddy & Willey, 1981) sorghum and beans (Osiru & Willey, 1972), mustard and chickpea (Kushwaha & De, 1987), sorghum and pigeon pea (Natarajan & De, 1980) and green gram & bulrush millet (May, 1982).

1.3 Rationale and overall objectives

1.3.1 Rationale

Researchers have indicated that one of the primary problems with the introduction of new irrigation systems, whether large or small in scale, has been a lack of understanding by the agencies involved of the context (physical, social and economic) into which the new irrigation practices are being brought (Carter, 1993). Carter (1993) and Turner (1994) have reported that lack of knowledge of existing farming systems, marketing constraints, labour limitations, soil properties, and water resources, are just some of the aspects which could lead to the implementation of non-viable irrigation systems. Deceived by the apparent simplicity of the technologies involved, development agencies often introduce such systems with inadequate prior understanding of either the farmer and the farming system, on the one hand, or the land, crop water-use and cropping on the other.

Carter (1993) pointed out that in most cases development programmes failed to invest the necessary time or resources required to research fully the context into which irrigation technologies are to be introduced. One of the problems independent small-scale farmers are confronted with in South Africa is the lack of support services especially specialised irrigation extension officers to advise regarding cropping systems as well as technical advice on engineering aspects (de Lange, 1994).

The reasons stated and experiences from other parts of the world provided strong motivation for this study in the Free State Province, directed at producing sustainable small-scale irrigation strategies for the future. The North-East Arid Zone (NEAZ) of Nigeria is a region of low rainfall (300 to 600 mm year^{-1}) and high potential evaporation rates (perhaps exceeding 2000 mm year^{-1}), which has experienced severe droughts over the last 20 years (Carter, 1993). These conditions of relatively low rainfall appear similar to those of the Free State Province in South Africa. In introducing development programmes in this part of Nigeria, Carter (1993) reported that appropriate research was first carried. Because applied research and rural development had gone hand-in-hand, research findings had been able to guide development strategies. Due to this participatory approach, costly mistakes in small-scale irrigation development were avoided. Carter (1993) concluded that it is not always possible simply to transplant successful technology and assume it will work in another area. Small-scale farmers in South Africa have been found to apply less irrigation water than conventional full irrigation which emphasises the need to investigate actual crop water requirements to determine optimum planting densities. Small-scale irrigation farmers have also been found to plant low densities in the field in order to reduce irrigation amounts (de Lange, 1994).

Concluding remarks in the Water Research Commission (WRC) Report (de Lange, 1994) challenge scientists to urgently look at crop water requirements under the following two conditions prevailing in some small-scale irrigation farming areas:

(i) The limited irrigation, low planting density situation,

(ii) The very hot, dry conditions with high evaporative demands found during summer in some areas.

Laker *et al.* (1987) in South Africa and Bunce (1990) in the USA, have shown how differently plants react under these abnormal conditions. Information on water use and radiation use of crop mixtures is needed to develop appropriate packages for agronomic practices. For these reasons this study examined the experiences of small-scale irrigation farmers. The objective was to seek sustainability and address problems through field experimentation based on experienced problems.

1.3.2 Overall objectives

(i) To evaluate the technological feasibility and sustainability of various irrigation farming production systems in terms of meeting the social aspirations of small-scale irrigation farmers.

(ii) To compare resource utilisation efficiency of mono-cropping and inter-cropping systems.

(iii) To compare nutrient content of mono -crop and inter-crop yields.

(iv) To produce recommendations that can be followed by extension officers dealing with small-scale irrigation farmers.

iv) To provide planners involved in the establishment of small-scale irrigation farmers with a decision support tool for evaluating the risk associated with various production strategies.

1.3.3 Specific study objectives

(i) To undertake a survey of production practices and agronomic strategies at existing small-scale farming irrigation schemes in the Free State Province, applying the participatory rural appraisal (PRA) approach.

(ii) To undertake social surveys simultaneously at these sites in order to determine expectations and aspirations of small-scale irrigation farmers.

(iii) To evaluate, through field experimentation, the implementation of relevant established small-scale production systems within the climatic constraints of the Free State Province.

  (a) To compare soil water use and utilisation efficiency of these production system combinations.

  (b) To compare photosynthetic active radiation (PAR) utilisation efficiency of these production system combinations.

  (c) To compare inter-cropping and mono-cropping practices in terms of dry matter production and grain yield.

  (d) To examine the effect of different irrigation strategies (supplementary and full irrigation).

(iv) To evaluate and quantify the nutrient content in mono-cropping and inter-cropping grain yields and determine benefits of inter-cropping in terms of nutrient content.

(v) To improve the dry matter subroutine of Putu-AnyCrop for mono-crop and inter-crop maize and beans with special reference to the effect of plant density.

Detailed literature on Putu AnyCrop and BEWAB Models is given in Chapter seven.

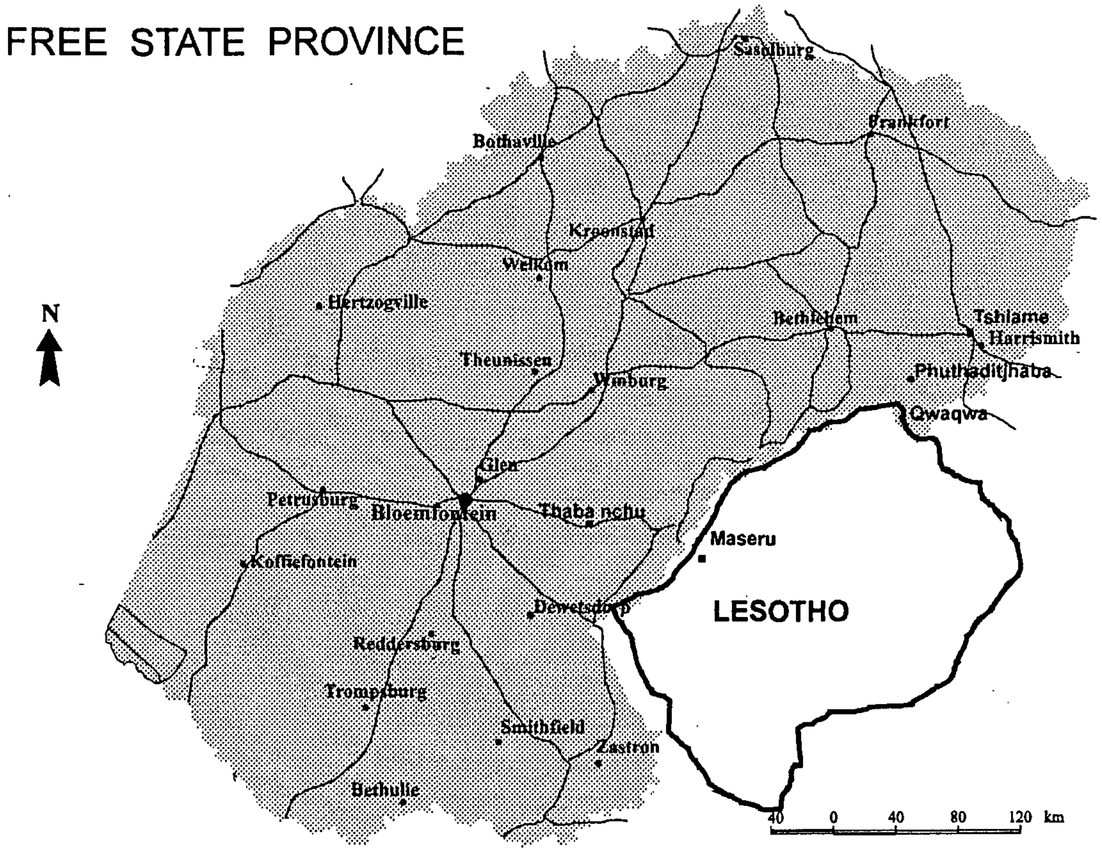
CHAPTER 2

MATERIALS AND METHODS

2.1 Socio-economic and agronomic survey

There are several research methodologies in this type of research although the majority of research that has recently been carried out within the field of small-scale farming has been qualitative by nature (Bembridge, 1997). It was argued by the researchers that a multi-disciplinary approach is particularly useful and best suited for documenting the experiences of small-scale irrigation farmers. A qualitative approach was therefore opted for, with application of the principles of participatory rural appraisal (PRA) (Appendix ii). Focus groups were identified for data collection. Supplementary information on the survey sites was also collected and documented (Appendix iv).

Prior to conducting the survey, a list of small-scale farmers was sought from the Free State Department of Agriculture (FSDA). As it is not obligatory for them to register all small-scale farmers, alternatives had to be considered although the FSDA consented to the survey request. The FSDA requested their communications officer to co-ordinate meetings with all known and available small-scale irrigation farmers and other non irrigation small-scale farmers in their areas through extension officers. Focus group interviews were eventually conducted between October and November 1996 with nine small-scale irrigation farming groups participating (Table 2.1). The respondents interviewed were all black small-scale farmers except in Brentpark (Kroonstad) were one focus group of coloured farmers was interviewed. The interviews were held in community halls of the respective farming communities. A number of small-scale farmers, other than garden farmers, namely cattle and poultry farmers also attended the focus groups. These farmers were welcomed to the meetings as they, together with small-scale irrigation farmers, form a group of small-scale farmers all experiencing similar constraints, frustrations, problems, expectations and aspirations. Because of the qualitative, descriptive nature of the research, the interview schedule was semi-structured (Appendix iii) and included several issues, with mainly open questions, to allow for probing and in order to give farmers the opportunity to supply elaborate, detailed answers. The questionnaire (Appendix iii) was not handed to the farmers to fill in but only used by interviewers as a guide for interviewing. The languages used in the interviews were Afrikaans, English and Sesotho. Prior to commencement of interviews, respondents gave permission for the interview conversation to be recorded on tape and in the language of their choice.



Map indicating districts where the survey was conducted

Figure 2.1 Map of the Free State province indicating major towns and districts in the province. The survey was conducted in Thaba Nchu, Bethlehem, Kroonstad, Harrismith and Qwaqwa.

In communities where electricity did not exist recording was not possible, hence notes were taken by hand. In some instances translators were used and the presence of translators was not seen as disturbing, or as having a negative influence on the discussions. In fact the translators in most cases were extension officers with whom the respondents were familiar. When the extension officers were unavailable, the chairpersons of the farming communities assumed the responsibility of translating. In retrospect, however, the interviews conducted in the presence of translators seemed to be equal in scope and openness to those conducted without translators. The recorded interviews were later transcribed at the University of the Orange Free State, Bloemfontein. Altogether 90 individual small-scale farmers attended these meetings, these were representatives and they represented about 300 small-scale farmers who were members of the various irrigation schemes. Among these 90 farmers, 32 (36%) were women and the rest were men (Table 2.1). With respect to age, 70% of the respondents were between 50 and 70 years old except in two communities (Makwane and Tshiame) where respondents were all between 18 and 35 years old. These age groups included pensioners and young people who had just finished matric. The number of respondents that comprised the focus groups varied from place to place (Table 2.1). The problems highlighted by the respondents were were not in any ranking order.

Table 2.1 Location of focus groups and numbers of small-scale farmers and numbers of small-scale farmers in each focus groups.

Town / District	Place	Number of small-scale farmers	Number of farmers who attended focus group meetings	
			Male	Female
Thaba Nchu	Sediba	40	13	5
Bethlehem	Kopanang	9	5	3
Qwaqwa	Tsheseng	15	-	4
Qwaqwa	Makeneng	16	1	2
Qwaqwa	Makwane	54	6	9
Qwaqwa	Mangaung	9	-	2
Harrismith	Tshiame	86	11	2
Kroonstad	Maokeng	29	8	1
Kroonstad	Brentpark	30	14	4
Total		288	58	32

The findings of the socio-economic survey were later used to design field experiments which examined specific agronomic constraints of a small-scale irrigation farming development. This approach ensures sustainability as experienced problems are addressed rather than imagined ones. This also makes technology transfer to small-scale farmers easier as the farmers are already aware that possible solutions are being sought for their problems.

2.2 Field experimentation

2.2.1 Experimental lay-out , treatments and climate

Field experiments were carried out during the 1996/1997 growing season (Experiment 1) and the 1997/1998 growing season (Experiment 2) at the agrometeorology experimental site located west of the University of the Orange Free State campus. The experiments were conducted on campus due to financial constraints as off-station experiments require a sound financial base. However, the findings of the research will be transferred to the small-scale farmers as technology transfer. The seasonal rainfall of the experimental area is in the range of 350 - 600mm year^{-1}. Long term average monthly maximum temperatures of the experimental site are in the range of 24 °C to 31°C while average monthly minimum temperatures varied between 8 °C and 15 °C (Table 2.3). Monthly mean December maximum and minimum temperatures were 4.5 °C and 1.7 °C higher in Experiment 2 than Experiment 1 respectively. In January, maximum and minimum temperatures were 1.3 °C and 0.2 °C higher in Experiment 2 than Experiment 1 respectively (Table 2.3, Appendix v, a & b). The monthly mean February maximum temperature was higher in Experiment 1 than Experiment 2 by 1.6 °C, while the minimum temperature was lower for Experiment 1 in comparison to Experiment 2 by 0.3 °C. In March, maximum and minimum temperatures were 3.7 °C and 0.7 °C higher in Experiment 1 than Experiment 2 respectively (Table 2.3, Appendix v, c & d). In April, maximum and minimum temperatures were 3.8 °C and 1.2 °C higher in Experiment 2 than Experiment 1 respectively (Table 2.3, Appendix v, e). Generally the data shows that 1997/1998 growing season was warmer than the 1996/1997 growing season. A late maturing maize cultivar SNK2147, and a dry bean cultivar PAN 127 were planted in both experiments. Weather parameters were collected throughout the growing season from an automatic weather station situated at the experimental site (Figure 2.2).

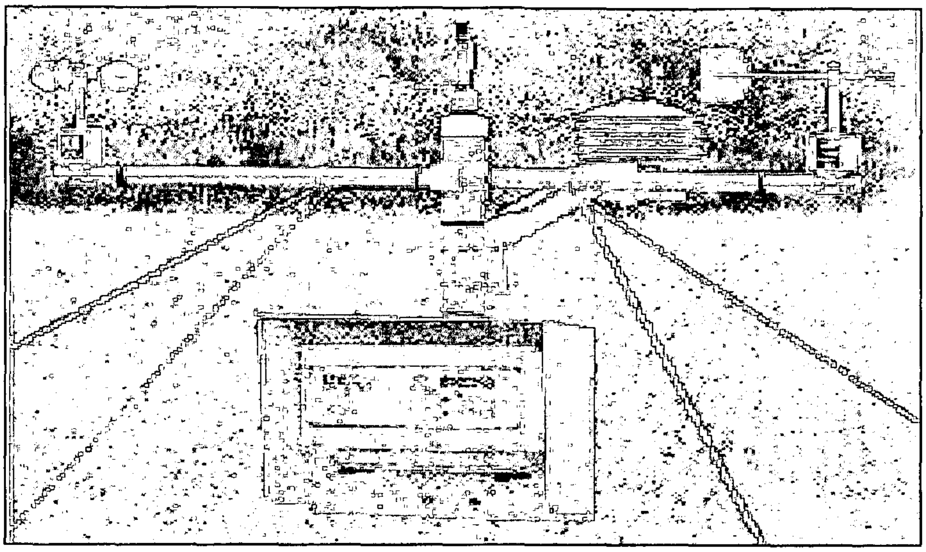


Figure 2.2 Automatic weather station at the agrometeorology experimental site located west of the University of the Orange Free State campus.

2.2.1.1 Experiment 1 (1996/1997)

Experiment 1 was arranged in a Randomised Complete Block Design with nine treatments randomly allocated in each of the three replications i.e. 27 plots. There were three maize plant densities in both mono-cropping and inter-cropping systems (Table 2.2)(see Appendix i for definitions of inter-cropping terminology). The treatments were as follows: T_1 - mono-crop beans with low plant density, T_2 - mono-crop beans with medium plant density, T_3 -mono-crop beans with high plant density, T_4 - mono-crop maize with low plant density, T_5 - mono-crop maize with medium plant density, T_6 - mono-crop maize with high plant density, T_7 -inter-crop maize/beans with low plant density, T_8 -inter-crop maize/beans with medium plant density and T_9 -inter-crop maize/beans with high plant density. Crops were established in accordance with local farming practices following a survey by Mukhala & Groenewald (1998). The additive method of inter-cropping as explained in Section on terminology (Appendix i) was applied (Willey, 1979a). In inter-cropping, two rows of beans were planted in between rows of maize plants and this was done in every alternate row (Figure 2.3 & 2.4). In both inter-cropping and mono-cropping systems, the row spacings were 0.75m and 0.4m respectively for maize and beans.

Table 2.2 Mono-cropping and inter-cropping maize and beans for three plant densities for 1996/1997 and 1997/1998 growing seasons.

		Plant densities (plants m^{-2})		
Cropping system	Crop	Low	Medium	High
Mono-cropping	Maize	2.2	4.4	6.7
	Beans	4.2	8.3	12.5
Inter-cropping	Maize	2.2	4.4	6.7
	Beans	2.1	4.2	6.3

Experiment 1 was grown under full irrigation conditions. The objectives were to:

(a) compare soil water use and utilisation efficiency and photosynthetic active radiation utilisation efficiency in inter-cropping and mono-cropping practices,

(b) compare inter-cropping and mono-cropping practices in terms of dry matter production and grain yield.

Rainfall was unevenly distributed (Appendix viii, a-i), totalling 346.3 mm during crop growth and an additional 466.3 mm of irrigation was applied to ensure water was non-limiting. During the growing season, the average monthly maximum temperature was in the range of 20.9 to 28.8°C with minimum monthly temperatures of 6.3 to 15.2°C (Table 2.3).

2.2.1.2 Experiment 2 (1997/1998)

Experiment 2 was arranged in a split plot design with three blocks. Main blocks had supplementary and full irrigation while sub-blocks had three plant densities. Two blocks had water withheld for a period of four weeks from 81 days after planting up to harvesting, the objective being to examine the effect of different irrigation strategies (supplementary and full). Rainfall distribution was unevenly distributed as in Experiment 1 totalling 380.5 mm during crop growth period. An additional 434.7 mm of irrigation was applied to the full irrigation block to ensure water was non-limiting and 347.7 mm was applied to two blocks with supplementary irrigation. During the growing seasons, the average monthly maximum temperatures were in the range of 21.0 to 33.3°C with minimum monthly temperatures of 4.9 to 16.0°C (Table 2.3).

←——— 0.75 m ———→ ←——— 0.75m ———→ ←——— 0.75m ———→

M	b	b	M		M	b	b	M
M	b	b	M		M	b	b	M
M	b	b	M		M	b	b	M
M	b	b	M		M	b	b	M
M	b	b	M		M	b	b	M
M	b	b	M		M	b	b	M
	←0.4 m→					←0.4 m→		

Figure 2.3 Field crop arrangement of an inter-cropping of maize and beans with inter-row distance of 0.75m for maize and 0.40m for beans, where M = maize and b = beans.

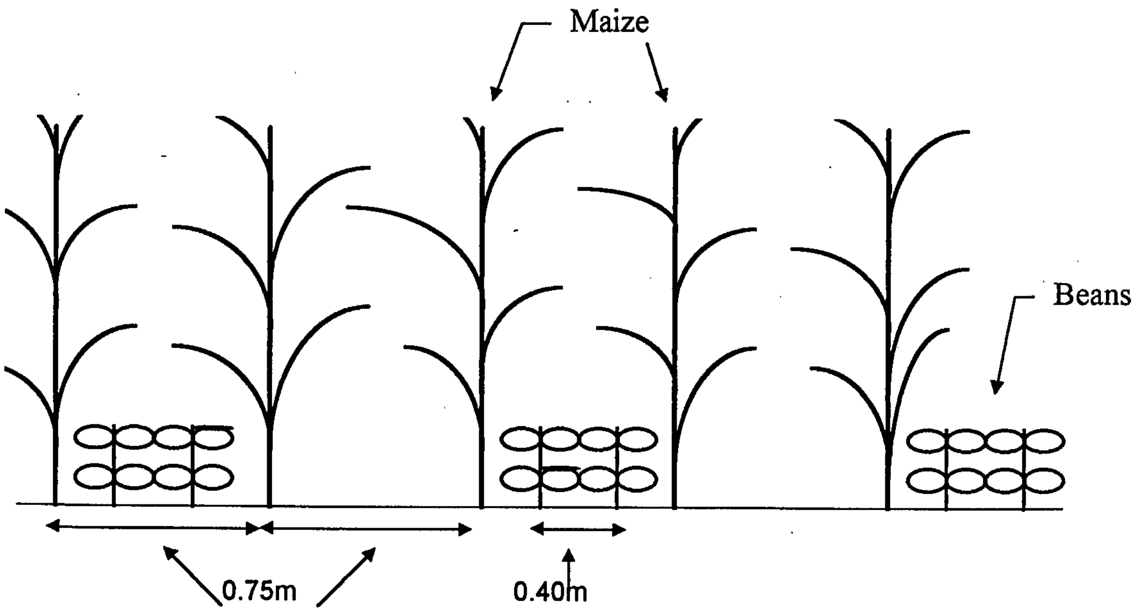


Figure 2.4 Field crop arrangement of an inter-cropping of maize and beans with inter-row distance of 0.75m for maize and 0.40m for beans.

Table 2.3 Weather data for the two growing seasons from the automatic weather station at the University of the Orange Free State campus. Eo (PTe) calculated using Priestly Taylor Equation. Eo (PMe) calculated using Penman Monteith Equation.

			Meteorological parameters						
Season	Month	Expt	Rad (PAR)	Mean Temp (max)	Mean Temp (min)	month Rfall	month Irrig	Eo (Pte)	Eo (Pme)
			Wm^{-2}	^oC	^oC	mm	mm	mm d^{-1}	mm d^{-1}
96/97	Dec	1	29.0	28.8	14.3	60.0	101.1	14.5	6.7
97/98	Dec	2	26.9	33.3	16.0	41.3	134.7	13.5	6.9
	Dec	Lta*		30.3	13.9	65.0			
96/97	Jan	1	28.2	28.5	15.7	101.0	109.0	14.1	6.1
97/98	Jan	2	23.7	29.8	15.9	108.7	120.0	11.8	6.0
	Jan	Lta		30.9	15.1	86.0			
96/97	Feb	1	27.4	30.7	15.7	29.4	153.5	13.7	6.4
97/98	Feb	2	19.3	29.1	16.0	125.0	93.0	9.6	4.9
	Feb	Lta		29.5	14.6	83.0			
96/97	Mar	1	15.4	24.7	13.7	127.0	41.8	7.7	3.1
97/98	Mar	2	16.5	21.0	13.0	105.5	87.0	8.2	3.8
	Mar	Lta		27.2	12.4	78.0			
96/97	Apr	1	12.6	20.9	6.3	28.9	51.5	6.3	2.4
97/98	Apr	2	14.2	24.7	7.5	0.0	0.0	7.3	3.3
	Apr	Lta		23.8	7.7	53.0			
96/97	May					9.5			

***Lta- long term average for 30 years.**

A centre pivot irrigation system was used to apply irrigation water. The centre pivot was not envisaged as the method by which small-scale farmers would irrigate but, due to its availability, served purely as a line-source system. Atmospheric Evaporative Demand (AED) was used to determine the amount of irrigation. The sum of AED was used to set the speed of the centre pivot to apply the required water. PUTU-Irrigation decision support system (IDSS) determines daily AED which usually varies between 0 and 15 mm d^{-1} (Mottram and De Jager, 1995). AED has been defined (De Jager & Van Zyl, 1989) as the rate of water from a crop experiencing no water stress in it's root zone plus rate of water evaporated from the top 150 mm of soil at existing soil water status. It represents the upper limit of evaporation determined by atmospheric conditions and degree of vegetation cover and constitutes the water necessary to ensure maximum yield. The required amount were obtained by allowing the centre pivot to run at a 20% speed.

2.2.2 Agronomic information

The experiments were carried out on a fine sandy loam Bloemdal vrede (3100) soil (Soil classification, 1991). Clay, sand and silt content in the top 300 mm was 20%, 63.5% and 9.4% respectively with soil pH 6.3. Prior to sowing, a commercial fertiliser was applied and incorporated in the soil in all plots during both experiments at a rate of 800 kg ha^{-1} 3:2:1 (25) NPK and 550 kg ha^{-1} LAN (Limestone ammonium nitrate) (28) giving a total of 254 kg N ha^{-1} 67 kg P ha^{-1} and 33 kg K ha^{-1}. Experiment 1 had no top dressing applied during the growing season while Experiment 2 had a top dressing applied 29 days after planting at a rate of 178 kg LAN per hectare giving an additional 50 kg N ha^{-1}. Experiment 1 was planted on 9th December 1996 while Experiment 2 was planted on 10th December 1997. Both experiments were planted by hand except for the buffer plots around the experimental plots which were sown using a planter. Regular weeding was carried out by hand, or hand hoe, keeping the plots virtually weed free throughout the growing season. Both experiments experienced severe cob thefts and were harvested on 5th May 1997 (143 Days after planting) and 7th April 1998 (119 Days after planting) for Experiment 1 and 2 respectively. Instead of harvesting the entire plot for Experiment 1, the harvest plot was reduced while for Experiment 2, the theft could not affect the analysis as the crop was harvested earlier at 119 days after planting instead of 143 days after planting. Hence the analysis was handled normally without special attention to theft.

2.2.3 Measuring Solar radiation

2.2.3.1 Photosynthetic active radiation (PAR)

A portable Sunscan canopy analysis system (SCAS) was used during experiments 1 and 2 to take radiation measurements in all the plots. The SCAS is described briefly in Appendix vi. The Sunscan canopy analysis system measures photosynthetic active radiation (PAR) in units of $\mu mol\ s^{-1}\ m^{-2}$ up to a maximum of 2500 μmol s^{-1} m^{-2}. Conversion of μmol s^{-1} m^{-2} to Wm^{-2} may be obtained using Equation 2.1 from Thimijan & Heins (1983). Values for the constant are presented in Appendix i.

$$\frac{\mu mol s^{-1} m^{-2}}{Constant} = Wm^{-2} \qquad 2.1$$

During Experiment 1, solar radiation measurements were done every 3 days over the period 35 to 73 days after planting and later every 7 days from 74 to 113 days after planting using the Sunscan canopy analysis system with a spectral response of PAR 400-700 nm. Measurements during Experiment 2 were taken every 7 days with the same instrument. Solar radiation measurements were taken between 1200 hours and 1400 hours for both experiments as radiation measurements should be measured in the four hour period centred on solar noon when irradiance is strongest (Russel *et al.*, 1989). To take measurements, the Sunscan canopy analysis system probe was placed immediately above the maize canopy, and beneath the maize and beans in mono-crop and maize/bean canopy in inter-crop, to measure total radiation intercepted and transmitted by the combined crop canopy. The Sunscan canopy analysis system probe was placed at an angle across the maize and bean rows so as to cover a width of 0.75m equivalent to the distance between the rows. The Sunscan canopy analysis system was also used to collect several other data sets (see for example Table 2.4). The data collected in both growing seasons included;

(a) Total PAR being received at the top of the canopy (Direct and Diffuse radiation components of PAR),

(b) transmitted PAR,

(c) intercepted PAR and

(d) Leaf area index

PAR measurements were taken both in the serial harvesting plots and experimental area starting from 35 days after planting (DAP) during Experiment 1 and 20 DAP during Experiment 2.

Table 2.4 Incident and intercepted radiation, leaf area index and zenith angle measured by a Sunscan canopy analysis system.

Created by SunData for Workabout
v1.05
Title : Radiation and LAI measurements
Location : West Campus

Latitude : 29.1N Longitude : 26.1W
3/18/98 Local time is GMT-2 Hrs
SunScan probe v0.36

Ext sensor: BFS Leaf Angle Distribution Parameter: 3 Leaf :Absorption 0.85
Group 1 :

Time	Plot	Sample	Transmit radiation	Spread	Incident radiation	Beam fraction	Zenith Angle	Leaf Area index
6:40:02	1	1	4.5	0.19	48.8	0.13	80.1	2.6
6:42:01	1	2	4.8	0.19	52.5	0.16	79.7	2.6
6:44:01	1	3	5.1	0.20	53.7	0.09	79.3	2.6
6:46:01	1	4	5.4	0.20	56.2	0.13	78.8	2.6
6:48:01	1	5	5.6	0.20	58.6	0.08	78.4	2.6
6:50:01	1	6	5.9	0.21	62.3	0.10	78.0	2.7
6:52:01	1	7	6.2	0.22	63.5	0.10	77.5	2.6
6:54:01	1	8	6.4	0.21	64.7	0.09	77.1	2.6
6:56:01	1	9	6.8	0.29	65.9	0.04	76.7	2.6
6:58:01	1	10	7.2	0.30	68.4	0.07	76.2	2.6
7:00:02	1	11	7.1	0.22	70.8	0.10	75.8	2.6
7:02:01	1	12	7.4	0.22	72.0	0.10	75.4	2.6
7:04:01	1	13	7.4	0.21	73.2	0.10	74.9	2.6
7:06:01	1	14	7.6	0.21	74.5	0.08	74.5	2.6
7:08:01	1	15	7.9	0.20	76.9	0.11	74.1	2.6
7:10:01	1	16	8.2	0.20	78.1	0.09	73.6	2.6

Transmission of beam radiation through vegetation is described using Beer's law, Equation 2.2.

$$S_b(b) = S_b(0)\ \exp(-k\,L) \qquad 2.2$$

where: $S_b(b)$ is the flux density below the canopy,

$S_b(0)$ is the flux density of the beam radiation on a horizontal surface above the canopy and

k is the extinction coefficient.

In the experiment S_b (L) and S_b (0) were determined using the Sunscan canopy analysis system (Appendix vi, Table 2.4.), leaving two unknowns, extinction coefficient *(k)* and leaf area index *(L)* in the Beer's law Equation. Leaf area index was also determined using the Sunscan canopy analysis system but in order to determine leaf area index *(L)* *k* had to be determined first. To determine *k*, the Sunscan canopy analysis system uses the Campbell (1986) ellipsoidal leaf angle distribution equation, Equation 2.3:

$$k = \frac{(x^2 + \tan(\theta)^2)^{1/2}\cos\theta}{x + 1.702(x + 1.12)^{-0.7080}} \qquad 2.3$$

where θ is the solar zenith angle and x is an ellipsoidal leaf angle distribution parameter which characterises the horizontal or vertical tendency of leaves in a canopy. The canopy leaf elements were assumed to be distributed in space in the same directions and proportions as the surface area of an ellipsoid, symmetrical about the vertical axis. The leaf angle distribution can then be described by a single parameter (x), the ratio of the horizontal to vertical axes of the ellipsoid. The solar zenith angle (θ) is the angle of the sun from the vertical and can be calculated from the Equation 2.4 (Forseth & Norman, 1993):

$$\cos\theta = \sin(\Lambda)\sin(\delta) + \cos(\Lambda)\cos(\delta)\cos(15(T - T_{SN})) \qquad 2.4$$

Where: Λ = Latitude, δ = Declination, T = Solar time, T_{SN} = Solar noon

Declination is the tilt of the earth on its axis. This value is usually defined in relation to the northern hemisphere, where declination is 0° on the spring and autumnal equinoxes (21st March, 22nd September), 23.5° on the summer solstice (22nd June), and -23.5° on the winter solstice (22nd December). Declination may be estimated from Equation 2.5 (Forseth & Norman, 1993):

$$\delta = -23.5\cos[360(D_j + 10)/365] \qquad 2.5$$

Where D_j is the Julian date.

2.2.3.2 Radiation use efficiency (RUE)

Radiation use efficiency is the ratio of dry matter produced per unit of the energy used in its production. The ratio is often a crucial component of crop growth models that relate dry matter production to energy received by the crop. A simple definition of RUE is the biomass (M, g m^{-2}) produced per unit of energy absorbed by the crop (E, MJ m^{-2}) Equation 2.6:

$$RUE_m = M / E \; (g \, MJ^{-1}) \qquad 2.6$$

where the subscript m indicates that RUE is based on mass per unit energy. Alternatively, the efficiency of radiation utilisation may be expressed as energy content of the biomass per unit ground area (EC, MJ m^{-2}) divided by energy absorbed by the crop (E, MJ m^{-2}) Equation 2.7:

$$RUE_e = EC / E \qquad 2.7$$

where the subscript e indicates that RUE is based on energy content of the biomass per unit of energy received (Gallo *et al.,* 1993). The method used to measure RUE was that used by Gallo *et al.* (1993) of biomass produced per unit of energy absorbed by the crop (Equation 2.6). Short term (7-9 days) estimates of RUE were determined as the change in biomass divided by the absorbed photosynthetic active radiation during the interval.

2.2.4 Measuring plant variables

2.2.4.1 Plant height

Plant heights were determined at 7 day intervals from 35 to 143 days after planting. Plant samples were harvested in each plot of inter-crop and mono-crop in the three population densities. Plant heights were determined on both maize and beans plants. Plant heights were determined only during Experiment 1. In the case of maize, tassels were included in the plant height measurements.

2.2.4.2 Dry matter production

Shoot (or above-ground) biomass was measured by clipping the crops at 10 mm from the ground level. Plant samples were harvested at 7 day intervals from 35 to 143 days after planting. Eight (8) plants were harvested in each plot of the inter-crop in the three plant densities and four plants were harvested in the mono-cropping plots. Dry matter production was determined on both maize and bean plants. Dry matter determination was done for pods, stems and leaves (dry beans) and cobs, tassels, stems and leaves (maize). The samples for drying were separated for both crops and oven-dried at 70°C for a period of 4 days and the dry weight recorded. Dry matter partitioning was computed as the product of total dry matter (TDM) times the fractional composition of plant parts from the plant samples (Gardner *et al.*, 1990).

2.2.4.3 Ellipsoidal Leaf Angle Distribution Parameter

Leaf inclination is the angle (α) between the leaf axis and the horizontal, while leaf orientation or azimuth ($\eta 1$) is the angle formed clockwise from due north by the horizontal projection of the leaf. Patterns of leaf inclination within a canopy may be represented by plotting the relative frequencies of leaf inclinations, typically at 10° intervals, from 0° for a horizontal leaf to 90° for a vertical one. A planophile canopy has its greatest frequency at the lower inclination angles, that is $\alpha = 0^\circ - 20^\circ$, whereas an erectophile canopy would show the greatest frequency at high inclination angles, e.g. $\alpha = 70^\circ - 90^\circ$ (Nobel *et al.*, 1993).

Leaf inclination may be estimated directly using a protractor with a levelling device against the leaf (Nobel *et al.,* 1993). Some crops, however, have long leaves e.g. maize, which sometimes droop towards the tip and therefore display a range of inclinations. In such cases, each leaf is divided into angle classes measured backward from the tip (Forseth & Norman, 1993), or the angle at the widest part of the leaf is used (Delta-T, 1996). The mean inclination angle is calculated arithmetically by adding all the angles and dividing by the number of angles. Once the mean angle has been calculated it is related to the graph (Figure 2.5) to determine x (Wang, 1988; Forseth & Norman, 1993).

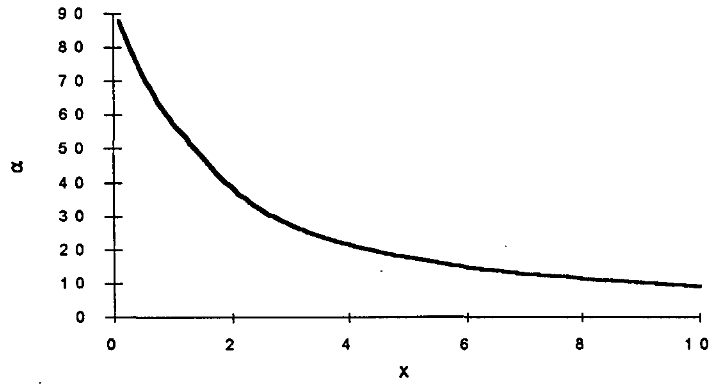


Figure 2.5 The relationship between the mean leaf inclination angle (relative to the horizontal) α and the single dimensionless parameter χ, which is the ratio of the two principal axes of an ellipsoid (after Wang & Jarvis, 1988).

An alternative method was also used to determine χ. Where a canopy shows a clear predominance of horizontal or vertical leaves, a small volume representative of a canopy is chosen. On the representative canopy, the number of leaves at more than 45° from the vertical and the number of leaves at less than 45° from the vertical are counted. In cases where leaves are curved, the angle at the widest part of the leaf is used. The χ is then estimated as the number of horizontal leaves (N_h) divided by the number of vertical leaves (N_v), multiplied by $\pi/2$ (Delta-T, 1996) as in Equation 2.8.

$$x = \frac{\pi N_h}{2N_v} \qquad 2.8$$

The factor $\pi/2$ comes from the fact that the vertical leaves are distributed about the vertical axis, so for any light ray, some will be seen face-on, and some edge-on. In effect the ellipsoidal distribution is approximated as a cylindrical distribution (Delta-T, 1996). Both methods were used for verification purposes.

2.2.4.4 Leaf area index

Leaf area index was determined using the Sunscan canopy analysis system. The Sunscan canopy analysis system has software which is used to calculate the various elements. The radiance from a strip at an angle θ of hemispherical sky is given by Equation 2.9:

$$R = 2\pi \sin(\theta)\, d\theta \qquad 2.9$$

and the irradiance on a horizontal surface due to that strip is given by Equation 2.10:

$$I_o = 2\pi \sin(\theta) \cos(\theta)\, d\theta \qquad 2.10$$

The total irradiance due to the hemisphere is obtained by integrating over the complete sky area using Equation 2.11:

$$\int_0^{\frac{\pi}{2}} 2\pi \sin(\theta)\cos(\theta) d\theta = \pi \qquad 2.11$$

For each strip of sky (irradiance I_o), the transmitted radiation is given by Equation 2.12

$$I = I_o \exp(-K L) \qquad 2.12$$

where K is the extinction coefficient from Campbell, so the total transmitted radiation is

$$I = \int_0^{\frac{\pi}{2}} 2\pi \sin(\theta)\cos(\theta)\exp(-K(x,\theta)L) d\theta \qquad 2.13$$

and the transmission fraction $\tau = I / I_o$ is given by:

$$\tau_{diff}(x,L) := \frac{1}{\pi}\int_0^{\frac{\pi}{2}} 2\pi \sin(\theta)\cos(\theta)\exp(-K(x,\theta)L) d\theta \qquad 2.14$$

This integral was evaluated numerically over the range x = 0 to 1000 and L = 0 to 10 (Delta-T, 1996).

A computer model has been created which calculates accurately the transmitted light below the canopy. Functions are used in the SunData software to predict LAI from the measured inputs in the field. The LAI values calculated by the SunData software are within ±10% ± 0.1 over the range of LAI less than 10 and Zenith Angle less than 60° when compared to the output of the full model. To verify the readings of the Sunscan canopy analysis system, leaf area index was also measured using the area meter (model 3100, LI-COR, Lincoln, NE). Leaf area index was computed as the ratio of green leaf area divided by the soil area represented by the sampled plants.

2.2.4.5 Yield and Analysis of Variance

At final harvest, maize plants numbering 50 to 110 were harvested in both mono-cropping and inter-cropping systems for 1996/1997 growing seasons. The plants harvested covered areas in the range of 15.9m^2 to 22.7m^2 (Appendix ix) For bean crops, plant areas ranging from 12m^2 to 13m^2 (Appendix x) were harvested. Both grain yield and dry matter were determined at final harvest. Statistical

Analysis System (SAS) was used to analyse the data. Differences among treatments means were compared using Tukey's Studentized Range (HSD) at 0.05 and 0.01 probability.

2.2.5 Measuring irrigation variables

Prior to using the neutron probe, it was calibrated against gravimetrically determined soil water contents, allowing the number of counts to be converted to volumetric soil water content values as indicated in Section 2.2.6.2.

2.2.5.1 Drained upper limit

Determination of drained upper limit (DUL) was made at a representative site chosen near the experiment (Figure 2.6). A 3 x 3m dam was prepared to determine the drainage curve. Two access tubes were installed in the dam with a distance of 1m between them. The dam was thoroughly wetted for a period of 14 days prior to taking readings. The dam was covered with a plastic sheet to ensure that no water evaporated from the soil surface or that rain could enter. Soil water content measurements using a neutron probe were taken at intervals of initially twice a day then daily, every two days, every week and finally every two weeks. DUL was defined as the highest field measured soil water content of a soil after it had been thoroughly wetted and allowed to drain until drainage became practically negligible.

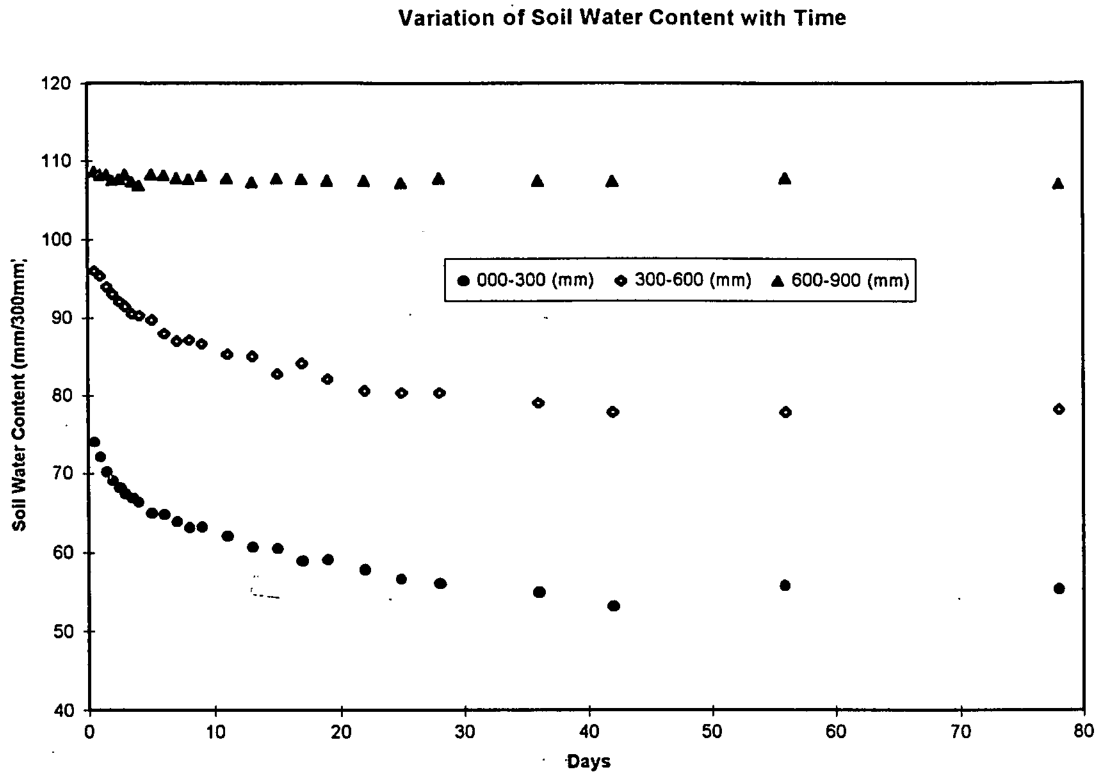


Figure 2.6 Drainage curves determined to at depth of 300, 600 and 900mm at a representative site chosen near the experiment.

The soil profile was considered to attain a negligible drainage rate and to reach the drained upper limit when the water content decrease was about 0.1 to 0.2% water content per day. From the drainage curve, the drained upper limit (DUL) was found to be 245 mm/900mm. The soil water depletion progressed very well until day 56 when heavy rain water which settled on top of the plastic sheet seeped into the profile through a small hole in the plastic sheet. This increased the soil water content again and took some time for the water content to percolate out of the profile.

2.2.5.2 Lower limit

The lower limit was defined as the lowest field-measured soil water content of a soil after plants had stopped extracting water and were at or near premature death or become dormant as a result of water stress (Ratliff *et al.*, 1983). The lower limit was determined using Equation 2.15 (Bennie *et al.*, 1988) (Table 2.5).

$$LL = 0.0038\,(silt + clay) + 0.013 \qquad 2.15$$

Table 2.5 Sand, Silt and Clay determined by the particle size distribution method from the soil samples obtained from the west campus agrometeorology experimental site.

Depth (mm)	Sand (%)	Silt (%)	Clay (%)
0 -300	63.5	9.4	20.0
300 - 600	73.4	5.8	26.0
600 - 900	58.5	11.0	31.0

Table 2.6 Calculation of the lower limit of the soil profile from the data in table 2.5 and the formula LL = 0.0038 (silt + clay) + 0.013 (Bennie *et al.*, 1988).

Depth (mm)	LL = 0.0038 (silt + clay) + 0.013	Soil water content (mm/300mm)
0 -300	0.00385 (9.4 + 20) + 0.013	37.9
300 - 600	0.00385 (5.8 + 26) + 0.013	40.6
600 - 900	0.00385 (11 + 31) + 0.013	52.4
	Total LL	130.9

Potential extractable soil water (PLEXW) or profile available water (PAW) is the difference in soil water content between DUL and LL (Ratliff *et al.*, 1983) as in Equation 2.16.

$$DUL - LL = PLEXW \tag{2.16}$$

2.2.6 Components of the water balance Equation

2.2.6.1 Change in soil water content

Soil water content was monitored every 7-9 days from 34 to 144 days after planting during Experiment 1 in all the plots using a neutron probe (Campbell Pacific Nuclear (CPN), model 530) (Appendix vii). The plots in Experiment 2, were monitored every 14 days from 26 to 110 days after planting. Two access tubes were installed in component crops in both growing seasons with one tube in the row while the other 20 cm off the row with a distance of 1m in between the two tubes. Inter-crop plots had four access tubes (monitoring points), while mono-crop plots had two tubes. The soils at the experimental site where shallow and hence, access tubes were installed only to a depth of 1m below the soil surface and measurements were taken at three levels of 0-300 mm, 300-600 mm and 600-900 mm. No special equipment was used to measure the SWC of surface layer except for the neutron probe. The average amount of soil water used by the crops in both mono-crop and inter-crop treatments were found by taking the arithmetic mean of the two or four tubes in the plots. This method was appropriate as the roots of both maize and beans were intertwined.

2.2.6.2 Neutron Probe Calibration

The neutron probe measuring equipment calibration was done to enhance the reliability of the data collected. Different opinions exist as to whether neutron probe measuring equipment should be calibrated in the laboratory or in the field. What is clear though is that each soil type requires its own calibration curve (Holmes, 1966). Calibration of the neutron probe measuring equipment was carried out by comparing CPN count ratios obtained by the probe to volumetric soil water content determined by gravimetric method (Figure 2.7). Conversion of soil water content determined by gravimetric method to volumetric soil water content (mm), required determination of bulk densities (ρ_b) of the experimental site soil at different depths which was achieved by the clod method (Blake & Hartage, 1986). Equation 2.17 was used to determine bulk density (ρ_b).

$$\rho_b = \rho_w W_{ods} / [W_{sa} - W_{spw} + W_{pa} - (W_{pa}\rho_w / \rho_p)] \qquad 2.17$$

where: ρ_w = density of water at temperature of determination,

W_{ods} = oven-dry weight of clod in air,

W_{sa} = net weight of soil sample (clod),

W_{spw} = net weight of soil sample plus candle wax in water,

W_{pa} = weight of candle wax coating in air, and

ρ_p = density of candle wax

The volumetric soil water content was determined using Equation 2.18

$$\theta_v = \frac{\rho_b}{\rho_w}\theta_m \text{ (cm}^3\text{ water per cm}^3\text{ soil)} \qquad 2.18$$

where: θ_v = volumetric soil water content,

θ_m = mass of water ,

ρ_b = bulk density,

ρ_w = density of water.

Mass of water was determined by gravimetric method where a soil sample was measured while wet and oven dried at 105 °C and then weighed again. The difference in weight between the wet and dry sample gave the mass of water.

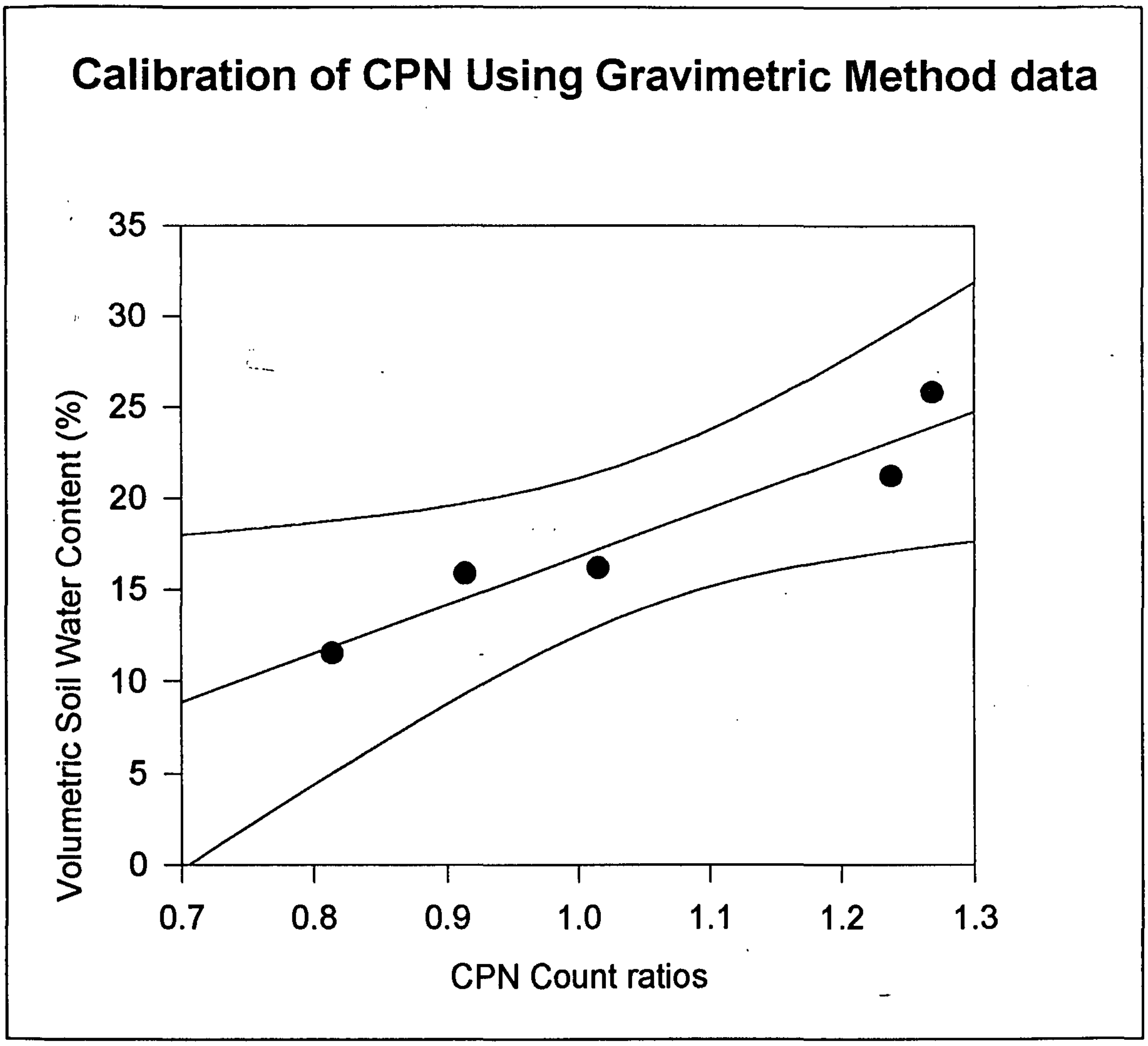


Figure 2.7 Calibration of the neutron measuring equipment carried out by comparing readings obtained by the probe to volumetric soil water content determined by the gravimetric method.

Coefficients:

a = -9.67, b = 26.49, r^2 = 0.92

Regression Equation: $Y = -9.67 + 26.49 * X$

where: a is the intercept and X is the count ratio

b is the slope (regression coefficient)

r^2 is the coefficient of determination

In field research, water use has commonly been defined as the ET (evapotranspiration) component of a water balance. Input of water to the root zone is composed of two terms, Rainfall (R_{fall}) and Irrigation (I_{irr}). Output of water from the root zone is composed of three terms, surface runoff (R_{off}); evapotranspiration (ET), which is the sum of evaporation from the soil surface (E_s) and transpiration from leaves of plants (E_v); and the deep drainage (D). Their relation is expressed by the water balance Equation:

$$\Delta W = R_{fall} + I\,irr \pm D - R_{off} - ET\,(E_v + E_s) \qquad 2.19$$

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

2.2.6.3 Rainfall and irrigation

Rainfall and irrigation were measured using plastic raingauges installed in the field. A total of 10 raingauges were installed in the field to measure the amount of irrigation applied. Irrigation was in most cases applied at night when the wind speed was calm to increase the efficiency of the centre pivot. Two raingauges were installed away from the area under the centre pivot to measure rainfall in cases where there was rainfall while irrigation was taking place (Table 2.3, Appendix viii, i).

2.2.6.4 Drainage and runoff

There was no runoff during both experiments. This was determined by visual assessment immediately after irrigation and rainfall. It was also made sure that runoff was negligible by applying irrigation at an appropriate speed of the centre pivot. There was also no deep drainage as observed from the drainage curve in Section 2.2.5.1. This is was so becuase of the hard pan on the 600-900mm layer which kept the water content constant through out the drainage determining process. The possible water loss from the profile would be through lateral movement which is difficult to measure.

2.2.6.5 Evapotranspiration

Reference crop ET is defined as the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water (Doorenbos & Pruitt, 1977; Allen *et al.*, 1989). A buffer crop at low plant density was planted in a wide area surrounding the lysimeter. The amount of water lost by ET was found by determining the weight of the soil mass at the beginning and at the end of a time interval. Lysimeter observations were done at 08:00, 12:00 and 18:00 local time. Evapotranspiration from the experimental plots (mm d^{-1}) was also determined using the water balance Equation 2.19.

2.2.6.6 Water use and water use efficiency

Water use efficiency (WUE) is usually defined as the total dry matter produced by plants per unit of water used,

$$WUE = (D/W)\ (g\ ha^{-1}\ mm^{-1}) \qquad 2.20$$

where D is the mass of above ground dry matter produced per unit ground surface area and W is the depth of water used (including direct evaporation from the soil surface). The grain yield obtained in inter-crop and mono-crop was converted into nutrients per hectare and for calculating water use efficiency in terms of nutrients, yield in nutrients was divided by water use. The higher the productivity per unit of water use, the higher the water use efficiency (Boyer, 1996). There is extensive evidence that WUE varies among species in the same environment and among climates for the same crops (Tanner & Sinclair in Taylor *et al.*, 1983). In this experiment, water use was determined using the water balance Equation 2.19. It has been indicated in Section 2.2.6.1 that soil water content was monitored from 34 to 144 days after planting for Experiment 1 and from 26 to 110 days after planting for Experiment 2. The delay was becuase access tubes could only be installed in the field after germination. Water use up to the time of monitoring was determined using BEWAB Simulation Model. Therefore, water was added to the amount determined by the water balance equation to Experiment 1 and Experiment 2 respectively.

2.2.7 Calculations

2.2.7.1 Land equivalent ratio

Land equivalent ratio (LER) a concept proposed by Willey and Osiru (1972), was used to evaluate the success of inter-cropping. Land equivalent ratio is defined as the total land area required under mono-cropping to give the yields obtained in an inter-cropping mixture. It is expressed as:

$$LER_T = LER_M + LER_B \qquad 2.21$$

where: LER_T - total land equivalent ratio and

LER_M - partial LER for maize per unit area

LER_B - partial LER for beans per unit area.

Partial LER is defined as the ratio of yield per unit area of the specific inter-crop (Yi) versus the mono-crop (Ym) that is:

$$Partial\ LER = Yi\ /\ Ym \qquad 2.22$$

An advantage is said to occur when $LER_T > 1$ implying that more land is needed to produce the same yield of mono-crop of each component compared to an inter-crop mixture. When $LER_T = 1$, there is no advantage to inter-cropping. Willey (1979a) cautions researchers as to the limitations of using LER_T particularly when it is used to compare the productivity of an inter-crop and a mono-crop as one major problem is that computation of LER requires maximum yields of mono-crops obtained at maximum plant densities.

2.2.7.2 Total nutrient content

In many African countries, inter-cropping is mostly practised by small-scale farmers whose diets do not contain dietary nutrients close to the Recommended Daily Allowances (RDAs). Analysing inter-cropping in relation to dietary requirements will be beneficial to small-scale farmers as it will provide an indication of quantities of nutrients essential for a healthy living.

Scepticism has been expressed regarding the use of LER for inter-cropping evaluation as two totally different crops are used. In mono-crop and inter-crop comparisons, Fukai & Midmore (1993) proposed that besides LER, expression in monetary return, product energy (caloric yield) or other forms of comparisons may be more appropriate. It was decided that the dietary need in small-scale rural communities necessitated the use of Total Nutrient Content (TNC) in evaluating benefits of inter-cropping. This method of analysing yield by using nutrient contents as indices of productivity, although very useful for inter-cropping has not been used by many scientists (Platt, 1962; Edjie, 1994; Edjie, 1995). TNC will be used to evaluate the energy and nutrient content in mono-crop and inter-crop grain yields. Stiff porridge will be used for nutrient content calculations. A 100g of raw maize meal (white) contain 13% (13g) moisture and therefore, 87g solid maize meal material while a 100g of stiff porridge contain 79.1% (79.1g) moisture and 20.9g solid maize meal material (Food Composition

Tables, Medical Research Council, 1991). Therefore, 416g of stiff porridge will be produced from 87g maize meal while 478g of stiff porridge will be produced from 100g of raw maize meal. As for beans, 100g of raw beans will produce 272g of cooked beans. Inter-crop Total Nutrient Content (TNC_{Ti}) per ha^{-1} was expressed as:

$$TNC_{Ti} = TNC_{TiM} + TNC_{TiB} \tag{2.23}$$

where M and B are maize and beans respectively. TNC_{TiM} is total nutrient content of maize inter-crop and TNC_{TiB} is the total nutrient content of beans inter-crop. Where as Total Nutrient Content for mono-crops (TNC_{mM}) was taken as the nutrient content in the mono-crop maize and TNC_{mB} was the nutrient content in mono-crop beans. Percentage nutrient content differences were calculated using data from the Food Composition Tables (Medical Research Council, 1991). Difference in total (maize/beans) inter-crop nutrient as a percentage of maize mono-crop was expressed as:

$$((TNC_{Ti} - TNC_{mM}) / TNC_{mM}) \times 100 \tag{2.24}$$

while difference in total (maize/beans) inter-crop nutrient as a percentage of beans mono-crop was expressed as:

$$((TNC_{Ti} - TNC_{mB}) / TNC_{mB}) \times 100 \tag{2.25}$$

An alternative method was used to compare nutrient content in mono-crop and inter-crop. One hectare of mono-crop maize (TNC_{mM}) and one hectare of mono-crop beans (TNC_{mB}) were added giving an equivalent of two hectares of inter-crop maize and beans (TNC_{Ti}). Then, one hectare of inter-crop maize/beans was multiplied by 2 giving an equivalent of 2 hectares of inter-crop maize/beans (TNC_{Ti} x 2). Difference in total (maize/beans) inter-crop nutrient as a percentage of maize mono-crop plus beans mono-crop was expressed as in Equation 2.26.

$$((TNC_{Ti} - (TNC_{mM} + TNC_{mB})) / (TNC_{mB} + TNC_{mB})) \times 100 \tag{2.26}$$

SAS was used to analyse the data. Treatment means were compared using Tukey's Studentized Range (HSD) at 5% and 1% probability.

2.3 Simulations

2.3.1 Putu Simulation Model

The initial Putu model, a mechanistic seasonal maize crop growth model, was first developed in 1973. Its initial construction was described by De Jager (1974) and De Jager and King (1974). The computing stages (modules) and partitioning of dry matter are described by De Jager (1974).

2.3.1.1 Determination of crop parameters for the expolinear growth function

The input parameters required to evaluate the expolinear equations are:

N_p, K, LAR, L_{pi}, t_b and C_m where

N_p = is the plant density

K = is the extinction coefficient

LAR = is the leaf area ratio

L_{pi} = initial leaf area per plant

t_b = is lost time (days)

C_m = is the maximum crop growth rate achieved when all incident light is intercepted ($f \approx 1$)($kg ha^{-1} d^{-1}$).

The strength of the expolinear approach lies in the power of L_p and t_b to account for sparse crop canopies. It is precisely during this growth stage that water may be saved by limiting soil evaporation. Hence accurate simulation of t_b is important (De Jager, 1998). Vegetative crop growth rate (CGR_v) was estimated by linear regression analysis of the linear regression phases durin 66-94 DAP (Gardner *et al.*, 1990). Vegetative crop growth rate (CGR_v) is also referred to as C_m (Gardner *et al.*, 1990; Goudriaan & Monteith, 1990). The parameter t_b was obtained by field experimentation by plotting serial harvest results of dry weight verses time. The maximum leaf relative growth rate (Rm) was obtained by Equation 2.27.

$$R_m = LAR * C_m * K \qquad 2.27$$

f_l was obtained by subsituting Rm and into the Equation 2.28.

$$f_l = \frac{\exp[-R_m t_b]}{1 + \exp[-R_m t_b]} \qquad 2.28$$

The plant density (N_p) was determined from the begining of the experiment while the extinction coefficient (K) was determined as explained in Section 2.2.3.1 by Equation 2.3.

2.3.1.2 Validation criteria

The following statistical parameters were used to describe the accuracy of grain yield simulations from the models under study:

(i) Coefficient of determination (r^2)

(ii) The simulation index (SI) of Willmot (1982)

(iii) The mean absolute difference between simulated and observed values expressed as a percentage of the mean observed value (MAD)

(iv) The root mean square error (RMSE)

(vi) The frequency of occurrence of simulated values being within 20% of the observed values (F80)

2.3.2 BEWAB simulation Model

BEWAB is an irrigation scheduling program developed at the University of the Orange Free State (Bennie *et al.*, 1988) based on the water balance irrigation scheduling principles. When using BEWAB (a program written in GW-BASIC language), scheduling of irrigation is done for a specific yield target using a water balance method. The total amount of irrigation water needed for a target yield, or the crop water demand is calculated with an empirical water production function. The inputs needed in the BEWAB Model are: type of crop, length of the growing season, target yield, depth of soil, silt and clay content for 200 mm depth intervals and selected rain storage capacity. The total consumptive water use over the season is estimated for a selected target yield from the upper boundary water production functions based on historic water use-yield relationships. The daily crop water demand from relative crop water demand is estimated from relative crop water demand curves, also based on historic data (Bennie, 1991). The output consists of a printout of a recommended water application schedule. The following inputs were used:

(i) A maize growing season of 150 days

(ii) Target yields of 10310, 9010 and 7895 Kg ha-1 from the actual experimental yields

(iii) A reserved rain storage capacity of 30mm

(iv) Overhead irrigation method

(v) A 3 day irrigation interval

CHAPTER 3

QUANTIFYING SOCIO-ECONOMIC AND AGRONOMIC FACTORS INFLUENCING SMALL-SCALE IRRIGATION DEVELOPMENT

3.1 Introduction

Most of the rural small-scale farmers in many African countries dream of improving their standard of life. They also desire to adopt appropriate technology so as to improve their individual and communal welfare. These are some of the reasons why they listen to the 'development experts' who visit their rural communities. These so called 'development experts' subjectively prescribe perceived benefits for the community. Considering that they posses the financial muscle, development is soon underway even before the community have adequate time to answer the consequences of their action. It is not until the development has failed that the experts begin to seek reasons for the failure. In an attempt to answer the question "What is wrong in development?" Kotze & Kotze (1996) pointed out *inter alia* the gap between the expert and the people. They state that it would seem as though the vast amount of information made available by advisors to developing countries has had no effect. Edwards (in Kotze & Kotze, 1996) attributes this state of affairs to the distance between the possessor and the receiver of the information. Too often the information is inappropriate and partial because of inappropriate research methods which usually only serve to satisfy nothing else but the expert's notions of science. Kotze & Kotze (1996) state that "the poor people appear incompetent and ignorant, and nobody dares to challenge the superior scientifically acquired knowledge." The appropriateness of the approaches and the methodology applied by the experts remain unquestionable. "Data, knowledge and insight that could be obtained from the poor, the illiterate and the far-off, are often ignored by the experts. It is precisely those who have learnt to survive with virtually nothing at their disposal who possess valuable knowledge. Indigenous networks of production, barter and mutual support, which evolved over centuries and could form the basis for development are sometimes destroyed by plans for commercial production" warn Kotze & Kotze (1996).

3.2 Literature review

3.2.1 Participatory approach to small-scale irrigation development

Planning of small-scale irrigation schemes by experts without consulting the target group that will carry out the farming has been going on in many developing parts of the world. In the quest to substantiate the causes of failure in development programmes, researchers evaluated irrigation techniques by small-scale farmers in different parts of the world and found that it was absolutely essential to approach small-scale irrigation planning by participatory analysis of irrigation farmers experiences and constraints, as they already know their local conditions (physical resources, infrastructure, and socio-economics) better than outside experts (Underhill, 1993; Carter, 1993; de Lange, 1994; Turner, 1994). Gessesse (1990) in Kloos (1991) reported that one of the causes of failure in small-scale irrigation programmes in Ethiopia was the failure to consult peasants in the project planning phase which meant that designs were based on the perspectives of the engineer completely ignoring the existence of the peasants. In fact, there has been increasing criticism against the top-down approach, which has failed to generate necessary community participation, self-reliance and local decision-making in Ethiopia and elsewhere in Africa (Kloos, 1991).

Development experts may possibly be misled by the scale and apparent simplicity of small-scale irrigation into thinking that a thorough knowledge of existing farming practices, markets, support services, soils and water are unnecessary. On the contrary, small-scale irrigation is complex, and its development requires detailed consideration of the many factors determining success or failure. Carter (1993) and Turner (1994) have stated that development of new irrigation system in an area should start with a study of the existing water management practices and the nature of the constraints acting upon the given practices. It is only when this path is followed that proposed changes will address identifiable and not imagined needs.

It is for the reasons stated above that it was decided that for this study to produce viable strategies for the future for sustainable small-scale irrigation farming and to address its specific problems in the Free State Province, a survey of existing circumstances had to be conducted.

3.3 Rationale and specific objectives

The mission of the Free State Department of Agriculture (FSDA) is to create a better life for the people through self-reliance and utilisation of agriculture and other resources within a sustainable system. The FSDA intends to settle more than 3000 farmers, of whom many will be small-scale farmers in the Free State Province over the next five years. Before April 1994, the FSDA had 1500 clients and by December 1996 it had 300 000 - an increase of 1900 percent in less than three years. Most of these clients live in and around townships. The FSDA aims to serve 80 000 households by March 1999. It is envisaged that this will improve the lives of some 400 000 people (Agriculture, December 1996). In South Africa it is estimated that 450 000 to 750 000 small production units could be classified under the global category of "small-scale agriculture sector" (Land reform and rural development research proposal, 1995).

Extreme rainfall variability limits the possibility of rainfed production for small-scale crop farming in Free State Province. Irrigation farming is one of the solutions to the problem of rainfall uncertainity. Furthermore, optimal utilisation of irrigation water will make more water available for human and industrial consumption. The Director-General of the United Nations Food and Agriculture Organisation (FAO), Dr. Jacques Diouf, addressing the 20th FAO Regional Conference for Africa today in Addis Ababa Ethiopia, on the 19th February 1998, called for an increase in irrigated agriculture throughout the African continent, which continues to be plagued by serious food deficiencies. "There can be no food security in Africa without the controlled utilisation and conservation of water resources and without intensifying production systems," Dr. Diouf said. "Irrigation is an important element of security in the face of widely fluctuating rainfall. It is also an ingredient of intensification considering that irrigated land is twice as productive as rainfed land." (FAO Press release, 1998)

The investigation in this thesis is intended to meet economic and social aspirations of emerging farmers while following the recommended procedure for successful development and sustainability of small-scale irrigation farming (Kloos, 1991; Underhill, 1993; Carter, 1993; de Lange, 1994; Turner, 1994). It will contribute to the Reconstruction and Development Programme (RDP) as well as striving towards the sustainable utilisation of natural resources and promoting rural prosperity. It is intended that the results will be made known to small-scale irrigation farmers, agricultural extension officers and community leaders. The needs of the community form the basis of the investigation and Participatory Rural Appraisal (PRA) as explained in depth in Appendix ii will be undertaken and thereafter verified by agronomic and agrometeorological experimentation.

Carter (1993) points out that one of the major problems with the introduction of new irrigation systems, whether large or small in scale, has been a lack of understanding by the agencies involved of the context (physical, social, and economic) into which the new irrigation practices are being introduced. Misled by the apparent simplicity of the technologies involved, development agencies often introduce such systems with inadequate prior understanding of either the farmer and farming system, on the one hand, or the land, crop water-use and cropping on the other. Carter (1993) and Turner (1994) found that ignorance of existing farming systems, marketing constraints, labour limitations, soil properties, and water resources, are just some of the aspects which can lead to the implementation of irrigation systems by outside agencies of which fail to 'fit' the circumstances.

In most cases development programmes fail to invest the necessary time and resources required to research fully the context into which they are introducing irrigation technologies (Carter, 1993). In South Africa, one of the problems independent small-scale farmers are confronted with is lack of support services especially the lack of specialised irrigation extension officers who should be advising regarding cropping aspects as well as engineering aspects (de Lange, 1994).

The specific objectives of the survey were:

(i) To undertake a survey of production practices and strategies at existing small-scale farming irrigation schemes in the Free State Province, applying a participatory rural appraisal (PRA) approach.

(ii) To undertake social surveys simultaneously at these sites in order to determine expectations and aspirations of small-scale irrigation farmers.

3.4 Results and Discussion

Focus group interviews were conducted between October and November 1996 with nine small-scale irrigation farming groups participating (Table 2.1). The respondents interviewed were all black small-scale farmers except in Brentpark (Kroonstad) were one focus group of coloured farmers was interviewed. The activities of the existing small-scale farmers revealed that the majority of them practice irrigation farming on communal land. Community gardening provides them with the opportunity to develop a full range of entrepreneurial and farming skills on a small-scale, as they have autonomy in decision-making on cultivation and marketing, but still have to co-operate in an organisational structure regarding shared water supply, infrastructure and equipment. This type of farming also provides the unemployed with the opportunity of improving their standard of life.

It was found that small-scale farmers grew a variety of crops, and desired to grow other crops but were unable to do so due to lack of resources (mainly financial and land resources). The variety of crops grown included: maize (*Zea mays*), wheat (*Triticum aestivum*) variety karee, dry beans (*Phaseolus vulgaris*), lucerne (*Medicago sativa*), onions (*Alium cepa*), tomatoes (*Lycopersicon esculentum)*, carrots, potatoes (*Solanum tuberosum*), cabbage (*Brassica oleracea)*, and sorghum (*Sorghum bicolor*). These crops were similar to those grown in other provinces of the Republic of South Africa (Bembridge, 1997). Crops that they would like to grow were sunflower (*Helianthus annus*) and groundnuts (*Arachis hypogaea*). The small-scale farmers were found to practise both mono-cropping and inter-cropping. A wide variety of production practices were implemented and this was attributed to uncertainty regarding the best spacings. Inter-row spacings of maize ranged from 90 cm with an intra-row spacing of 30 cm down to 70 and 25 cm respectively. The problem of the lack of knowledge with regard to plant spacings was common to all farming communities. All extension officers except those in Thaba Nchu did not have manuals to guide the farmers on production practices of the various crops.

Despite the socialisation process aimed at removing gender inequalities both within the household and within the community and which is supported by customary behaviour and attitudes, women did not take leading roles in decision making meetings although they made up more than 70% of the small-scale farmers as was observed in the focus groups (Table 3.5). High unemployment rates of women, may possibly contribute towards this high percentage of female small-scale farmers. Without exception, these women (as well as the majority of male small-scale farmers) fall into the category of people with access to small pieces of land (seldom bigger than 0.1 ha) that they can use for subsistance farming. In food plots and community garden schemes, Bembridge (1997) found that 90% of the participants were women. This was attributed to the size of land as it was found that land allocations of 10 ha or more had 77-95% men participation and allocations of 1 ha or less had 72-85% women participation. Similar size of land of 0.1 ha have been found to be allocated to small-scale irrigation farmers in Zimbabwe (Pearce, 1993). In addition to small pieces of land, soils which have been used for long periods of time, in the case of Mangaung for up-to 35 years had lost fertility. Soil acidity was another problem highlighted by the farmers. The farmers identified soil acidity by the presence of a small plant called *Bodila* (local name) which is believed grows only in acidic soils.

The research found that problems exist regarding water availability and extension services to advise small-scale farmers regarding methods of irrigating crops, and the amounts of water to apply. Water availability is a problem not in the Free State Province alone but other provinces as well. A survey in the North-West Province of 125 communal gardens with an average of 0.5 ha and with over 2000 participants, revealed that approximately 50% of the gardens had water availability constraints (Bembridge, 1997).

With a poor resource base coupled with lack of market incentives due to low crop prices, lack of co-ordination in production among small-scale farmers, and lack of market information resulting in oversupply or under supply of perishable vegetables with corresponding price fluctuations, small-scale irrigation farmers realise that farming will not produce all the income that the household needs. Low income from irrigation has also been reported by Bembridge (1997) from other provinces besides the Free State. Lack of storage and transport facilities exacerbates this situation. They are, at best, prepared to engage in farming on a part-time or sideline basis, still hoping for some alternative doors for them to open. In fact, in Asia, Ambler, in Turner (1994), describes how farmers abandoned irrigation farming when alternative occupations proved more profitable. Turner (1994) states that for small-scale farmers, irrigation is only one part of their livelihood and the time and effort they are willing to invest in it depends on the other options available to them. Except for one woman, who preserved some of her crops for future consumption, all the women small-scale farmers did not, and indicated that there was not enough yield for preserving or even to be sold.

With regard to labour, all (100%) small-scale farmers made use of human labour as no mechanical implements were available, and when available, they were either not in a working condition (as was the case at Kopanang), or there was no one to operate them (as was the case at Tshiame), or the implements were not fully equipped (as was the case at Maokeng). It was reported in *Agriculture* (December 1996) that "Officials from Kroonstad and Glen were supporting small-scale farmer groups from these communities (Maokeng and Brentpark) in developing dairy farms, including infrastructure on available commonages. A tractor provided through the Presidential Lead Project (PLP) has been used for the production of fourteen hectares". However, at a focus group held on the 19th of November 1996 at Maokeng, the farmers did not appreciate the provision of equipment as no implements and funds to run the tractor were provided. Many farmers (90%) were disillusioned as the assistance was not coming in the way they thought it would. Bassis *et al.* (1991) states that more than 100 years ago (1856) the French social thinker Alexis de Tocqueville wrote "Evils which are patiently endured when they seem inevitable become intolerable once the idea of escape from them is suggested". The modern term for this phenomenon is *rising expectations*. James Davis (in Bassis *et al.* 1991) has argued that severe poverty and extreme powerlessness lead to apathy and hopelessness. People who expect little in life and who are preoccupied with the daily struggle for existance are unlikely to take to the streets in protest, however if their economic and political situations improve, their expectations rise. They soon begin to believe that a better life is not only possible but lies just around the corner. When these hopes fail to materialise, they become angry and frustrated. The gap between what they expect and what they have now seems intolerable. Although they may be better-off than they were in the past, in relation to what they anticipated, their situation has deteriorated. This is, in fact, what was reported by small-scale farmers (90%) in the research. Focus groups (100%) revealed that they were expecting an improvement in their socio-economic position after the 1994 election, and that the situation showed great promise - at least that life would be more than a preoccupation with the daily struggle for existence. Only 2% of the small-scale farmers became well-off farmers who's expected need satisfaction met with their actual need satisfaction. For the rest of the farmers (98%) it seems as if the gap between what they wanted and what they got became intolerable. The focus group in Kroonstad accused government of only giving them promises upon promises. In Kroonstad, focus group participants claimed that each farmer in the area was promised 200 ha of land. It was only later that they found out that the "promised land" was to be "given" to ten cattle farmers collectively for escape. At the moment there are already ten farmers with seventy cattle, and according to them "...too many people on one farm".

Regarding their future as small-scale farmers and their aspirations as young farmers, "The Community Young Farmers Co-operative" at Makwane agreed upon five prerequisites for becoming successful small-scale farmers - and that these were:

(i) capital

(ii) knowledge/skills

(iii) need to be well organised

(iv) co-operation amongst themselves and all relevant stakeholders, and

(v) the will to develop.

Of all these, only the organisation i.e. the Community Young Farmers Co-operative and the will to develop had materialised.

Community participation is important in small-scale irrigation development. Kloos (1991) showed that irrigation scheme operations were unsuccessful due to unsatisfactory community participation. In addition, Bembridge (1997) reported that major constraints throughout most of the small-scale farmer irrigation projects in South Africa were as a result of lack of strong organisation and leadership. From a discussion with the Community Young Farmers Co-operative it became clear that:

(i) they had not decided to turn to farming voluntarily, but because they had no other option due to lack of job opportunities,

(ii) despite this "drawback", they were highly motivated to make a success of their enterprise (as was the case with other focus groups),

(iii) they did not have the basic essential knowledge or skills to farm,

(iv) they had neither capital nor access to credit,

(v) they have extension support in agronomic aspects but not irrigation engineering, but due to lack of capital and other resources, the advice, suggestions and recommendations could not always be implemented,

(vi) they faced unstable markets and prices, and

(vii) their "poor" situation was not because of laziness or carelessness, but rather due to externally imposed constraints in terms of resources and technological base.

They concluded by saying that they were not yet farmers because they did not know and have not been taught how to farm. Problems identified by cattle and poultry farmers corresponded with all the above mentioned. In addition, this sector encounter problems with the high risk of diseases spreading from one animal to another, lack of vaccine and other medicines as well as the service of a veterinary surgeon, transportation of their cattle and cattle-theft. They require knowledge regarding stockbreeding, trade in livestock and how to participate at a stock-fair.

3.5 Conclusion

The findings outlined above show that future interventions aimed at alleviating poverty, improving the quality of life, ensuring sustainability, improving equity and reducing economic vulnerability of small-scale irrigation farmers should take into account a number of different factors. These include the following:

i Small-scale irrigation farming is a means of improving crop yields, extending the growing season and improving human nutrition, because it can improve the living standards of the rural communities.

ii Participatory approaches are needed in guiding small-scale irrigation farming as they provide farmers the type of assistance they require and at the same time allow them to maintain full authority over land and water management and management decisions.

iii Government should endeavour to promote rural social infrastructure and provide suitable credit facilities, relevant extension, information services and legal support.

iv Special attention is required to deal with acidic and poor soils which pose problems to small-scale irrigation farmers with limited financial resources.

v Traditional practices should be supplemented and encouraged rather than replaced. On the global scale there is increasing awareness of the potential for developing small-scale, low-technology irrigation systems which use the skills and energy of the local communities. Recent development literature is replete with calls for 'development from below', village-based development projects and the need to understand what has been referred to as 'indigenous technical knowledge'.

vi Market incentives should be provided through co-ordination of farmers, access to market information and storage and transport facilities to avoid oversupply or under supply of perishable vegetables and fruit during the harvest and off-season periods.

vii Small-scale farmers are able to organise themselves and willing to play a role in irrigation development and manage irrigation systems in the long term providing government renders technical support and training in areas identified by the farmers themselves.

Participatory rural appraisal was successfully conducted in nine small-scale irrigation farming schemes (Table 2.1) during this research. The small-scale farmers were allowed to dominate and express themselves as they possessed the information required. The research generated a lot of information with respect to understanding and awareness of the problems of small-scale irrigation farmers from the focus groups. The research reports on what the farmers have in terms of land and other resources, what kind of assistance they need in terms of financial resources and what technical assistance they need (extension and training). One problem identified in the survey common to the farming communities was the lack of knowledge with regard to plant spacings and water application to maximise resource use. This work will address this problem through field experimentation and the findings of the research will be transferred to the farming communities involved in the survey and others.

CHAPTER 4

WATER USE EFFICIENCY BY MONO AND INTER-CROPPING SYSTEMS

4.1 Introduction

In areas where land and/or water are limiting, inter-cropping is sometimes used in an attempt to increase or stabilise crop production. Increasing evidence that substantial yield advantage can be achieved from inter-cropping compared to mono-cropping has been provided by research in the recent years (May, 1982; Watiki, *et al.*, 1993; Mukhala *et al.*, 1998). In most cases the advantage has been attributed to the fact that different crops can 'complement' each other and make better total use of the resources when growing together rather than separately (Beets, 1982). In South Africa, the few number of reports available attest to the fact that very little research has been conducted on small-scale farming with respect to inter-cropping (Austin & Marais, 1987; Ayisi & Poswell, 1997; Liphazi *et al.*, 1997). Currently a great demand for water for industry, agriculture and household use exists. The South African Government is attempting to improve the life of rural communities and increase food security by supporting research into small-scale farming. This work was conducted to ascertain ways of maximising the available water resources through inter-cropping as inter-cropping is a common practice in the country and offers potential for improving water use efficiency (Reddy & Willey, 1981).

Definitions

Inter-crop maize - implies maize alone from an inter-cropping practice

Inter-crop beans - implies beans alone from an inter-cropping practice

Inter-crop maize/beans - implies maize + beans from an inter-cropping practice

Mono-crop maize - implies maize from a mono-cropping practice

Mono-crop beans - implies beans from a mono-cropping practice

Water use - the total amount of water used by a crop up to time of maturity

Cumulative water use - the total amount of water with time used by a crop up to time of maturity

Water use efficiency - total dry matter produced by plants per unit of water used

4.2 Literature review

4.2.1 Yield and water-use efficiency

Productivity of crops depends upon phase differences in periods of peak demand for natural resources by component crops. Snaydon & Harris (1981) in Morris *et al.* (1990) stated that inter-cropped species which compete for the same limiting factor, but at partially different times, or from partially different soil zones utilise the factor more efficiently than it would by a mono-crop of either component species. Studies by Enyi (1973) showed that maize inter-cropped with either beans or cowpeas had lower yield than maize inter-cropped with pigeon pea. The cause of the low yields was probably because the high rates of nutrient absorption by the two legumes coincided with uptake by the maize crop, while the greatest nutrient demand by pigeon pea occurred after the maize had been harvested. In a maize/pigeon pea inter-crop, Sivakumar & Virmani (1980) found that mono-crop pigeon pea produced a higher yield than inter-cropped pigeon pea (1833 kg ha^{-1} and 1520 kg ha^{-1} respectively). Haizel (1974) reported that periods of peak demand for nutrients and light occurred 56 days after planting for maize and from 56 to 120 days after planting for cowpea. In a pearl millet/groundnut experiment at ICRISAT in India, Reddy & Willey (1981) found that mono-crop millet and mono-crop groundnut over their full growing periods had a total water use of 303 mm and 368 mm respectively, while the millet/groundnut inter-crop had a total water use of 406 mm. In this case total water use was greater in inter-crops than in mono-crops.

Land for agricultural production has been a serious political issue in South Africa since the new dispensation just as it has been in Zimbabwe. South Africa is poorly endowed agricultural speaking with only 13% of the surface area being arable, of this 13% an area of only 1 million hectares is irrigable. Furthermore, high potential arable land comprises only 22% of the total arable land (Erasmus, 1995). Researchers have shown that more land is required for mono-cropping than inter-cropping to produce the same yield per unit area. Such conclusions are based upon the use of Land Equivalent Ratios (LER) (Pilbeam *et al.,* 1994; Liphadzi *et al.,* 1997; Ayisi & Poswall, 1997). Reddy and Willey (1981) also reported that land equivalent ratio (LER) for inter-cropping gave 28% more total dry matter and 26% more reproductive seed yield than growing the two crops separately. In a sorghum/cowpea inter-crop, Shackel & Hall (1984) measured xylem pressure potential and osmotic potential throughout the growing season. It was found that sorghum and cowpea exhibited contrasting levels of dehydration avoidance when grown as mono-crops, but inter-cropping did not cause any substantial change in the water relations of either species. The total quantities and patterns of soil water depletion were similar for both species as mono-crops and as inter-crops. For the same crop combination as Shackel & Hall (1984), Morris *et al.* (1990) found similar results. In a pearl millet/groundnut inter-crop, Reddy & Willey (1981) found that total water use was higher in inter-cropping than in mono-cropping, but total water use efficiency was better as a greater proportion of the water was used to produce dry matter and seed yield and less lost as evaporation from the soil surface.

Weather has been known to affect the water use efficiency in crops. In an experiment on rainfed castor beans (*Ricinus communis* L.) sown on different dates, Vijaya Kumar *et al.* (1996) found that water use efficiency was significantly affected by saturation vapour pressure deficit, temperature and wind speed. Vijaya Kumar *et al.* (1996) further reported that water use efficiency showed inverse relationships with saturation vapour pressure deficit and temperature and a direct relation with wind velocity. In a 4 year study the variations in water use efficiency of castor beans (*Ricinus communis* L.) ranged from 0.72-1.25 g litre^{-1} of water.

4.3 Rationale and specific objectives

Development of agriculture and production potential of the rural communities is a prerequisite for food security in South Africa. As indicated in chapter three, a survey was conducted in the Free State Province to ascertain the economic and social aspirations of small-scale irrigation farmers. Some of the recommendations of the survey were that:

(i) research is needed to extract the best production system from existing farming systems and social conditions, and new technologies to increase water availability, improve application effectiveness, water use and water use efficiency,

(ii) it is essential to monitor water use, changes in land use and the effects of both on water availability and soil degradation, and to develop policies to prevent overuse,

(iii) traditional practices should be supplemented and encouraged rather than replaced, and it must be recognised that for many small-scale farmers irrigation farming is only part of their livelihood and they can only make it a full-time preoccupation if the benefits in terms of income improve tremendously.

Information on yield and water use efficiencies of crop mixtures is needed to develop appropriate packages of agronomic practices that will address the recommendations of the survey. The Null Hypotheses will be stated as follows that::

(i) Plant density affects yield in inter-cropping and mono-cropping production systems
(ii) Mono-cropping systems outyield inter-cropping production systems
(iii) Water use efficiency is better in mono-cropping than in inter-cropping systems
(iv) Full irrigation increases yield in inter-cropping production systems

Therefore, the objectives of this study were:

(i) To compare yields at different plant densities in inter-cropping and mono-cropping production systems,
(ii) To compare yields in inter-cropping and mono-cropping production systems,
(iii) To compare water use and water use efficiency in inter-cropping and mono-cropping production system combinations by measuring root zone soil water content throughout the growing season using a neutron probe and
(iv) To compare the effect of three levels of irrigation application on the yield of inter-cropping production systems.

4.4 Results and discussion

4.4.1. Seed yield of maize and beans

Experiment 1

In both mono-cropping and inter-cropping systems of Experiment 1, maize seed yield was found to increase as the maize plant density increased from the low (2.2 plants m^{-2}) to the high (6.7 plants m^{-2}) plant density (Figure 4.1, Table 4.1 & Appendix ix). Inter-cropping system reduced seed yield of maize by 8% at medium and 13% at high density, and statistically significant reductions of 24% were observed at low maize density. The reduction in the maize seed yield could be attributed to competition by the bean plants for nutrients and water. The peak demand of the nutrients by the bean plants coincided with the maize plant s as reported in Enyi (1973).

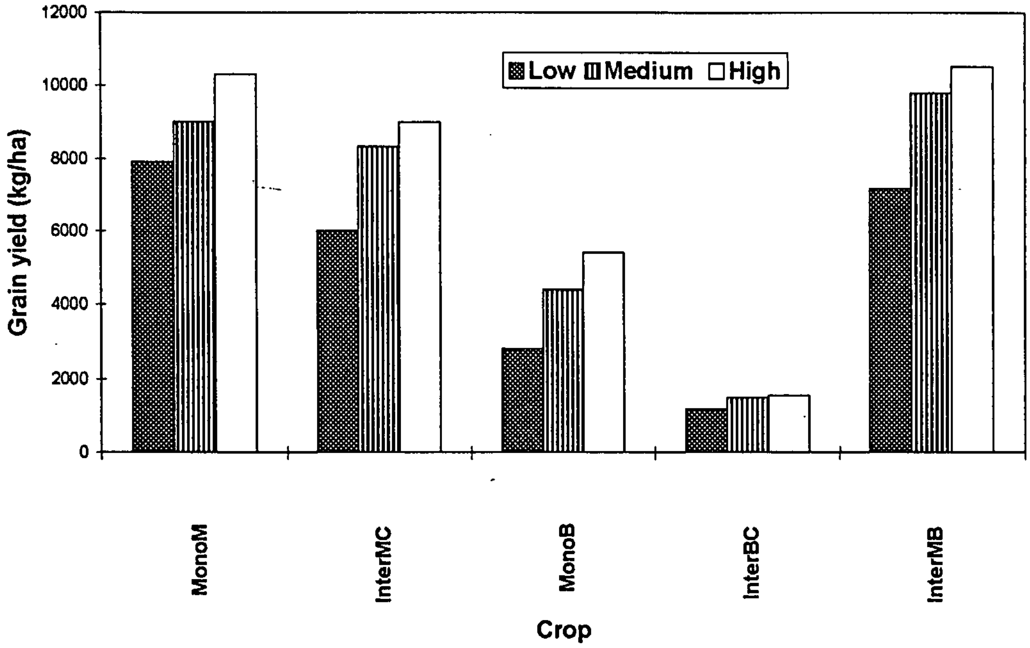


Figure 4.1 Comparison of mono-crop and inter-crop seed yield of maize and beans for 1996/1997 growing season, where MonoM = Mono-crop maize, MonoB = Mono-crop Beans, InterMC = Inter-crop maize component, InterBC = Inter-crop beans component and InterMB = Inter-crop of Maize/Beans (see Appendix i).

As was observed with maize seed yield in both mono-cropping and inter-cropping systems, bean seed yield also increased with increase in plant density from low to high (Figure 4.1, Table 4.1 & Appendix x). Inter-cropping was again observed to reduce the yield of beans critically by 59%, 66% and 72% at low, medium and high plant density respectively (Figure 4.1, Table 4.1 & Appendix x). The reduction in inter-cropped bean yields was due to reduced photosynthesis caused by reduced radiation resulting in increased mesophyll and stomata resistance to CO_2 diffusion as reported in Crookston *et al.* (1975). It was observed that inter-cropping (maize/beans) yielded higher than mono-crop maize and mono-crop beans (Figure 4.1 & Table 4.1). Reductions in bean yields in inter-cropping were due to insufficient utilisation of solar radiation for dry matter production, and in this regard Wahua *et al.* (1981) reported that in order to improve solar radiation availability in cowpea, maize cultivars with erect leaves should be used. The reduction in the bean seed yield could also be attributed to competition by the maize plants for nutrients and water. Enyi (1973) reported that in an inter-crop of beans and maize, the peak demand of nutrients by the bean plants coincided with the maize plants. The findings of Ntare (1989) in Watiki *et al.* (1993) concluded that as maize plants became increasingly taller than cowpea plants, radiation became less available to cowpea suggesting that reduced radiation was the cause of reduced yield. Findings of Crookston *et al.* (1975) reinforced the theory that low seed yields obtained in inter-cropped beans was due to reduced photosynthesis and transpiration because of low light.

Table 4.1 Comparison of mono-crop and inter-crop seed yield of maize and beans at three plant densities under full irrigation for 1996/1997 growing season.

	Mono-crop yield (kg/ha)			Inter-crop yield (kg/ha)		
Maize	Low	Medium	High	Low	Medium	High
Rep 1	7710	8372	10295	5991	8236	8770
Rep 2	7975	9551	9943	5609	8313	8950
Rep 3	8000	9106	10691	6401	8381	9250
Mean	7895	9010	10310	6000	8310	8990
Beans	Low	Medium	High	Low	Medium	High
Rep 1	2675	4200	5300	1100	1442	1495
Rep 2	2930	4570	5470	1225	1480	1570
Rep 3	2810	4430	5400	1125	1517	1525
Mean	2805	4400	5390	1150	1480	1530

Experiment 2

Experiment 2 had only inter-cropping plots (maize/beans) which were a replication of the inter-cropping practice in Experiment 1 which showed that inter-cropping (maize/beans) out yielded mono-cropping (Figure 4.2 & Table 4.2). The only difference in Experiment 2 was the application of water, where block I and III (split plot design) were under supplementary irrigation while block II was under full irrigation. The average seed yields of maize in Experiment 2 (4838 kg ha^{-1}) were much lower than the average yields (7685 kg ha^{-1}) in Experiment 1 and the reason for this was that the crop was harvested almost 3 weeks earlier than the crop in Experiment 1 due to uncontrollable theft of cobs at the experimental site. Similar responses to density were observed as in Experiment 1. Inter-crop maize seed yield was observed to increase as the plant density increased from 2.2 (low) to 6.7 (high) plants m^{-2} (Figure 4.2, Table 4.2 & Appendix xi). Statistical analysis showed statistically significant differences in seed yield with respect to density at 1% level. Seed yield from the three irrigation levels (I ,II & III) statistically significantly different.

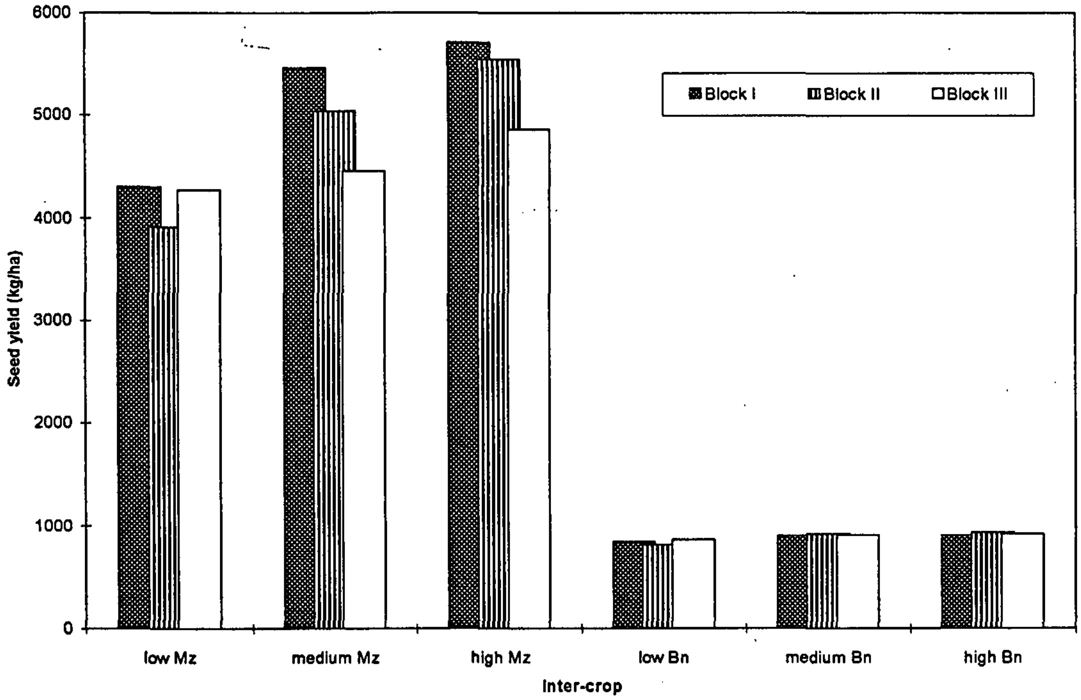


Figure 4.2 Comparison of inter-crop maize/beans seed yield for three plant densities (low, medium and high) under supplementary (Block I & III) and full irrigation (Block II) for 1997/1998 growing season.

Despite block II having received more water (full irrigation) than blocks I and III (supplementary), it was not related to the amount of seed yield obtained (Table 4.2 & Appendix xi). However, there was a relatively short period (30 to 35 DAP) of water logging in the low density full irrigation which took place when the crop was about 0.5m high which could have leached fertiliser nutrients thereby contributing towards the low yields obtained (Table 4.2 & Appendix xi).

.i 48 738 49

Table 4.2 Comparison of inter-crop seed yield of maize for three plant densities under supplementary and full irrigation for 1997/1998 growing season.

Irrigation	Inter-crop maize seed yield (kg/ha)			Yield (kg/ha)
(Block)	Low density	Medium density	High density	Mean
Supp. (I)	4298	5458	5708	5155 a
Full (II)	3914	5045	5543	4834 a
Supp. (III)	4264	4453	4856	4524 a
Mean	4159 b	4986 a	5369 a	4838

Supp. = Supplementary. Means with the same letter are not significantly different at 5% level by Tukey's Studentized Range (HSD) Test.

Analysis of variance showed that the interaction of density by irrigation was not significant at 5% level implying that the irrigation levels applied did not affect the seed yield. There was no significant difference between maize and bean yield under full and supplementary irrigation (Table 4.2 & Table 4.3). However, statistical analysis for maize yield with respect to density showed significant differences at 1% level indicating that there were yield differences between the three plant densities. Low plant density inter-crop maize yielded lower than medium and high density. However, there were no statistically significant differences in bean yields between low, medium and high plant density (Table 4.3).

Table 4.3 Comparison of inter-crop seed yield of beans for three plant densities under supplementary and full irrigation for 1997/1998 growing season.

Irrigation	Inter-crop beans seed yield (kg/ha)			
(Block)	Low density	Medium density	High density	Mean
Supp. (I)	844	894	901	880 a
Full (II)	813	923	931	889 a
Supp. (III)	858	901	917	892 a
Mean	838 b	906 a	916 a	

Supp. = Supplementary. Means with the same letter are not significantly different at 1% level by Tukey's Studentized Range (HSD) Test.

4.4.2 Land equivalent ratio

Land equivalent ratio (LER) a concept proposed by Willey and Osiru (1972), was used to evaluate the success of inter-cropping. The land equivalent ratio (LER) as defined in Chapter 2 Section 2.2.7.1 was calculated using mean seed yields of mono-crops of maize and beans. The total LER was lowest in the high maize plant density due to partial LER of beans being low as a result of reduced solar radiation for biomass production. (Table 4.4). With increase in maize plant density, there was an increase in partial LER up to the medium density and a decreased again but with beans there was a consistent decrease in partial LER.

Table 4.4 Total land equivalent ratio (LER) and partial LER of maize and beans grown under three maize plant densities.

Maize Density		Maize	Beans
(plants m^{-2})	Total LER	Partial LER	Partial LER
2.2	1.17	0.76	0.41
4.4	1.26	0.92	0.34
6.7	1.15	0.87	0.28

The findings show that there was an advantage of inter-cropping of LER of 1.26 at medium density over the 1.17 and 1.15 obtained at low and high plant densities for maize. The medium density total LER of well over unity (1.26) suggests a much greater advantage for inter-cropping at this plant density. In effect it indicates that 26% more land would be needed by a mono-cropping to produce the same yield as an inter-cropping system (Table 4.4).

4.4.3 Water use in inter-crop and mono-crops

Experiment 1

Water use of mono-crop and inter-crop maize and beans were measured by solving for ET in the water balance equation as explained in Section 2.2.6.1 of Chapter 2. According to the results in Table 4.5, there were no significant differences in the cumulative water use at three plant densities for the maize/beans inter-crop, maize mono-crop and beans mono-crop, indicating that plant density did not influence the cumulative water use. From the mean values, it is also clear that the water use of the maize/beans inter-crop (706 mm) was in the same order as the mono-crop maize (718 mm). On the contrary, the beans mono-crop used significantly less water than the maize/beans inter-crop and the maize mono-crop to reach maturity.

Water use up to the time of maize harvest in low, medium and high plant densities in mono-crops maize was 710.0, 751.0 and 694.0 mm respectively (Table 4.6, Figure 4.7 & Appendix x ii & xiii). While water use up to the time of harvest in low, medium and high plant densities in mono-crop beans was 513.0, 565.0 and 491.0 mm respectively (Table 4.6, Figure 4.7 & Appendix xii & xiii). It was observed, however, that there were remarkable differences in water use between mono-crop maize and mono-crop beans at low, medium and high plant densities of 196.5, 185.8 and 202.8 mm respectively (Table 4.6 & Figure 4.7). These differences were statistically significant at 1% level implying that there are differences in water use in mono-crop maize and mono-crop beans (Figure 4.6 & Appendix xiii).

Table 4.5 Mean measured cumulative water use in mono-crop maize and mono-crop beans and inter-crop maize/beans for 1996/1997 growing season.

	Mean Water use (mm)		
	Inter-crop	Mono-crop	
Crop/	141 days after planting		101 days after planting
Density	Maize/Beans	Maize	Beans
Low	705	710	513
Medium	730	751	565
High	684	694	491
Mean	706 **a**	718 **a**	523 **b**

Means with the same letter are not significantly different at 5% level by Tukey's Studentized Range (HSD) Test.

However, measurements were taken to observe the cumulative water use among inter-crop beans and inter-crop maize until bean crop harvest (see definitions). Interesting observations came out as in most cases (Table 4.6) inter-crop beans and inter-crop maize had slightly higher water use than mono-crops. This was because maize roots in the case of inter-crop beans were also taking up water and bean roots were taking up water in the case of maize. This would require further work to account exactly how much water is attributed to either crop.

Table 4.6. Mean water use (mm) determined from Experiment 1 for inter-crop and mono-crop maize and beans harvested at 101 and 141 days after planting.

Density/	101 days after planting			141 days after planting		
Crop	Low	Medium	High	Low	Medium	High
Inter-crop B	526.8	543.7	510.9	-	-	-
Mono-crop B	513.0	565.2	491.2	-	-	-
Inter-crop M	545.5	576.1	540.7	695.2	714.1	669.4
Mono-crop M	553.7	582.0	530.5	709.5	751.0	694.0
Inter-crop MB	536.1	559.9	525.8	704.6	730.2	684.3

Experiment 2

The analysis of variance showed that the interaction of density by irrigation was not significant at 5% level implying that the irrigation applied (supplementary and full) did not affect the water use in the three plant densities. There were no significant differences between water use in low, medium and high density. However, the analysis of variance showed that there were significant difference in water use between full and supplementary irrigation at 1% level (Table 4.7 & Appendix xiii) implying that full irrigation (block II) used up water more than supplementary irrigation (block I and III).

Table 4.7 Comparison of mean water use in three plant densities under supplementary and full irrigation for 1997/1998 growing season.

Irrigation	Seasonal water use (mm)			
(Block)	Low	Medium	High	Mean
Supp. (I)	542.5	536.4	543.3	540.7 **a**
Full (II)	629.5	644.5	641.8	638.8 **b**
Supp. (III)	528.4	537.5	553.8	539.9 **a**
Mean	566.8 **a**	572.8 **a**	579.6 **a**	

Means with the same letter are not significantly different at 1% level by Tukey's Studentized Range (HSD) Test.

4.4.4 Water use efficiencies in inter-crops and mono-crops

Experiment 1

Comparison of water use efficiencies was done with respect to production of nutrients for human consumption per hectare (as was the case in the comparison of the yield of nutrients per hectare in Chapter 6). In comparing water use efficiencies of inter-crop maize/beans and mono-crop maize, it was found that inter-crops were in most cases more efficient in producing the various nutrients per hectare per millimetre (mm) of water. It was found that there were no differences in energy produced per mm of water between mono-crop maize and inter-crop maize/beans while mono-crop beans. Statistical analysis of the means of the three densities within a cropping system showed that mono-crop beans produced more energy than mono-crop maize and inter-crop maize/beans separately (Table 4.8). Mono-crop beans were found to produce more protein than mono-crop maize and inter-crop maize/beans. Statistical analysis of the means of the three densities within a cropping system showed that mono-crop beans were more efficient in producing protein than mono-crop maize and inter-crop maize/beans (Table 4.8). High levels of production efficiency of carbohydrates were found in mono-crop maize and inter-crop maize/beans. Statistical analysis of the means of the three densities within a cropping system showed that inter-crop maize/beans and mono-crop maize produced carbohydrates more efficiently than mono-crop beans. These cropping systems were more efficient by 66% (Table 4.8). Cooked maize did not contain any vitamin C while mono-crop beans produced vitamin C more efficiently than inter-crop maize/beans by 75%. It was found that there were no differences in Vitamin E produced per mm of water between mono-crop maize and inter-crop maize/beans. Statistical analysis of the means of the three densities within a cropping system showed that inter-crop maize/beans and mono-crop maize produced vitamin E more efficiently than mono-crop beans. The production efficiency was about 64% (Table 4.8). The observed results for iron and sodium were similar to those for vitamin E. As for calcium, magnesium, phosphorus and potassium, mono-crop beans was observed to produce the named nutrients more than mono-crop maize and inter-crop maize/beans (Table 4.8). On the overall, out of all the nutrients studied, it was found that 60% production efficiency was by inter-crop maize/beans while the remaining 40% was shared between mono-crop maize and mono-crop beans. Therefore it can be concluded that inter-crops produce nutrients more efficiently than mono-crops.

Table 4.8 Full irrigation calculated water use efficiencies of mono-crop maize, mono-crop beans and inter-crop maize/beans for three plant densities for the 1996/1997 growing season using measured seasonal water use values in Table 4.5.

Nutrient	Plant density	Mono-crop Maize	Mono-crop Beans	Inter-crop Maize/Beans
Energy (MJ ha^{-1} mm^{-1})	Low	19.7	8.8	17.7
	Medium	21.3	12.6	23.5
	High	26.3	17.7	26.9
	Mean	22.5 a	13.1 b	22.7 a
Protein (g ha^{-1} mm^{-1})	Low	1117	1294	1241
	Medium	1204	1842	1621
	High	1491	2597	1848
	Mean	1271 c	1911 a	1570 b
Carbohydrate (g ha^{-1} mm^{-1})	Low	10425	2587	8751
	Medium	11240	3684	11621
	High	13918	5193	13367
	Mean	11861 a	3822 b	11246 a
Vitamin C (μg ha^{-1} mm^{-1})	Low	0.0	0.149	0.044
	Medium	0.0	0.212	0.055
	High	0.0	0.299	0.061
	Mean	0.0 c	0.220 a	0.053 b
Vitamin E (μg ha^{-1} mm^{-1})	Low	0,080	0.021	0.067
	Medium	0.086	0.030	0.089
	High	0.107	0.042	0.103
	Mean	0.091 a	0.031 b	0.086 a
Calcium (g ha^{-1} mm^{-1})	Low	1.06	10.41	3.92
	Medium	1.15	14.82	4.95
	High	1.42	20.89	5.51
	Mean	1.21 c	15.38 a	7.79 b
Iron (g ha^{-1} mm^{-1})	Low	0.11	0.37	0.19
	Medium	0.12	0.53	0.25
	High	0.14	0.75	0.28
	Mean	0.12 c	0.55 a	0.24 b
Magnesium (g ha^{-1} mm^{-1})	Low	9.57	8.78	9.95
	Medium	10.32	12.50	13.04
	High	12.78	17.61	14.89
	Mean	10.89 b	12.96 a	12.63 a
Phosphorus (g ha^{-1} mm^{-1})	Low	21.81	23.35	23.66
	Medium	23.51	33.24	30.96
	High	29.11	46.86	35.29
	Mean	24.81 c	34.49 a	29.97 b
Potassium (g ha^{-1} mm^{-1})	Low	31.91	54.73	40.76
	Medium	34.41	77.92	52.92
	High	42.61	109.84	60.06
	Mean	36.31 c	80.83 a	51.25 b
Sodium (g ha^{-1} mm^{-1})	Low	0.532	0.149	0.451
	Medium	0.573	0.212	0.599
	High	0.710	0.298	0.689
	Mean	0.605 a	0.220 b	0.580 a

Means with the same letter are not significantly different at 1% level by Tukey's Studentized Range (HSD) Test.

4.4.5 General conclusion for 1996/1997 growing season

In 60% of the cases, it was found that inter-cropping produced more nutrients per unit area than mono-crop maize and beans separately. Inter-cropping utilised water more efficiently than mono-crop maize (Table 4.8). In terms of nutrients, there were a number of occasions when mono-crop beans were found to be more efficient than inter-crop maize/beans as well as few occasions when mono-crop maize were more efficient than inter-crop maize/beans (Table 4.8).

4.4.6 Water use efficiencies of inter-crops

Experiment 2

During 1997/1998 growing season, the consequences of applying full and supplementary irrigation on water use efficiencies of inter-crop maize/beans were investigated. Mean water use efficiencies of inter-crop maize/beans in three levels of irrigation were investigated. In Table 4.2, it was reported that there were no statistically significant differences in maize seed yield. It was found that in all cases for all nutrients there were significant differences in water use efficiency (Table 4.9). The full irrigation water applied in block II did not improve the water use efficiency as far as energy was concerned and in fact it contributed to the reduction in the water use efficiency of this treatment as the seed yield was not significantly different from the supplementary irrigation blocks (Table 4.2). However, there were no differences in production efficiency of energy between full and supplementary irrigation level III. Protein production was more efficiently produced by supplementary irrigation levels I & II than full irrigation. Carbohydrates were as well produced more efficiently by supplementary irrigation levels I & II than full irrigation although there were no significant difference between full irrigation and irrigation level III (Table 4.9). Similar observations were observed for vitamin C production were vitamin C was more efficiently produced by supplementary irrigation levels I & II than full irrigation while vitamin E was produced more efficiently by supplementary irrigation than full irrigation although there were no significant difference between supplementary irrigation level III and full irrigation (Table 4.8). The same was observed for iron, magnesium and sodium production were these nutrients were more efficiently produced by supplementary irrigation levels I & II than full irrigation although there were no statistically significant difference between full irrigation treatment and supplementary irrigation level III.

As for phosphorus and potassium, it was evident that supplementary irrigation treatment produced the nutrients more efficiently that full irrigation (Table 4.8). The production efficiency between the treatments were 19% and 12% respectively.

As indicated earlier on, full irrigation treatment experienced a relatively short period of water logging (30 to 35 DAP) in the low density which took place when the crop was about 0.5m high which could have leached fertiliser nutrients thereby contributing towards the low yields obtained (Table 4.2). This could have affected the seed yield which has been reflected in the water use efficiency. If it had not been for water logging, block II could have probably yielded a higher yield than what was harvested.

4.4.7 General conclusion for 1997/1998 growing season

In the three levels of irrigation, it was found that although there were no significant differences in seed yield of beans and maize (Table 4.2 & Table 4.3) but there were significant differences in production efficiency between full irrigation and supplementary irrigation treatments in the production of nutrients per unit water. In most cases full irrigation did not improve the production of inter-cropping system with regard to quantities of nutrients (nutrients were used as a means of comparison) produced per unit area (Table 4.9). In conclusion, full irrigation did not have better water use efficiency than supplementary irrigation, instead supplementary irrigation produced the nutrients more efficiently than full irrigation.

Table 4.9 Full and supplementary irrigation (I, II & III) calculated water use efficiencies of inter-crop maize/beans for three plant densities for the 1997/1998 growing season using measured seasonal water use values in Table 4.6.

Nutrient	Plant density	Irrigation levels		
		I	II	III
Energy (MJ ha^{-1} mm^{-1})	Low	39.2	31.9	40.6
	Medium	45.0	37.0	41.8
	High	45.4	38.8	42.3
	Mean	43.2 b	35.9 a	41.5 ab
Protein (g ha^{-1} mm^{-1})	Low	1163	930	1194
	Medium	1416	1125	1228
	High	1447	1210	1272
	Mean	1342 a	1088 b	1232 a
Carbohydrate (g ha^{-1} mm^{-1})	Low	8157	6436	8330
	Medium	10322	8012	8557
	High	10628	8778	8998
	Mean	9702 a	7742 b	8628 ab
Vitamin C (μg ha^{-1} mm^{-1})	Low	0.042	0.035	0.044
	Medium	0.045	0.039	0.046
	High	0.045	0.039	0.045
	Mean	0.044 a	0.038 b	0.045 a
Vitamin E (μg ha^{-1} mm^{-1})	Low	0.063	0.049	0.064
	Medium	0.079	0.062	0.066
	High	0.082	0.067	0.069
	Mean	0.075 a	0.060 b	0.066 ab
Calcium (g ha^{-1} mm^{-1})	Low	3.72	3.05	3.86
	Medium	4.14	3.48	3.98
	High	4.16	3.59	3.99
	Mean	4.01 a	3.37 b	3.95 a
Iron (g ha^{-1} mm^{-1})	Low	0.18	0.15	0.19
	Medium	0.21	0.17	0.19
	High	0.21	0.18	0.20
	Mean	0.20 a	0.17 b	0.19 a
Magnesium (g ha^{-1} mm^{-1})	Low	9.31	7.42	9.55
	Medium	11.43	9.03	9.82
	High	11.70	9.76	10.20
	Mean	10.81 a	8.74 b	9.86 ab
Phosphorus (g ha^{-1} mm^{-1})	Low	22.2	17.7	22.8
	Medium	27.1	21.5	23.4
	High	27.7	23.1	24.3
	Mean	25.6 a	20.8 b	23.5 a
Potassium (g ha^{-1} mm^{-1})	Low	38.3	30.8	39.4
	Medium	45.9	36.8	40.5
	High	46.7	39.3	41.7
	Mean	43.6 a	35.6 b	40.6 a
Sodium (g ha^{-1} mm^{-1})	Low	0.42	0.33	0.43
	Medium	0.53	0.41	0.44
	High	0.55	0.45	0.46
	Mean	0.50 a	0.40 b	0.45 ab

Means with the same letter are not significantly different at 1% level by Tukey's Studentized Range (HSD) Test.

4.5 Conclusion

In any farming activity, the maximisation of the resources to obtain the best yield is the ultimate goal of the farmer. Maize and beans seed yield increased with increase in plant density from low to high. Inter-cropping reduced the yield of beans significantly by 59%, 66% and 72% at low, medium and high density respectively. Significant reductions in bean seed yield in inter-cropping were observed probably due to insufficient solar radiation for dry matter production as reported by Wahua *et al.* (1981). It was observed that inter-cropping (maize/beans) out yielded both mono-cropping maize and beans per unit area.

The medium plant density had an LER of 1.26 giving a greater advantage to inter-cropping. This indicated that 26% more land would be needed to produce the same yield of inter-crop (maize/bean) if mono-crops were used to produce the same seed yield. The LER in the medium density was higher than the low and high density by more than 8% suggesting that the medium plant density was the best cropping density in which to grow the crop combination.

Comparisons between mono-cropping and inter-cropping were done with respect to water use, water use efficiency and irrigation level at the end of the season. The differences between mean cumulative water use in maize/beans inter-crop and mono-crop maize were not statistically significant implying that there was no difference in water use in mono-crop maize and inter-crop maize/beans up to the time of maize harvest. Comparison of mean water use in mono-crop maize and mono-crop beans showed notable water use differences and these differences were statistically significant implying that there were differences in water use between mono-crop maize and mono-crop beans. Mono-crop maize used more water than mono-crop beans.

With regard to full and supplementary irrigation, the analysis of variance showed that there were significant difference in water use between full and supplementary irrigation at 1% level implying that full irrigation (level II) used up more water than supplementary irrigation (level I & III). The seed yields from full and supplementary irrigation were not found to be significantly different, this was in spite of the full irrigation treatment having received more water than supplementary irrigation treatments resulting in no direct relationship with the amount of yield. But on overall, supplementary irrigation treatments had better water use efficiency than full irrigation (Table 4.9).

Water use efficiencies with respect to nutrients produced per hectare (as was the case in the comparison of yield per hectare) were compared between inter-crop maize/beans with mono-crop maize and inter-crop maize/beans with mono-crop maize. In comparing water use efficiencies of inter-crop maize/beans and mono-crop maize, inter-crop maize/beans were more efficient in producing the various nutrients per hectare per millimetre (mm) of water. In comparing water use efficiencies of inter-crop maize/beans against mono-crop beans, again revealed inter-crop maize/beans produced the various nutrients per hectare per millimetre (mm) of water more efficiently than did mono-crop beans. Comparisons of water use efficiencies between mono-crop maize and mono-crop beans revealed that mono-crop beans were more efficient in producing the various nutrients.

Following the findings of Experiment 1, inter-crops were subjected to different irrigation levels in Experiment 2 to ascertain the water use efficiencies. Comparison of water use efficiencies were done for full and 2 levels of supplementary irrigation. In comparing water use efficiencies of inter-crop maize/beans under three irrigation levels, it was found that in all cases for all nutrients there were significant differences in water use efficiency with irrigation levels in the range of 348 - 435 mm plus rainfall of 380 mm. The higher amount of water applied in full irrigation (level II) did improve the water use efficiency, and in fact contributed to the lowering of the water use efficiency considering that the seed yield was not significantly different from the irrigation levels. In conclusion, full irrigation did not have better water use efficiency than supplementary irrigation, instead supplementary irrigation produced the nutrients more efficiently than full irrigation.

CHAPTER 5

RADIATION USE EFFICIENCY AND DRY MATTER PRODUCTION BY MONO AND INTER-CROPPING SYSTEMS

5.1 Introduction

Inter-cropping is the growing of two or more crop species simultaneously on the same piece of land (Willey & Osiru, 1972; Ofori & Stern, 1987). This kind of farming has been practised for centuries by small-scale farmers in tropical and subtropical countries. During all this time, maize is one crop that has been inter-cropped with a number of legumes including pigeon pea (Sivakumar & Virmani, 1980), cowpea (Wahua *et al.*, 1981; Watiki *et al.*, 1993), beans (Ayisi & Poswell, 1997; Siame *et al.*, 1997) and groundnuts (Liphazi *et al.*, 1997). There has been limited research in South Africa regarding inter-cropping as observed from existing reports. In the past, commercial farmers were able to provide all the food requirements of the country, thus justifying the lack of research into inter-cropping. In spite of all this, inter-cropping production systems are beneficial to small-scale farming communities.

Inter-cropping of maize and beans is particularly important for South Africa as a survey in the Free State Province (Mukhala & Groenewald, 1998) revealed that Inter-cropping of maize and beans was more prevalent than other crop combinations. It was therefore assumed that this is a representative practice in the country. Research has also found that in many rural communities of South Africa, maize based dishes are consumed by more than 90% of the rural black people (Rose, 1972; Richardson *et al.*, 1982; Iputo & Makunzeni, 1993). In Venda, survey findings indicated that maize porridge was consumed more than once per day by 100% of the respondents while only 10% consumed beans (Vorster *et al.*, 1994).

One of the reasons advanced by Beets (1982) for adopting multiple cropping systems was that it allowed better utilisation of atmospheric and soil environmental factors. Plants of different growth habits often have different environmental requirements. When these crops are grown together, they may intercept more radiation together while at the same time these crops may have different rooting habits that may utilise different nutrients at different times.

5.2 Literature review

5.2.1 Radiation use efficiency

Solar radiation is a major resource determining growth and yield of component crops in inter-cropping, particularly when other resources, like water and nitrogen are not severely limiting crop growth. Ntare (1989) in Watiki *et al.,* (1993) studying a maize/cowpea inter-crop found that as maize plants become increasingly taller than cowpea plants, radiation became less available to cowpea. Wahua *et al.*, (1981) working with a maize/cowpea inter-crop found that solar radiation availability to cowpea may be improved by the use of maize cultivars with erect leaves in the upper canopy. Weather parameters have also been known to affect radiation use efficiency in crops. In an experiment on rainfed castor beans (*Ricinus communis* L.) sown on different dates, Vijaya Kumar *et al.*, (1996) reported that radiation use efficiency was affected by weather parameters substantially. In a 4 year study, the variations in radiation use efficiency of rainfed castor beans (*Ricinus communis* L.) ranged from 0.79-1.19 g MJ^{-1}.

Intercepted radiation has been defined as the difference between solar radiation received at the surface of the canopy and that received by the soil surface, and therefore includes the fraction of incoming radiation reflected from the canopy. Mean total solar radiation (in the wavelength range of 0.4 - 3 μm) varies from season to season ranging from 12 MJ m^{-2} d^{-1} in cloudy upland regions to more than 24 MJ m^{-2} d^{-1} in some semi-arid regions. The best way to compare the interaction of canopies with sunlight is by using the fraction of sunlight intercepted by a canopy. This is termed fractional interception (f), which is expressed in equation 5.1:

$$f = S_i / S \qquad 5.1$$

where S is the radiation received above the canopy and S_i is the radiation transmitted through the canopy. This fraction is not affected much by the absolute value of S, making it useful for modelling dry matter production (Squire, 1990). For most canopies in no water stress conditions, fractional interception (f) may be related to the leaf area index (L) of the leaf canopy above a given level by the expression of Monteith (1970) given in equation 5.2:

$$f = 1 - \exp(-kL) \qquad 5.2$$

where k is the extinction coefficient. The value of k increases as the amount of solar radiation intercepted by a given leaf area increases. The value of k varies with waveband of incoming radiation and is expressed by f_T for total solar radiation in the wavelength 0.4 - 3 μm, or f_p for photosynthetically active radiation (PAR) in the wavelength 0.4 - 0.7 μm.

In a maize/pigeon pea inter-crop, it was reported that PAR utilisation efficiency (dry matter produced per unit of intercepted PAR) was lower for mono-crop pigeon pea than it was for inter-crops. Mono-crop maize was also less efficient than an inter-crop situation (Sivakumar & Virmani, 1980). Studies have also shown that the photosynthetic response of plants was affected by the light intensity at which it was grown (Burnside & Bohning, 1957; Moss *et al.*, 1961; Wolf & Blaster, 1972). Strong correlations also exist between the yield of a crop and its light environment (Shibles & Weber, 1965; Cooper, 1966; Earley *et al.*, 1966; Pendleton *et al.*, 1967). It is for these reasons that considerable attention has been devoted to optimising crop leaf area index and breeding plants that maximise light penetration into the lower canopy (Pearce *et al.*, 1965; Wolfong *et al.*, 1967). Crookston *et al.*, (1975) working on Bean (*Phaseolus vulgaris* L.) leaves reported that shading had been found consistently to result in thinner and smaller leaves. Crookston *et al.*, (1975) also undertook a study to determine the nature of the photosynthetic reduction of Bean (*Phaseolus vulgaris* L.) leaves grown under low light levels. They found that low light increased the inter-node length and decreased the leaf thickness. In addition, the leaf area and the number of stomata per unit area were also reduced by 49% and 36% respectively with respect to the normal light treatment.

Crookston *et al.*, (1975) also found that shading of bean plants reduced photosynthesis by 38% while transpiration was reduced by 8%. There was, however, an increase in mesophyll and stomatal resistance to diffusion of CO_2 by 98% and 48% respectively. These increases in resistance caused decreases in both photosynthesis and transpiration although the photosynthetic decrease was considerably larger than the decrease in transpiration.

5.3 Rationale and specific objectives

In any farming system, better utilisation of atmospheric and soil environmental factors are important. As explained in materials and methods (Chapter 2), Experiment 1 had mono-crop maize, mono-crop beans and inter-crop maize/beans while Experiment 2 had only inter-crop maize/beans. With regard to utilisation of natural resources, the Null Hypotheses may be stated as follows:

(i) There is no difference in the number of cobs and weight per plant with change in plant density in both mono and inter-cropping systems,

(ii) Percentage interception of PAR is not affected by leaf area index (LAI),

(iii) There is no difference in dry matter production with change in plant density in both mono and inter-cropping systems and

(iv) A mono-cropping production system utilises radiation more efficiently than an inter-cropping system.

This study was aimed at quantifying the benefits of inter-cropping in terms of yield components, efficiency of photosynthetic active radiation utilisation, and dry matter production of these production system combinations. The specific aims of this study were:

(i) To compare inter-cropping and mono-cropping practices in terms of yield components,

(ii) To observe the development of LAI in inter-cropping and mono-cropping practices,

(iii) To observe the effect of LAI on PAR interception percentage,

(iv) To compare inter-cropping and mono-cropping practices in terms of dry matter production and

(v) To compare photosynthetic active radiation utilisation efficiency of the two production system combinations.

5.4. Results and discussion

5.4.1 Inter-crop and mono-crop yield components

5.4.1.1 Number of cobs per plant

The number of cobs per plant were compared in the three inter-crop maize plant densities for (Experiment 1) the 1996/97 growing season and between inter-cropping and mono-cropping (Table 5.1). It was found that the number of cobs varied with plant densities and decreased with increase maize in plant density. The mean number of cobs were 2.03, 1.66 and 1.2 (Table 5.1) for low, medium and high plant density respectively in both mono-crop and inter-crop maize. In 1997/1998 growing season, low, medium and high density plants were observed to possess 1.8, 1.2 and 1.0 cobs per plant respectively (Table 5.2). Similar results were observed in both experiments and statistical analysis showed significant differences in cob number per plant with respect to density at 1% level (Table 5.1 and Table 5.2). The difference in number of cobs between the two experiments due to the difference in the sample size. The sample size in Experiment 1 was bigger than in Experiment 2 while the trend is evident in both experiments that a lower density will have more cobs than a higher density. However, it was also found that there were minor differences in cob number between inter-cropping and mono-cropping systems. Statistical analysis showed that these differences were not significant. Therefore, it can be concluded that there is no difference in the number of cobs between inter-cropping and mono-cropping systems at the densities under the study.

Table 5.1 Comparison of number of cobs per plant in inter-crop and mono-crop maize for three plant densities under full irrigation for 1996/1997 growing season.

	Mean number of maize cobs per plant			
Cropping system	Low density	Medium density	High density	Mean
Mono-cropping	2.04	1.73	1.25	1.7 a
Inter-cropping	2.02	1.58	1.16	1.6 a
Mean	2.03 a	1.66 b	1.20 c	

Means with the same letter are not significantly different at 1% level by Tukey's Studentized Range (HSD) Test.

Table 5.2 Comparison of cobs per plant in inter-crop maize for three plant densities under supplementary (I & III) and full irrigation (II) for 1997/1998 growing season.

Irrigation level	Mean number of cobs per plant			
	Low density	Medium density	High density	Mean
I	2.0	1.1	1.0	1.36 a
II	1.7	1.2	1.0	1.33 a
III	1.8	1.2	1.0	1.31 a
Mean	1.8 a	1.2 b	1.0 c	

Means with the same letter are not significantly different at 1% level by Tukey's Studentized Range (HSD) Test.

Statistical analysis also revealed that there were no significant differences in cob number per plant with respect to irrigation treatments at 1% level (Table 5.2).

5.4.1.2 Weight of maize cobs per plant

The weights of maize cobs per plant were also compared between inter-cropping and mono-cropping at the three plant densities for Experiment 1 (Table 5.3). It was found that the weight of cobs per plant decreased with increase in plant density. Mono-crop maize low, medium and high density plants were found to have cobs weighing 453, 236 and 182 grams per plant respectively. Inter-crop maize low, medium and high density plants were found to have cobs weighing 444, 226 and 166 grams per plant respectively. Statistical analysis showed that there were no significant differences in cob weight per plant between inter-cropping and mono-cropping systems (Table 5.3). Similar results were again obtained in Experiment 2, where the mean weight of cobs per plant for inter-crop maize were 220, 133 and 95 grams for low, medium and high plant density respectively. The reason for the differences in average cob weight per plant in the two growing seasons was that Experiment 2 was harvested 3 weeks earlier than Experiment 1, which restricted the seed filling period. However, the trend is again evident in both experiments that lower density planting results in havier cobs compared to high density planting. Statistical analysis showed that significant differences at the 1% level occurred in the weight of cobs per plant at different densities (Table 5.4).

Table 5.3 Comparison of weight of maize cobs per plant for three plant densities under full irrigation for 1996/1997 growing season.

Cropping system	Mean weight of maize cobs per plant (grams)			
	Low density	Medium density	High density	Mean
Mono-cropping	453	236	182	290 a
Inter-cropping	444	226	166	280 a
Mean	449 a	231 b	174 c	

Means with the same letter are not significantly different at 1% level by Tukey's Studentized Range (HSD) Test.

Table 5.4 Comparison of weight of inter-crop maize cobs per plant for three plant densities under supplementary and full irrigation for 1997/1998 growing season.

Irrigation levels	Mean weight of cobs per plant (grams)			
	Low density	Medium density	High density	Mean
I	228	146	101	158 a
II	207	135	98	147 a
III	226	119	86	143 a
Mean	220 a	133 b	95 c	

Means with the same letter are not significantly different at 1% level by Tukey's Studentized Range (HSD) Test.

5.4.1.3 Plant height

The progress in plant height during the growing season for the various treatments in Experiment 1 is presented in Figure 5.1 and Appendix xv for inter-crop and mono-crop maize and Figure 5.2 and Appendix xv for inter-crop and mono-crop beans. The typical sigmoidal shape was very prominent for the maize crop, starting at an average height of 50 cm at day 35 after planting and reaching a maximum average of 225 cm at 80 days after planting. This showed an average stem growth rate of 8 cm ± 2 cm d^{-1} from 47 to 53 DAP. The effect of plant density on height in both maize and beans in inter-cropping was small. It was observed that both maize and beans at high plant density were taller than maize and bean plants in low and medium density. The average growth rate for beans from 43 to 50 DAP was 1.3 cm ± 0.3 cm d^{-1}. In inter-crop, bean plants were taller than plants in mono-crops

(Figure 5.1, Figure 5.2 & Appendix xv). This agrees with Crookston *et al.*, 1975 who observed that low light increased the length of inter-nodes. As indicated earlier on, there were no yield components measurements taken during Experiment 2.

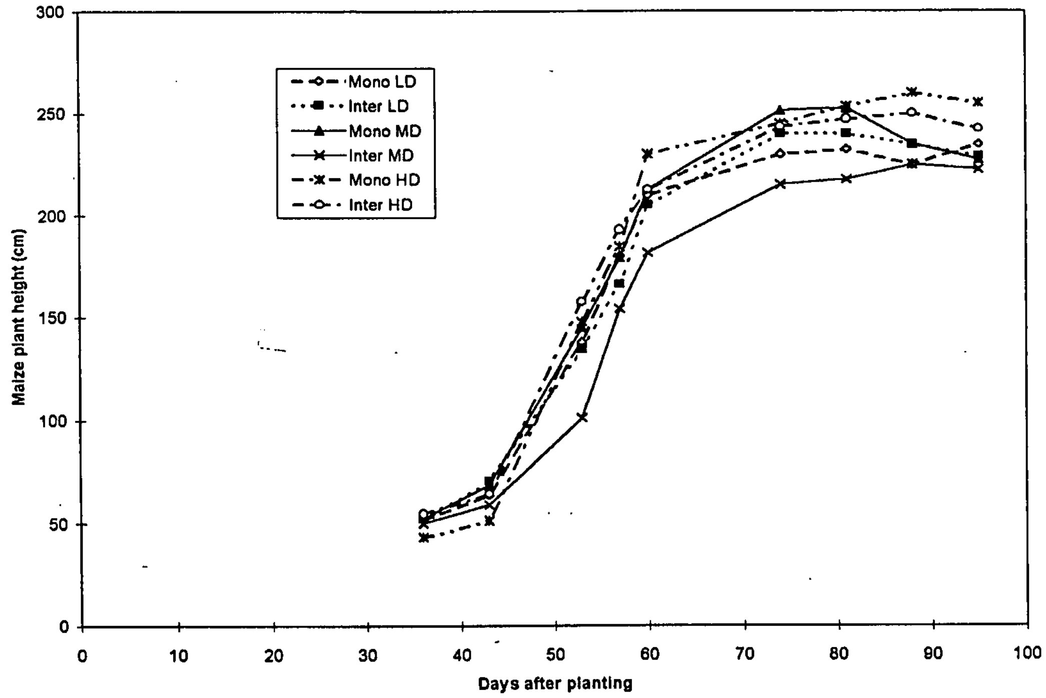


Figure 5.1 Progress in maize stem height during the 1996/1997 growing season for the various treatments, where LD represents low plant density, MD medium plant density and HD high plant density .

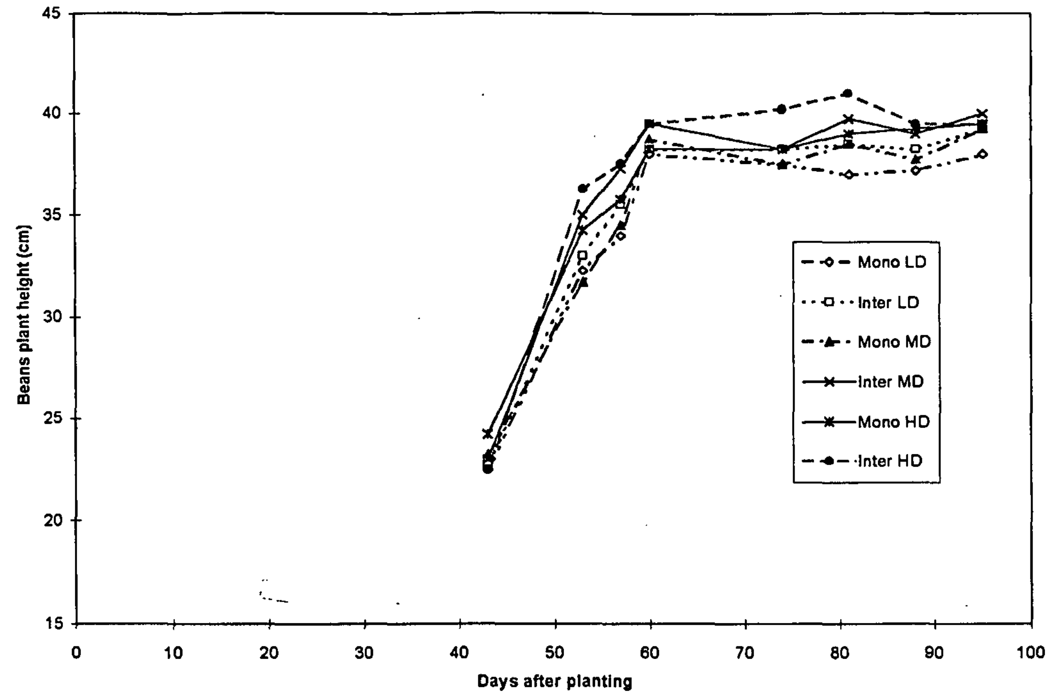


Figure 5.2 Progress in beans plant height during the 1996/1997 growing season for the various treatments, where LD represents low plant density, MD medium plant density and HD high plant density.

5.4.2 Leaf area index development

Experiment 1

Leaf area index of the maize mono-crop increased rapidly from 36 days after planting (DAP) in low, medium and high plant densities until 53 days after planting. The high density LAI continued increasing until reaching the peak of 5.3 at 74 DAP (Figure 5.3 & Appendix xvi). Medium density LAI increased slowly until reaching the peak of 5 at 81 DAP. Low density LAI increased steadily from 53 DAP to 81 DAP after which it reached its peak of 3.5. After reaching the peak leaf area index at 81 DAP, the LAI at all three plant densities started decreasing as senescence of leaves took place. In the three plant densities, the peak LAI was reached during flowering stage which was between 70 and 80 days after planting (DAP). It was observed that the density of plants had an effect on LAI because the high density plants had a higher LAI than the low density throughout the growing season (Figure 5.3 & Appendix xvi). The low leaf area index at all three plant densities at 67 days after planting was due to the cloudy sky during the time of measurement.

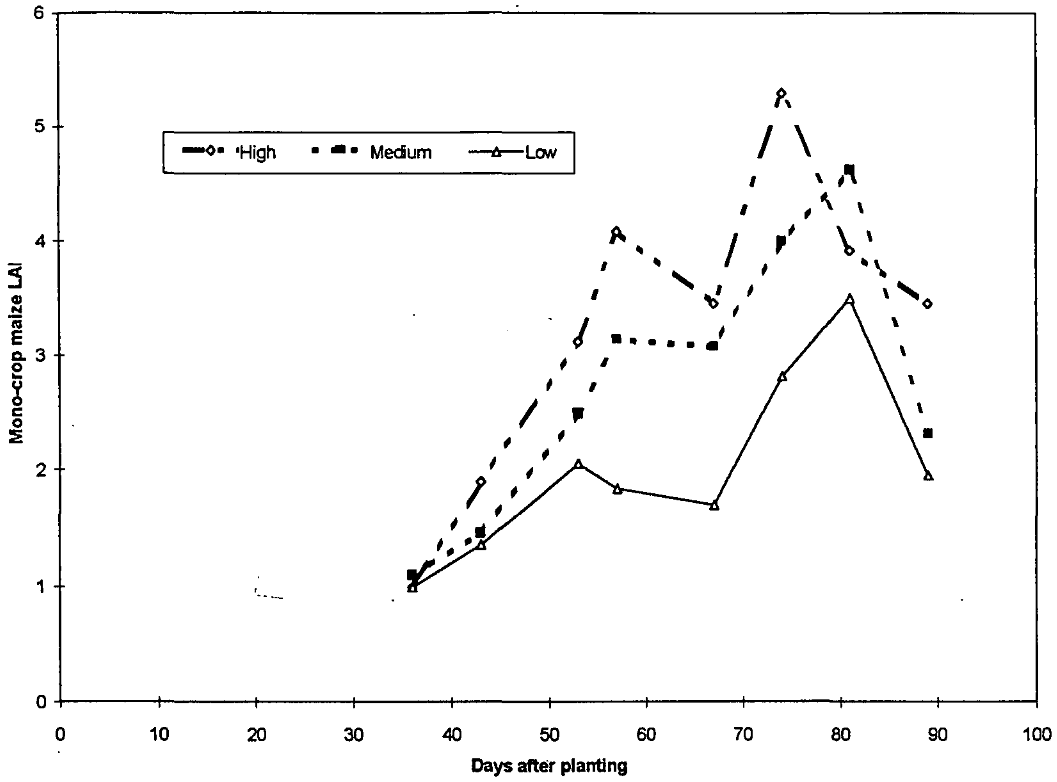


Figure 5.3 Comparison of mono-crop maize leaf area index for three plant densities grown for the 1996/1997 growing season.

Medium and low density plants were able to reach their peak 7 days later than the high density (Figure 5.3 & Appendix xvi). This pattern of mono-crop maize leaf area index, where a slow initial increase in LAI was followed by an exponential growth continuing until anthesis was also reported by Van Averbeke (1991). In comparison to inter-crop maize/beans, it was found that mono-crop maize had a lower leaf area index (Appendix xvi) (data not plotted).

Experiment 2

Leaf area index data for the 1997/1998 growing season is plotted in Figure 5.4. From the plotted lines for inter-crop maize/beans, it was clear that an increase in LAI up to 38 days after planting was small in low and medium plant densities, but a rapid increase occurred between 38 and 49 days after planting. The low plant density LAI continued increasing until reaching the peak of 3.7 at 72 DAP (Figure 5.4 & Appendix xvi). Medium plant density LAI increased slowly until reaching the peak of 4.3 at 70 DAP. High plant density LAI increased rapidly from 26 to 47 DAP after which it slowed down until reaching a peak of 5.6 at 69 DAP. It was again found that the density of plants had an effect on LAI since the high density plants had a higher LAI than the low density through out the growing season (Figure 5.4 & Appendix xvi). High and medium density plants were also able to reach their peak 12-13 days earlier than the low density (Figure 5.4 & Appendix xvi). The development of the leaf area index for inter-cropping was found to be similar to that of Experiment 1. In comparison to mono-crop maize, it was found that inter-cropping had total leaf area index higher than mono-cropping maize (Appendix xvi).

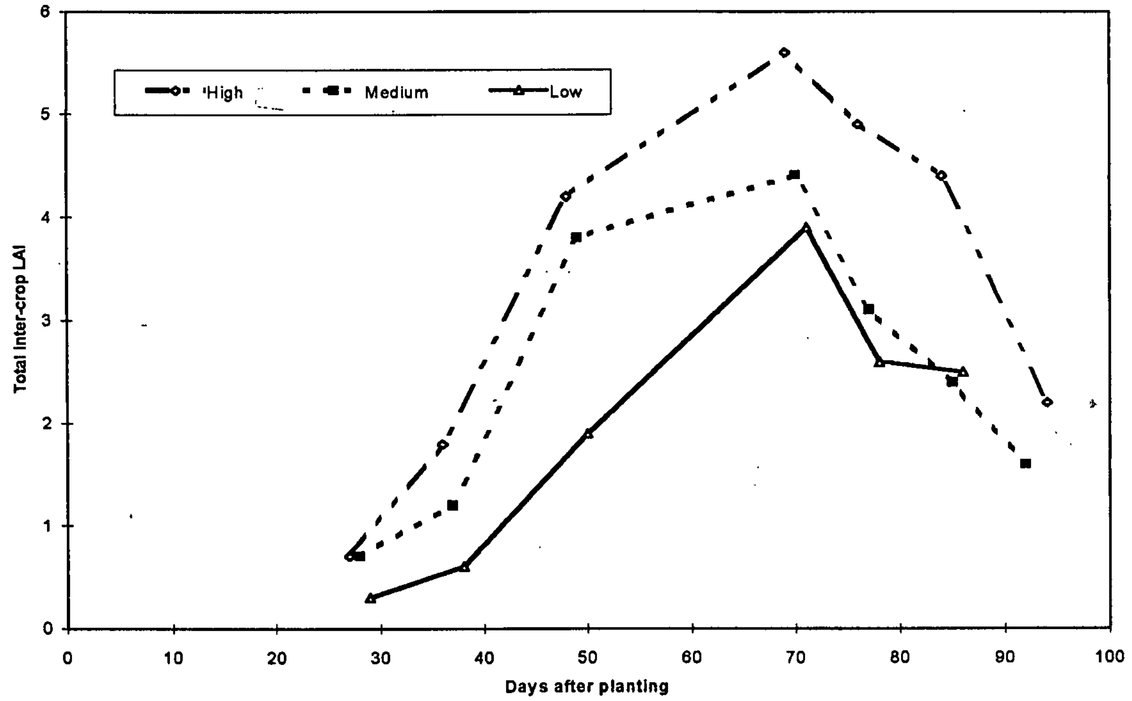


Figure 5.4 Comparison of inter-crop maize/bean total leaf area index for three plant densities for the 1997/1998 growing season.

5.4.3 Radiation interception

Radiation interception varied according to plant density in both inter-cropping and mono-cropping systems. It was observed that there was a increase in radiation interception with increase in plant density. Percentage photosynthetic active radiation interception was observed to increase with time at low, medium and high plant density. The rate of increase of PAR interception percentage was lower in low density than in medium density and high plant density (Figure 5.5). The rate of increase of total inter-crop leaf area index (LAI) between 40 and 48 DAP was 0.13 ± 0.03 d^{-1} for low density and 0.23 ± 0.03 d^{-1} for medium and high density. Percentage photosynthetic active radiation interception was also found to behave in a similar manner as leaf area index and was found to be higher in the high density than in the low density (Figure 5.6). It can therefore be concluded that there is a direct relationship between leaf area index and radiation interception.

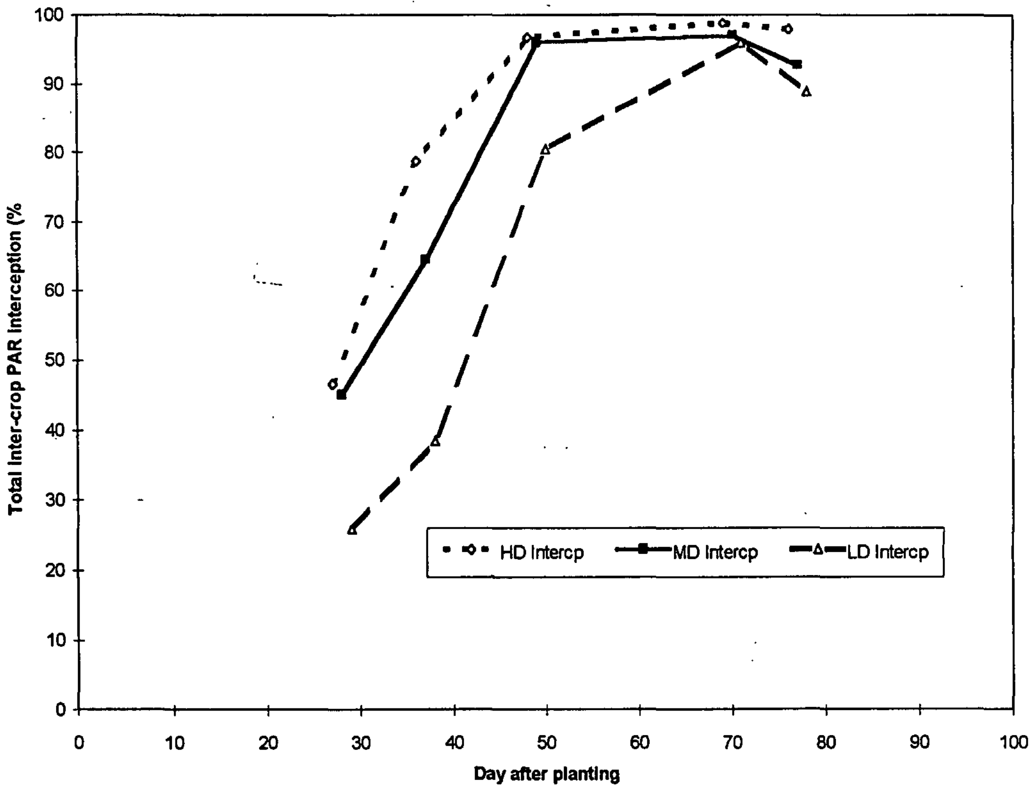


Figure 5.5 Comparison of total photosynthetic active radiation interception (%) by inter-crop maize/beans for three plant densities for the 1997/1998 growing season.

Seasonal changes in the photosynthetic active radiation interception for the three inter-cropping densities (Figure 5.5) showed that interception closely followed the pattern of canopy development (Figure 5.4). Photosynthetic active radiation interception was low in low density with a slow increase in leaf area index up to 37 days after planting then increased rapidly. Photosynthetic active radiation interception increased rapidly in medium and high plant density together with leaf area index (Figure 5.4, 5.5 and 5.6), after which increasing leaf senescence contributed to a steady decrease in LAI. The maximum photosynthetic active radiation interception percentage was reached at 70 days after planting (DAP) when low density reached 96% while medium and high densities reached 97% and

99% respectively. Total PAR interception was higher in inter-cropping than in mono-crop maize and mono-crop beans of the corresponding densities. It was observed that leaf area index had an influence on the radiation interception in the sense that as the leaf area index increased so did the radiation interception. Only graphs for the inter-cropping system for Experiment 1 and Experiment 2 are presented. There were small differences between densities in the relationship between leaf area index and radiation interception and only a fitted line through the data is plotted (Figure 5.6).

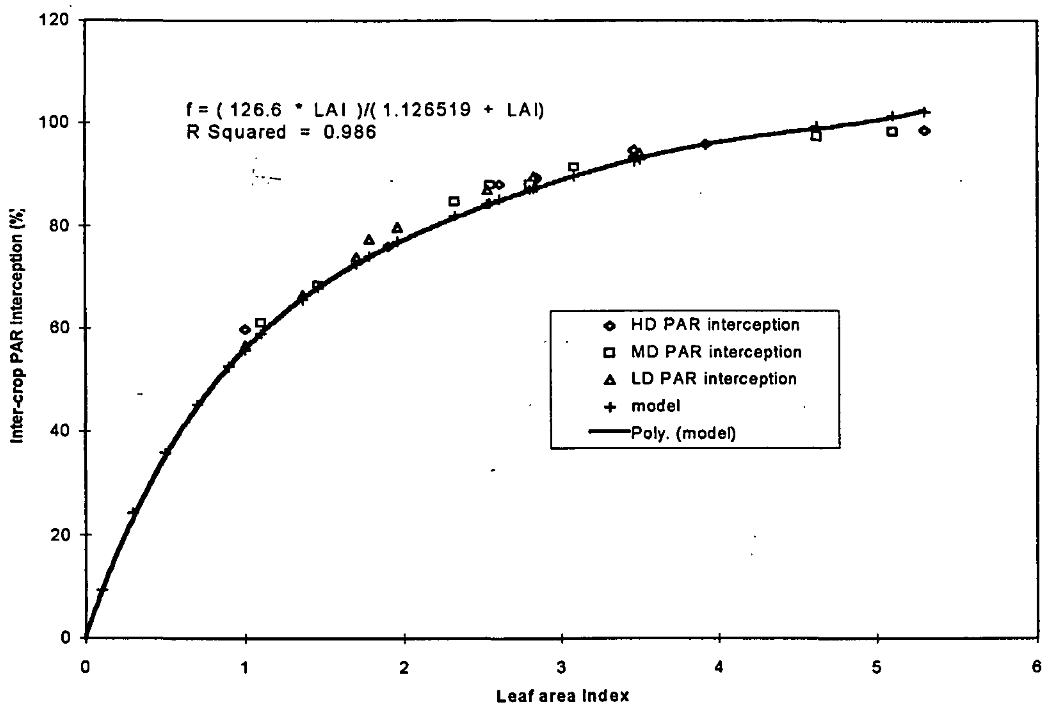


Figure 5.6 Relationship between leaf area index and fractional interception (%) of photosynthetic active radiation in inter-crop maize for the 1996/1997 growing season.

5.4.4 Dry matter production

As it has already been observed with respect to seed yield in beans that inter-cropping systems impact more on beans or any legume than the cereal. Bean dry matter production will therefore be discussed more than maize. Dry matter production of inter-cropped beans and mono-cropped beans were compared (Figures 5.7, 5.8, 5.9, 5.10 & Appendix xvii). It was observed that dry matter production in inter-crop beans was less than in mono-crop beans. The reduction in inter-cropped bean dry matter became severe with increase in maize plant density. This may be attributed to a reduction in radiation availability to the beans. Gardiner & Cracker (1981) reported that in a maize/beans inter-crop at the highest population, less than 20% of the incident solar radiation was able to reach the upper surface of the inter-cropped bean canopy. Therefore, the total decrease in dry matter production in beans growing under an inter-cropping system was as a result of the influence of low available PAR for interception which caused low leaf (Figure 5.7 & Appendix xvii), stems (Figure 5.8 & Appendix xvii) and seeds + pods (Figure 5.9 & Appendix xvii) development. These observations agree with what Crookston *et al.* (1975) reported that shading of beans reduced photosynthesis by 38% while transpiration reduced by 8%. The increase in mesophyll and stomatal resistance to diffusion of CO_2 by 98% and 48% respectively might also have affected dry matter production in inter-cropped beans. Crookston *et al.* (1975) further reported that photosynthesis decrease was considerably larger than the decrease in transpiration and this could have been the major cause of low dry matter accumulation.

It was also found that dry matter production of the various yield components in inter-cropped beans was similar to mono-cropped beans up to 43 days after planting. Thereafter, it was found that dry matter production reduced in inter-cropping. These findings are similar to observations of Gardiner & Cracker (1981) in a maize/bean inter-crop although they reported equal dry matter production in inter-crop and mono-crop up to 34 days after planting and this could be attributed to differences in the plant densities used in the two studies.

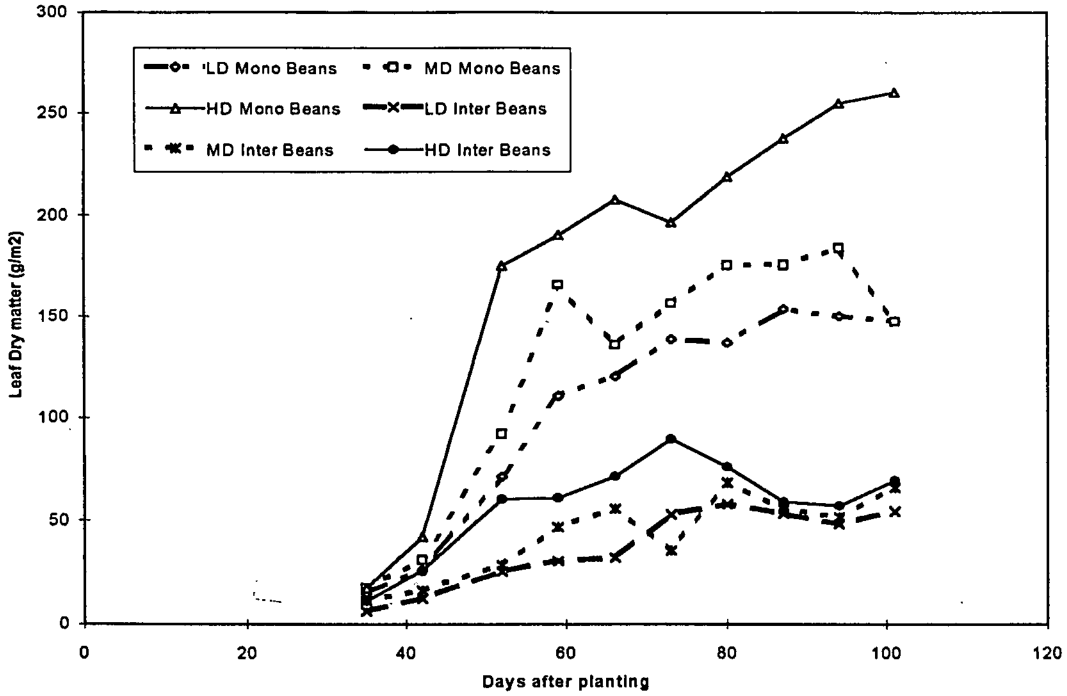


Figure 5.7 Comparison of leaf (standing) dry matter production in inter-cropped beans and mono-crop beans for three plant densities for the 1996/1997 growing season.

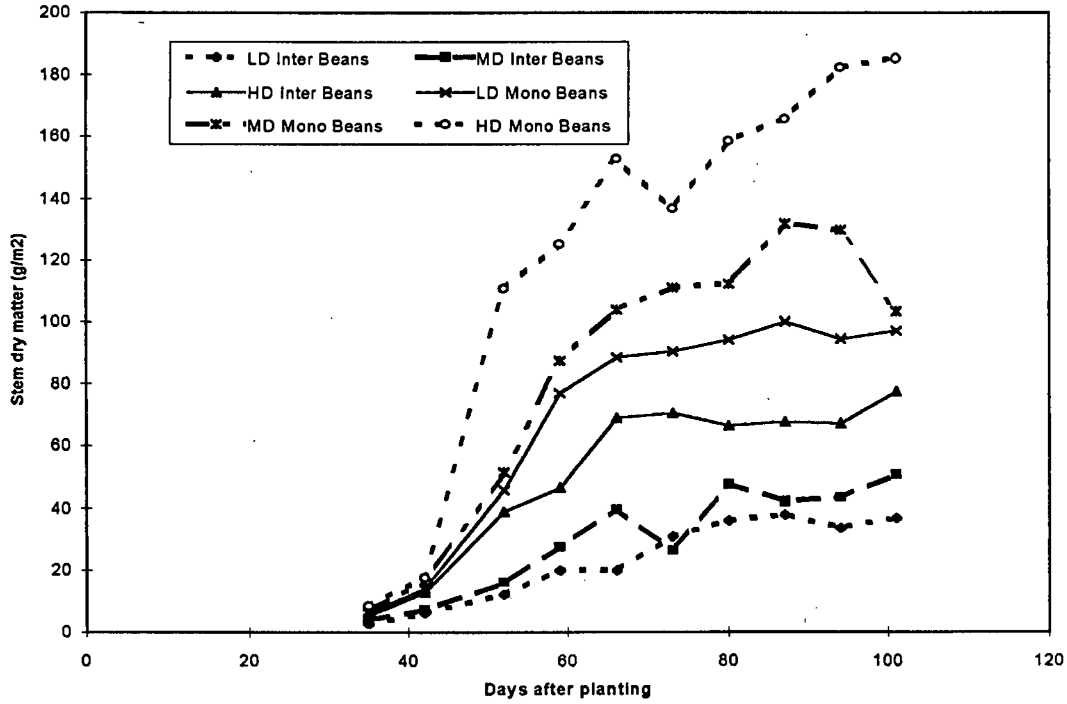


Figure 5.8 Comparison of stem (standing) dry matter production in inter-cropped beans and mono-crop beans for three plant densities for 1996/1997 growing season.

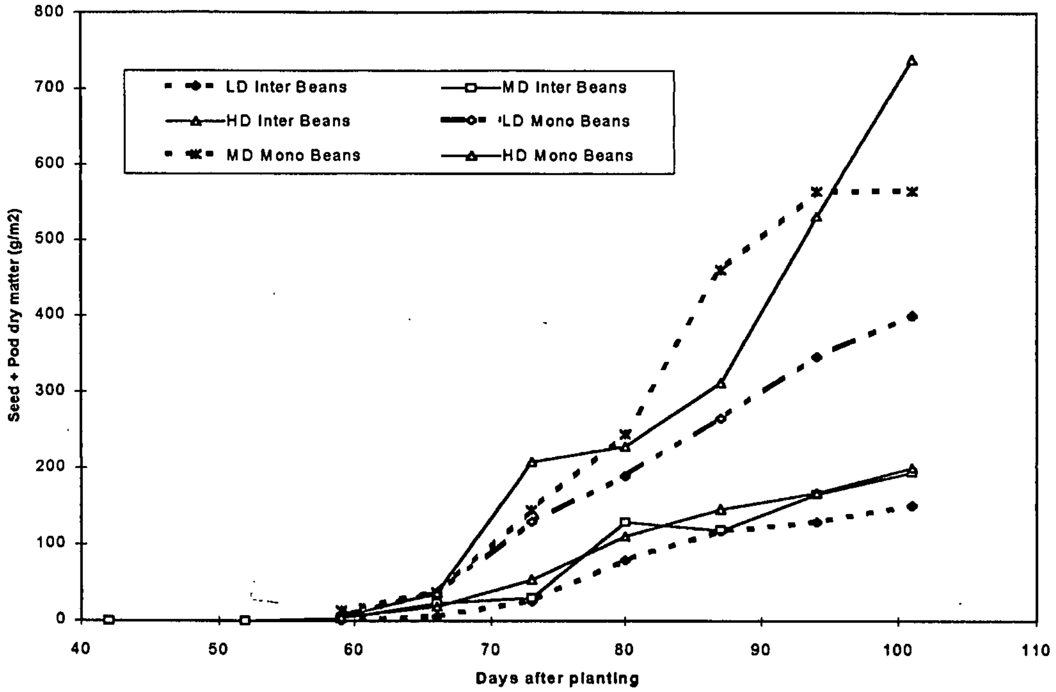


Figure 5.9 Comparison of seed + pod (standing) dry matter production in inter-cropped beans and mono-crop beans for three plant densities for the 1996/1997 growing season.

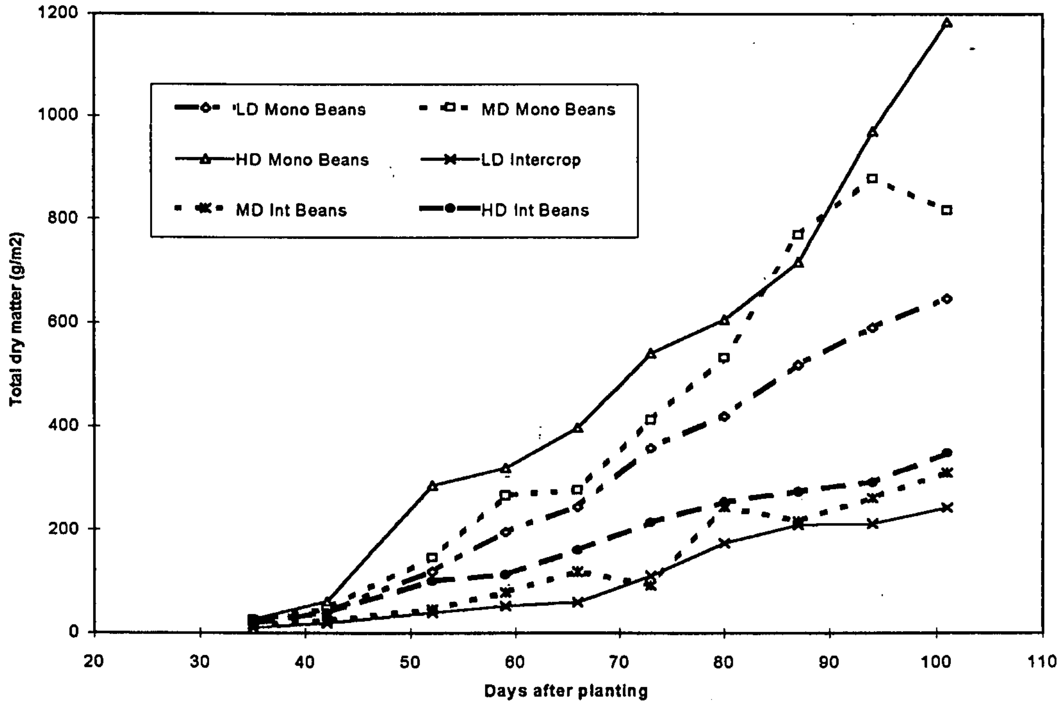


Figure 5.10 Comparison of total dry matter production in inter-cropped beans and mono-crop for three plant densities for the 1996/1997 growing season.

Dry matter production of inter-cropped maize and mono-cropped maize were compared as in beans (Appendix xvii). It was observed that dry matter production in inter-crop maize was less than in mono-crop maize. The reduction in the maize dry matter could also be attributed to competition by the maize plants for nutrients and water as it was reported in inter-crop seed yield. Enyi (1973) reported that in an inter-crop of beans and maize, the peak demand of nutrients by the maize plants coincided with the beans plants. It was also found that dry matter production of the various yield components in mono-crop and inter-cropped maize was similar to mono-cropped beans but this differed right from the early stages (Appendix xvii).

5.4.5 Radiation use efficiency

Radiation use efficiency is the ratio of dry matter produced per unit of the energy used in its production. Radiation use efficiency was calculated based on photosynthetic active radiation intercepted for the period from 66 to 73 days after planting (DAP) for both mono-crops and inter-crops as explained in section 2.2.3.2 of Chapter 2. In the three plant densities, it was observed that the mean radiation use efficiency for mono-crop maize were 1.13, 1.40 and 1.42 g MJ^{-1} for low medium and high plant density respectively, while inter-crop maize/beans were 1.2, 1.41 and 1.59 g MJ^{-1} for low medium and high plant density respectively (Table 5.5). There was no significant difference in radiation use efficiency in mono-cropped beans as a mean of 0.50 g MJ^{-1} was observed at all three plant densities. It was also found that radiation use efficiency was positively related to plant density considering that as plant density increased so did radiation use efficiency. The data shown in Table 5.5 indicates that inter-cropping systems use photosynthetic active radiation (PAR) more efficiently that mono-cropping systems.

Table 5.5 Radiation use efficiency (g MJ^{-1} Photosynthetic active radiation) of mono-crop maize and mono-crop beans and inter-crop maize/beans under three plant densities between 66 and 73 days after planting for the 1996/1997 growing season.

Cropping System	Crop	Mean Radiation Use efficiency in three plant densities (gMJ^{-1})		
		Low	Medium	High
Mono-cropping	Maize	1.13	1.40	1.42
	Beans	0.49	0.50	0.50
Inter-cropping	Maize/Beans	1.20	1.41	1.59

5.5 Conclusion

In any farming activity, the maximisation of the resources to obtain the best yield is the ultimate goal of the farmer. The number of maize cobs per plant were found to vary with plant densities and decreased with increase in plant density. Low, medium and high density inter-crop maize plants were found to have 1.8, 1.2 and 1.0 cobs per plant respectively. The pattern was similar for the mass of maize cobs per plant as it also varied with plant density and decreased with increase in plant density. Low, medium and high density plants were found to have 220, 132 and 95 grams of cobs per plant respectively. It was concluded that there is no significant difference in cob number and cob weight per plant between mono-cropping and inter-cropping systems. In both mono-crop and inter-crop, maize and beans plants in high plant density were taller than plants in low and medium densities while inter-crop bean plants were taller than mono-crop bean plants.

It was also found that the density of plants had an effect on LAI because the high density plants had a higher LAI than the low density throughout the growing season. This pattern was similar in both mono-cropping and inter-cropping systems. This pattern of LAI mono-crop maize varying with density was also reported by Van Averbeke (1991). It can be concluded that there is no difference in Photosynthetic active radiation interception after 70 DAP (Figure 5.5). The leaf area index also had an influence on the radiation interception as the interception was higher in higher plant density and vice-versa. Photosynthetic active radiation interception is greatly influenced by the plant density of the crop. In this experiment it can also be concluded that there was a decrease in radiation interception with decrease in maize density in both inter-cropping and mono-cropping systems and the effect of plant density was greater in mono-cropping. These results concur with results reported by Watiki *et al.* (1993) in a maize/cowpea inter-crop experiment in Australia. It was found that radiation use efficiency was positively related to plant density because as plant density increased, radiation use efficiency also increased. Mono-crop maize radiation use efficiency ranged from 1.13 to 1.42 g MJ^{-1} while inter-crop maize/beans radiation use efficiency ranged from 1.2 to 1.59 g MJ^{-1}. These values agree with what Watiki *et al.* (1993) reported for a maize/cowpea inter-crop. The observations indicate that inter-cropping uses photosynthetic active radiation more efficiently by 6-12% than mono-cropping.

CHAPTER 6

NUTRIENT BENEFITS OF INTER-CROPPING MAIZE AND BEANS IN RURAL BLACK COMMUNITIES

6.1 Introduction

Land for agricultural production has been a serious political issue in South Africa since the new dispensation just as it has been in Zimbabwe. South Africa is poorly endowed with agricultural land with only 13% of the surface area being available for crop production. In the 13% arable area only 1 million hectares are irrigable. High potential arable land comprises only 22% of the total arable land (Erasmus, 1995). It has also been shown through this work that inter-cropping provides more nutrients per unit area in comparison to mono-cropping. Over the last decade researchers have investigated the nutritional status of rural and urban black people especially children between the ages of 1-12 years (Mackeown *et al.*, 1989, Steyn *et al.*, 1992). In order to comprehend the occurence of nutritional deficits, one needs to investigate actual foods consumed as well as the dietary habits of the particular group under study. To improve the nutritional status of the rural black communities, in-depth understanding of the farming practices and traditional food consumption is vital. Research has found that the diet of Xhosa-speaking people of Transkei and Ciskei includes traditional foods, such as maize meal porridge and sour milk and other combined dishes of maize meal and beans, pumpkin or green leafy vegetables (Beyers *et al.*, 1979). Inter-cropping is practised in many African countries including South Africa on a small-scale. Inter-cropping is defined as the growing of two or more crop species simultaneously on a given piece of land (Willey & Osiru, 1972; Ofori & Stern, 1987). If small-scale farmers practice inter-cropping, some of these crops making up traditional foods may be available at less cost and at the same time with increased nutrient availability.

It was with the aim of reducing nutrient deficiency and its offshoots that the Department of Health in 1979 endorsed fortification of maize meal with riboflavin and niacin resulting in all maize meal now being fortified (de Hoop & Kotze, 1990). Researchers have shown that most rural black South

Africans in many parts of the country predominantly consume maize based meals (Rose, 1972; Richardson *et al.*, 1982). Considering the widespread consumption of maize meal, de Hoop & Kotze (1990) recommended that fortification of maize meal with riboflavin, niacin, thiamine, folic acid, vitamin A and zinc be made compulsory and that it should be monitored by an independent authority. In rural Transkeian communities, Iputo & Makuzeni (1993) found that there was a heavy dependence on commercially available food and reiterated the need for further investigation by national planners into the food production systems and future potential.

6.2 Literature review

6.2.1 Staple food consumption by rural black communities

Maize constitutes a major component of the diet of many South Africans particularly rural black people. It has been found that in many rural areas of South Africa, maize based dishes in the form of soft porridge with sugar are the single most common food item eaten by black children (Richardson *et al.*, 1982; Iputo & Makuzeni, 1993). Similar results in a survey conducted by Vorster *et al.,* (1994) in Venda, have verified that maize porridge was consumed more than once per day by 100% of the respondents while only 10% consumed beans. In Transkei, 92% claimed to eat maize regularly while 31% ate sorghum (*sorghum bicolor*) and 67% ate dried beans (*Phaseolus vulgaris*) (Rose, 1972). Krige and Senekal (1997) found that mealie-meal porridge contributed an average of 43% of the total daily energy intake among pre-school children of farm workers in Stellenbosch.

Iputo & Makunzeni (1993) in a survey on protein-energy malnutrition (PEM) in Transkei found that mealie based food at breakfast was eaten by 56%, 60% and 67% of the well-nourished, marasmus and kwashiorkor children respectively. During lunch, 48%, 56% and 64% of the well-nourished, marasmus and kwashiorkor children consumed mealie based food respectively. The levels were not down during supper as 55%, 55% and 63% of the well-nourished, marasmus and kwashiorkor children consumed mealie based food respectively. This consumption of mealie based foods at all meal times exhibits how much black people depend on maize. This situation of poor nutrition will persist unless the consumption pattern and nutrient content of the meals change.

It has also been shown that rural black children consume 95% (294g day^{-1})[1] more maize than white children, while urban black children consume 85% (143g day^{-1}) more than white children (Richardson *et al.*, 1982). These statistics continue to support the over dependency on maize based meals among both the rural and urban black communities although it is more evident among the rural black people.

6.2.2 Nutrient intake by rural black people

Under-nutrition is considered to be a major problem world-wide including South Africa where it is prevalent among Black, Coloured and Asian children and is probably due to inadequate dietary intake in these population groups. Nutrients play a major role in the physiological processes that take place in a human body. Therefore, for good health, it is important that adequate nutrients are present in the daily diets. Maize (*Zea mays L.*) and dry bean (*Phaseolus vulgaris*) inter-cropping is one crop combination that is grown in South Africa although only to a limited extent. It is evident from Table 6.1, that a diet combining maize and beans will provide a better balanced (nutritional diet) than of either maize or beans. Hence, it may be concluded that inter-cropping of maize and beans should provide the required nutrients in a balanced diet for good health.

A survey conducted among men and women in Venda found that both men and women had an adequate mean total protein daily intake while the mean daily intake of vitamin D, B_6, folate and ascorbic acid was low in comparison to recommended dietary allowances (RDA) (Vorster *et al.*, 1994). Walker (1979) found that there were border-line or low cases of a number of elements e.g. calcium and vitamins, Vitamins C and D in comparison to recommended dietary allowances among South African rural black people.

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[1] Grams per day of cooked food, for instance, wet weight.

Table 6.1 Maize and bean nutrient composition per 100g edible food (Medical Research Council, Food composition tables, 1991).

Nutrient content	Beans, Haricot dried (cooked) 63.2% moisture	Beans, Haricot dried (raw) 12.4% moisture	Maize meal stiff porridge (cooked) 79.1% moisture	Maize meal (raw) 13% moisture
Energy (KJ)	594.0	1402.0	371.0	1521.0
Protein (g)	8.7	22.3	2.1	9.2
Carbohydrate (g)	17.4	35.5	19.6	75.1
Vitamin C (mg)	1.0	3.0	0.0	0.0
Vitamin E (mg)	0.14	0.34	0.15	0.30
Calcium (mg)	70.0	155.0	2.0	10.0
Iron (mg)	2.5	6.4	0.2	3.0
Magnesium (mg)	59.0	173.0	18.0	123.0
Phosphorus (mg)	157.0	443.0	41.0	241.0
Potassium (mg)	368.0	1140.0	60.0	346.0
Sodium (mg)	1.0	14.0	1.0	11.0
Vitamin B_6 (mg)	0.164	0.437	0.014	0.3
Folate (μg)	140	370	3	33
Zinc (mg)	1.06	2.54	0.22	2.3
Thiamine (mg)	0.2	0.65	0.08	0.5
Riboflavin (mg)	0.06	0.23	0.01	0.12
fibre (g)	9.0	25.2	0.8	10.6
Copper (mg)	0.3	0.88	0.02	0.2

A major source of protein is meat but Richardson *et al.*(1982) found that rural and urban black children consumed 65% and 30% less meat than white children respectively, and that this 35% difference between rural and urban children is critical. In fact, in Transkei very few people claimed to eat meat more than once a month with the majority only once in every three months (Rose, 1972; Walker, 1979). It has also been found that legumes/pulses which rural people could grow and eat were consumed 70% and 88% less by rural and urban black children than white children (Richardson *et al.*, 1982).

In a survey, farm workers in Stellenbosch were found to have a mean calcium intake of less than 50% of the RDA (Krige & Senekal, 1997) while rural adults in Venda had high calcium and iron intake although they had a low intake of dairy products and meat. The high calcium and iron content was mainly because of the regular intake of large amounts of *maroho*, a green leafy wild plant which contains 264 mg calcium and 6.1 mg iron per 100 g uncooked weight (Vorster *et al.*, 1994).

6.3 Rationale and specific objectives

Inter-cropping will broaden the availability of nutrients in the rural areas as two or more crops are grown on the same piece of land. Most studies conducted on inter-cropping have concentrated on seed yield. Scientists have shown that more land is required in mono-cropping than in inter-cropping to produce the same seed yield per unit area using Land Equivalent Ratios (LER) for various crop combination (Pilbeam *et al.*, 1994; Liphadzi *et al.*, 1997; Ayisi & Poswall, 1997). In rural Transkeian communities, Iputo & Makuzeni (1993) found that there was a heavy dependence on commercially available food and reiterated the need for further investigation by national planners into food production systems and their future potential. Little is known about nutrient content present in inter-crop seed yields and therefore, the specific aims of this study were to:

(i) quantify the nutrient content in mono-cropping and inter-cropping seed yields and,

(ii) determine benefits or otherwise of inter-cropping seed yield in terms of nutrient content.

6.4. Results and discussion

Nutrient content in mono-crops and inter-crops of beans and maize were calculated as explained in materials and methods (Chapter 2). Table 6.2, 6.3 and 6.4 shows quantities of total nutrients obtained from beans and maize mono-crops and inter-crops per hectare in low, medium and high plant densities grown at the agrometeorology experimental site during the 1996/1997 growing season.

Table 6.2 Mean nutrients (per 100g edible food) produced at three different plant densities by mono-crop and inter-crop beans per hectare. (calculated from the Medical Research Council, food composition tables, 1991).

Mono-crop beans

Yield (kg/ha)*	2805		4400		5390	
Density	Low	Stdev	Medium	Stdev	High	Stdev
Energy (MJ)	4532	206	7109	302	8709	138
Protein (kg)	664	30	1041	44	1275	20
Carbohydrate (kg)	1328	60	2082	88	2551	40
Vitamin C (kg)	0.076	0.0035	0.120	0.0051	0.147	0.0023
Vitamin E (kg)	0.011	0.0005	0.017	0.0007	0.021	0.0003
Calcium (kg)	5.3	0.24	8.4	0.36	10.3	0.16
Iron (kg)	0.19	0.009	0.3	0.013	0.37	0.006
Magnesium (kg)	4.5	0.20	7.1	0.30	8.6	0.14
Phosphorus (kg)	12.0	0.54	18.8	0.80	23.0	0.36
Potassium (kg)	28.1	1.28	44.0	1.87	54.0	0.86
Sodium (kg)	0.08	0.003	0.12	0.005	0.15	0.002

Inter-crop beans

Yield (kg/ha)*	1150		1480		1530	
Density	Low	Stdev	medium	Stdev	High	Stdev
Energy (MJ)	1858	107	2391	61	2472	61
Protein (kg)	272	16	350	9	362	9
Carbohydrate (kg)	544	31	700	18	724	18
Vitamin C (kg)	0.031	0.0018	0.040	0.0010	0.042	0.0010
Vitamin E (kg)	0.004	0.0003	0.006	0.0001	0.006	0.0001
Calcium (kg)	2.2	0.13	2.8	0.07	2.9	0.07
Iron (kg)	0.08	0.004	0.1	0.003	0.1	0.0003
Magnesium (kg)	1..8	0.11	2.4	0.06	2.5	0.06
Phosphorus (kg)	4.9	0.28	6.3	0.16	6.5	0.16
Potassium (kg)	11.5	0.66	14.8	0.38	15.3	0.38
Sodium (kg)	0.031	0.002	0.040	0.001	0.042	0.001

* Actual yield measured from the agrometeorology experimental site during the 1996/1997 growing season

Table 6.3 Mean nutrients (per 100g edible food) produced at three different plant densities by mono-crop and inter-crop maize per hectare. (calculated from the Medical Research Council, food composition tables, 1991)

Mono-crop maize

Yield (kg/ha)*	7895		9010		10310	
Density	Low	Stdev	medium	Stdev	High	Stdev
Energy (MJ)	14001	285	15978	1056	18283	664
Protein (kg)	793	16	904	60	1035	38
Carbohydrate (kg)	7397	151	8441	558	9659	351
Vitamin C (kg)	0.0	0.0	0.0	0.0	0.0	0.0
Vitamin E (kg)	0.057	0.001	0.065	0.004	0.074	0.003
Calcium (kg)	0.8	0.02	0.9	0.06	1.0	0.04
Iron (kg)	0.08	0.002	0.09	0.006	0.10	0.004
Magnesium (kg)	6.8	0.14	7.8	0.51	8.9	0.32
Phosphorus (kg)	15.5	0.31	17.7	1.17	20.2	0.73
Potassium (kg)	22.6	0.46	25.8	1.71	29.6	1.07
Sodium (kg)	0.38	0.01	0.43	0.03	0.49	0.02

Inter-crop maize

Yield (kg/ha)*	6000		8310		8990	
Density	Low	Stdev	medium	Stdev	High	Stdev
Energy (MJ)	10641	702	14737	129	15943	430
Protein (kg)	602	40	834	7	902	24
Carbohydrate (kg)	5622	371	7785	68	8423	227
Vitamin C (kg)	0.0	0.0	0.0	0.0	0.0	0.0
Vitamin E (kg)	0.043	0.003	0.060	0.001	0.064	0.002
Calcium (kg)	0.57	0.038	0.79	0.007	0.86	0.023
Iron (kg)	0.06	0.004	0.08	0.001	0.09	0.002
Magnesium (kg)	5.2	0.34	7.1	0.06	7.7	0.21
Phosphorus (kg)	11.8	0.78	16.3	0.14	17.6	0.48
Potassium (kg)	17.2	1.14	23.8	0.21	25.8	0.70
Sodium (kg)	0.29	0.019	0.40	0.003	0.43	0.012

*Actual yield measured from the agrometeorology experimental site during the 1996/1997 growing season

Table 6.4 Nutrients (per 100g edible food) produced at three different plant densities by inter-crop maize/beans per hectare for 1996/1997 growing season. (calculated from the Medical Research Council, food composition tables, 1991).

Inter-crop maize/beans

Nutrients/Density	Low	Stdev	Medium	Stdev	High	Stdev
Energy (MJ)	12499	627	17128	189	18415	450
Protein (kg)	874	30	1184	16	1264	28
CHO (kg)	6166	348	8486	86	9147	233
Vitamin C (kg)	0.031	0.0	0.040	0.0	0.042	0.0
Vitamin E (kg)	0.047	0.003	0.065	0.001	0.070	0.002
Calcium (kg)	2.8	0.101	3.6	0.078	3.8	0.081
Iron (kg)	0.14	0.003	0.18	0.003	0.19	0.004
Magnesium (kg)	7.0	0.27	9.5	0.12	10.2	0.23
Phosphorus (kg)	16.7	0.60	22.6	0.30	24.2	0.54
Potassium (kg)	28.7	0.78	38.6	0.58	41.1	0.87
Sodium (kg)	0.32	0.018	0.44	0.004	0.47	0.012

In terms of nutrient content, it was found that inter-crops (maize/beans) overall produced higher nutrient yield than mono-crop maize. There was no significant difference in total overall energy content in mono-crops and inter-crops at high plant density while inter-crops had 7.2% more total overall energy at medium and 11% less than mono-crop at low plant density (Figure 6.1, Table 6.3 & 6.4). Inter-crops had more protein at low, medium and high density than mono-crops by 10%, 31% and 22.2% respectively (Figure 6.1, Table 6.3 & 6.4). Thus inter-cropping would most definitely improve protein accessibility in undernourished children in the case of say children in Stellenbosch who were found to consume less than 67% of the RDA and this contributed to growth stunting in the children observed in that study (Krige & Senekal, 1997). At low and high plant density, mono-crops where found to have 16.6% and 5.3% more carbohydrates than inter-crops while there was no difference at high density (Figure 6.1, Table 6.3 & 6.4).

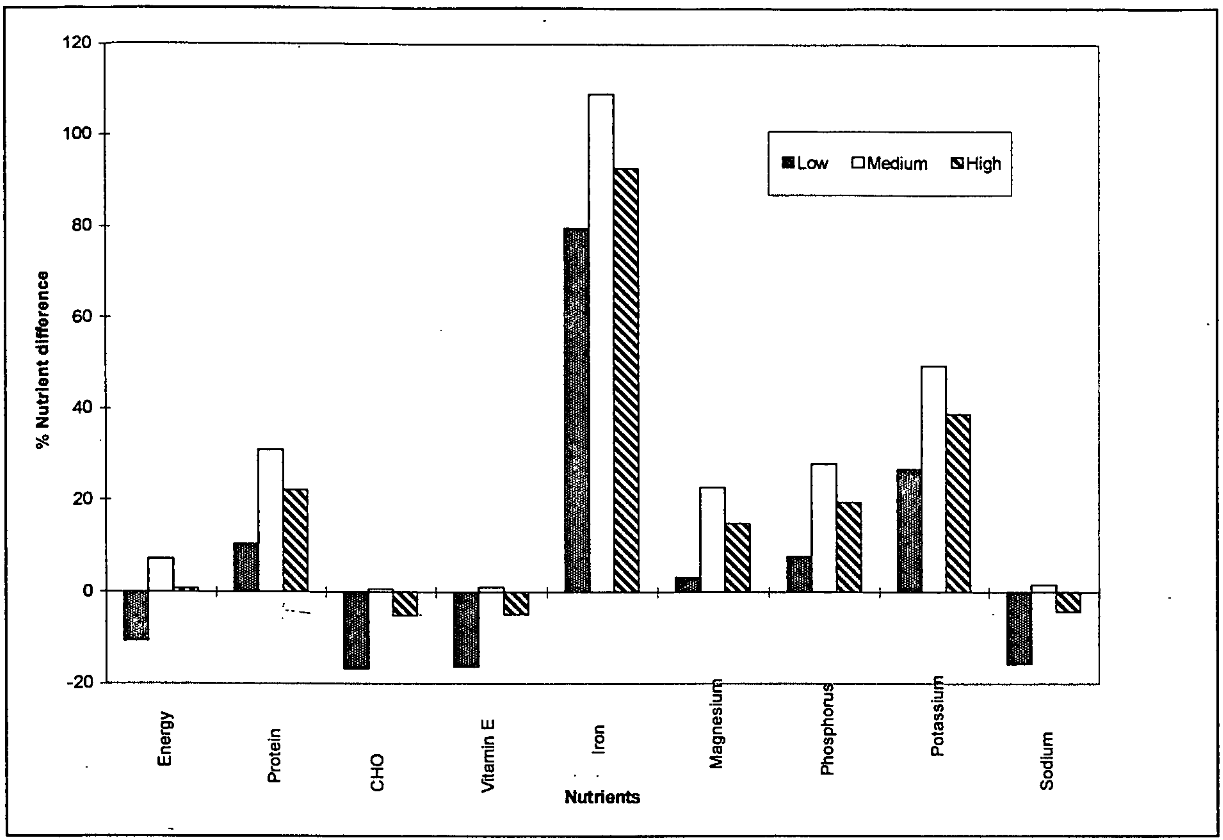

Figure 6.1 Total (maize/beans) inter-crop nutrient content calculated as a percentage of maize mono-crop for three plant densities grown during the 1996/1997 growing season.

Inter-crops were found to have more magnesium than mono-crop maize in the low, medium and high densities (3.2%, 22.9% and 14.9%) respectively. Similar results were found for phosphorus and potassium showing more nutrients in inter-crops than mono-crop maize (7.7%, 28% and 19.5%) and (26.8%, 49.6% and 39%) respectively (Figure 6.1, Table 6.3 & 6.4). Mono-crop maize was found to contain 15.7% and 4.4% more sodium than inter-crops at low and high plant density while inter-crops had 1.6% more sodium at medium plant density.

With reference to Figure 6.2 in terms of nutrient content, it was again found that inter-crops had overall higher nutrient content than mono-crop beans. There was more energy content in inter-crops at low, medium and high of 175.8%, 140.9% and 111.5% respectively. Mono-crop beans continued having less protein at low and medium plant density than inter-crops by 31.7% and 13.7% respectively while there was no difference at high plant density (Figure 6.2, Table 6.2 & 6.4). With respect to beans mono-crops, inter-crops were found to have carbohydrates of more than 258% at all three plant densities. Beans mono-crops were found to have more vitamin C of more than 59% at all three plant densities. The reverse was the case for vitamin E were inter-crops had more than 242% at all three plant densities (Figure 6.2, Table 6.2 & 6.4). Inter-crops also contained more sodium at low, medium and high density of 316.9%, 265.5%, 221.5% respectively (Figure 6.2, Table 6.2 & 6.4).

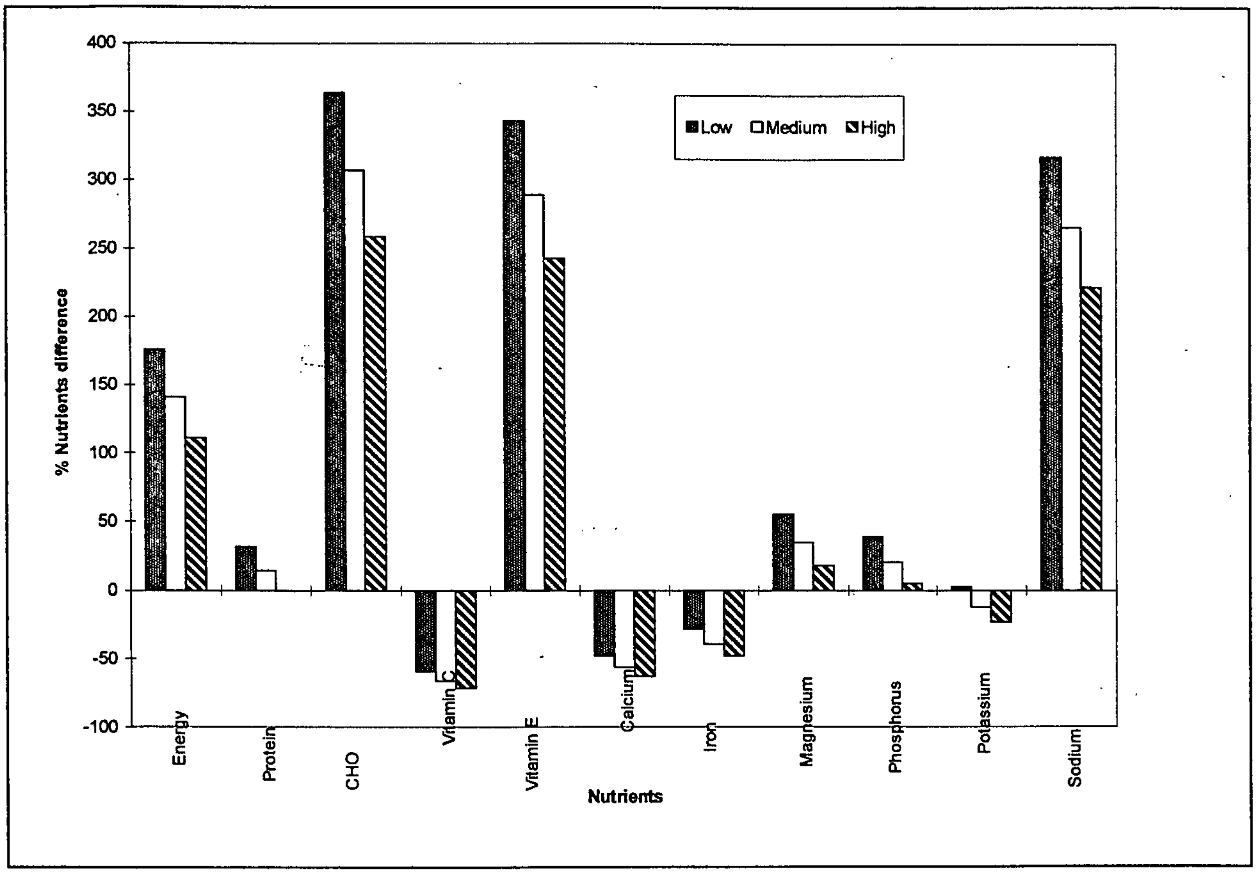

Figure 6.2 Total (maize/beans) inter-crop nutrient content calculated as a percentage of beans mono-crop for three plant densities.

Dietary calcium deficiency has been found to be responsible for rickets and bone deformities in rural South African children. Farm workers in Stellenbosch have been found to have a mean calcium intake of less than 50% of the RDA (Krige & Senekal, 1997) while rural adults in Venda had high calcium and iron intake despite their low intake of dairy products and meat. This was mainly because of the regular intake of large amounts of *maroho*, a green leafy wild plant which contains 264 mg calcium and 6.1 mg iron per 100 g uncooked weight (Vorster, *et al.*, 1994). Inter-crops were found to have more magnesium than mono-crop beans at low, medium and high density of 55.7%, 34.9% and 17.8% respectively while mono-crop beans had higher potassium at medium and high plant density of 12.3% and 23.8%) respectively. Mono-crop beans was found to contain more potassium of

2.3% only at low plant density. Inter-crops were found to contain more calcium and phosphorus at all three plant densities (48.3%, 56.9% and 63.2%) and (39.2%, 20.3% and 4.9%) respectively (Figure 6.2, Table 6.2 & 6.4).

With reference to Figure 6.3 in terms of nutrient content, using an alternative method of analysis as explained in materials and methods (Chapter 2) Section 2.2.7.2, it was also found that inter-crops seed yields had overall higher nutrient content than mono-crop beans seed yields. There was more energy content in inter-crops at low, medium and high plant densities of 34.9%, 48.4% and 36.4% (Figure 6.3, Table 6.5). Inter-crops had more protein at low, medium and high plant density than mono-crops by 20.1%, 21.7% and 9.5% respectively (Figure 6.3, Table 6.5). With respect to carbohydrates inter-crops were found to have carbohydrates of more than 41% at all plant densities than mono-crops. Mono-crops were found to have vitamin C of more than 18% at all three plant densities than inter-crops. The reverse was the case for vitamin E were inter-crops had more than 41% at all three plant densities (Figure 6.3, Table 6.5). Inter-crops also contained more magnesium and phosphorus at low, medium and high plant density of 24.1%, 28.6%, 16.3% and 21.5%, 24% and 11.8% respectively. Inter-crops had more potassium at low and medium plant density of 13.2% and 10.6% but less at high plant density by 1.6%. Mono-crops had more iron at low and medium plant density of 6.5% and 18.3% but less at high plant density by 1.8% (Figure 6.3, Table 6.5).

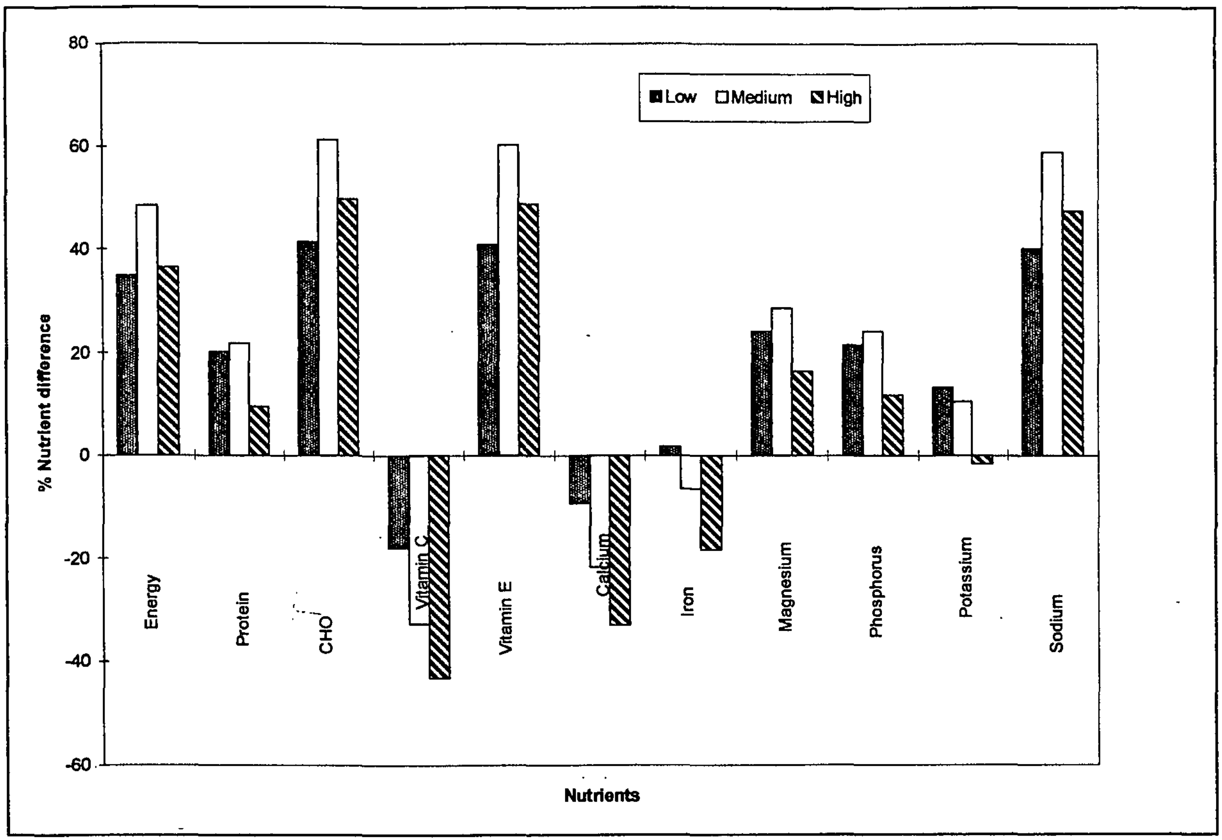

Figure 6.3 Total (maize/beans) inter-crop nutrient content calculated as a percentage of sum of mono-crop maize and mono-crop beans for three plant densities.

Table 6.5 Mean nutrients (per 100g edible food) produced at three different plant densities by mono-crop and inter-crop maize and beans per hectare (calculated from the Medical Research Council, food composition tables, 1991). Two hectares of mono-crop maize and mono-crop beans were summed up and one hectare of inter-crop yield was multiplied by 2 to compare 2 hectares of inter-crop (1 ha mono-crop maize + 1 ha mono-crop beans) with 2 hectares of inter-crop.

Mono-crop maize + mono-crop beans

Density	Low	Stdev	medium	Stdev	High	Stdev
Energy (MJ)	18533	246	23087	679	26992	401
Protein (kg)	1456	23	1946	52	2310	29
Carbohydrate (kg)	8724	105	10523	323	12210	196
Vitamin C (kg)	0.08	0.002	0.12	0.003	0.15	0.001
Vitamin E (kg)	0.07	0.001	0.08	0.002	0.09	0.002
Calcium (kg)	6.10	0.129	9.24	0.206	11.25	0.099
Iron (kg)	0.27	0.005	0.39	0.009	0.47	0.005
Magnesium (kg)	11.29	0.171	14.81	0.406	17.52	0.230
Phosphorus (kg)	27.45	0.430	36.45	0.982	43.22	0.549
Potassium (kg)	50.72	0.869	69.88	1.789	83.52	0.964
Sodium (kg)	0.45	0.006	0.55	0.017	0.64	0.010

Inter-crop maize/beans x 2

Density	Low	Stdev	medium	Stdev	High	Stdev
Energy (MJ)	24998	627	34255	189	36829	450
Protein (kg)	1749	30	2369	16	2529	28
Carbohydrate (kg)	12332	348	16972	86	18293	233
Vitamin C (mg)	0.063	0.0	0.080	0.0	0.083	0.0
Vitamin E (mg)	0.095	0.003	0.130	0.001	0.141	0.002
Calcium (kg)	5.526	0.101	7.223	0.078	7.545	0.081
Iron (kg)	0.271	0.003	0.360	0.003	0.380	0.004
Magnesium (kg)	14.0	0.27	19.0	0.12	20.4	0.23
Phosphorus (kg)	33.3	0.60	45.2	0.30	48.3	0.54
Potassium (kg)	57.4	0.78	77.3	0.58	82.2	0.87
Sodium (kg)	0.64	0.018	0.87	0.004	0.94	0.012

Inter-crops had more magnesium at low and medium densities by 14.3% and 12.3% respectively while there was no significant difference at high plant density. Regarding phosphorus, low and medium densities inter-crops had more by 11.7% and 8.1% respectively while high plant density mono-crop had more phosphorus by 4.0% than inter-crops. The opposite was the case for potassium where mono-crops at medium and high plant densities had more potassium by 3.4% and 15.3 % respectively while low plant density inter-crop had more potassium by 4.0% than mono-crops.

It was observed in chapter 4 (Table 4.2) that during the 1997/1998 growing season, there were no significant differences in the seed yield between treatments under full and supplementary irrigation. This is followed in this section where it has been observed that there is no significant difference in nutrient content between full and supplementary irrigation (Tables 6.6, 6.7, 6.8 and 6.9). But it was also observed in chapter 4 that water use efficiency was significantly different between full and supplementary irrigation.

Table 6.6 Nutrients (per 100g edible food) produced at three different plant densities by inter-crop maize/beans per hectare for 1997/1998 growing season under supplementary irrigation. (calculated from the Medical Research Council, food composition tables, 1991).

	Block I Nutrient production /ha					
Nutrient	Low	Stdev	Medium	Stdev	High	Stdev
Energy (MJ)	8983	366	11124	749	11578	407
Protein (kg)	631	27	759	45	786	25
CHO (kg)	4425	180	5537	389	5774	211
Vitamin C (kg)	0.023	0.0014	0.024	0.0006	0.025	0.0007
Vitamin E (kg)	0.034	0.001	0.043	0.003	0.044	0.002
Calcium (kg)	2.0	0.111	2.2	0.078	2.3	0.061
Iron (kg)	0.10	0.005	0.11	0.005	0.12	0.003
Magnesium (kg)	5.1	0.21	6.1	0.38	6.4	0.21
Phosphorus (kg)	12.0	0.50	14.5	0.87	15.0	0.48
Potassium (kg)	20.8	0.91	24.6	1.34	25.4	0.76
Sodium (kg)	0.23	0.009	0.29	0.020	0.30	0.011

Table 6.7 Nutrients (per 100g edible food) produced at three different plant densities by inter-crop maize/beans per hectare for 1997/1998 growing season under full irrigation. (calculated from the Medical Research Council, food composition tables, 1991).

	Block I I Nutrient production /ha					
Nutrient	Low	Stdev	Medium	Stdev	High	Stdev
Energy (MJ)	8254	1358	10439	791	11334	1811
Protein (kg)	585	88	725	43	777	98
CHO (kg)	4052	689	5164	423	5634	970
Vitamin C (kg)	0.022	0.0023	0.025	0.0012	0.025	0.0012
Vitamin E (kg)	0.031	0.005	0.040	0.003	0.043	0.007
Calcium (kg)	1.9	0.220	2.2	0.079	2.3	0.059
Iron (kg)	0.09	0.012	0.11	0.004	0.12	0.008
Magnesium (kg)	4.7	0.72	5.8	0.37	6.3	0.85
Phosphorus (kg)	11.1	1.69	13.8	0.85	14.8	1.92
Potassium (kg)	19.4	2.77	23.7	1.23	25.2	2.68
Sodium (kg)	0.21	0.035	0.27	0.022	0.29	0.049

Table 6.8 Nutrients (per 100g edible food) produced at three different plant densities by inter-crop maize/beans per hectare for 1997/1998 growing season under full irrigation. (calculated from the Medical Research Council, food composition tables, 1991).

	Block III Nutrient production /ha					
Nutrient	Low	Stdev	Medium	Stdev	High	Stdev
Energy (MJ)	8949	823	9354	1302	10093	82
Protein (kg)	631	43	660	70	704	8
CHO (kg)	4401	449	4599	701	4983	39
Vitamin C (kg)	0.023	0.0021	0.024	0.0024	0.025	0.0008
Vitamin E (kg)	0.034	0.003	0.035	0.005	0.038	0.0
Calcium (kg)	2.0	0.128	2.1	0.147	2.2	0.054
Iron (kg)	0.10	0.005	0.10	0.007	0.11	0.002
Magnesium (kg)	5.0	0.37	5.3	0.61	5.6	0.06
Phosphorus (kg)	12.0	0.84	12.6	1.37	13.4	0.14
Potassium (kg)	20.8	1.18	21.8	1.96	23.1	0.30
Sodium (kg)	0.23	0.023	0.24	0.036	0.26	0.002

Table 6.9 Mean nutrients (per 100g edible food) produced at three different plant densities by inter-crop maize/beans per hectare for 1997/1998 growing season under full and supplementary irrigation. (calculated from the Medical Research Council, food composition tables, 1991).

Nutrient	Mean nutrient production /ha		
	Block I	Block II	Block III
Energy (MJ)	10562 a	10009 a	9466 a
Protein (kg)	726 a	696 a	665 a
CHO (kg)	5245 a	4950 a	4661 a
Vitamin C (mg)	0.024 a	0.024 a	0.024 a
Vitamin E (mg)	0.040 a	0.038 a	0.036 a
Calcium (kg)	2.167 a	2.155 a	2.131 a
Iron (kg)	0.109 a	0.107 a	0.104 a
Magnesium (kg)	5.846 a	5.586 a	5.325 a
Phosphorus (kg)	13.9 a	13.3 a	12.7 a
Potassium (kg)	23.6 a	22.8 a	21.9 a
Sodium (kg)	0.270 a	0.255 ab	0.241 b

Means with the same letter are not significantly different at 1% level by Tukey's Studentized Range (HSD) Test.

6.5 Conclusion

From the literature reviewed, it is clear that nutrient deficiency is a serious but a yet common problem among rural black people in South Africa. Dietary calcium deficiency has been found to be responsible for rickets and bone deformities in rural South African children. This work has shown that inter-cropping provides more nutrients than mono-cropping per hectare. This has an advantage in that while maximising the nutrient yield per hectare there is also maximisation of the land which is quite limited in South Africa especially among rural black communities. The findings agree with the recommendations of Vorster *et al.*, (1994) that when intake of animal products and fruits are low, then maize as a staple food supplemented with legumes, vegetables and nuts (beans, pumpkin, maroho and peanuts) can yield a reasonably well balanced diet. This study has quantified and found that inter-cropping contains more nutrients per unit area than mono-cropping. Therefore, encouraging small-scale farmers to practice inter-cropping would benefit them in terms of nutrient availability in their meals as researchers have shown that most of the rural black South Africans consume maize meal daily as a staple diet. Their eating patterns need to change to accommodate more legumes/pulses than are currently consumed. This study has also found out that practising inter-cropping would be beneficial as this would increases the quantities of nutrients that would be available for consumption by rural black communities. Hence, this will reduce the deficiencies that occur due to inadequate nutrients in diets of rural black communities. There is also a need to further investigate the nutrient content of most of the crops grown in inter-cropping systems.

CHAPTER 7

SIMULATION OF MONO AND INTER-CROPPING SYSTEMS

7.1 Introduction

South Africa is changing rapidly with high population growth rate and also major changes in the political and economic systems. This has created an urgent need to verify new and revise many existing small-scale agricultural systems. Agricultural decision makers at all levels need an increasing amount of information to better understand the possible outcomes of their decisions and to assist them in developing plans and polices that meet their intended goals. Dynamic mathematical simulations of maize growth are indispensable for determining the maize production potential of different climates, for identifying those areas where present knowledge is deficient, and for identifying the processes and most important parameters which control maize growth and development. Modelling is perhaps the most economical way of generating a range of possible solutions to key questions, while real solutions will come from experiments designed to test model predictions. The models to be used in this research are the Putu and BEWAB Models developed by De Jager and King (1974) and Bennie *et al.*, (1988) respectively. The name Putu was taken from the Zulu language and means porridge.

Hutson (1996) reported that much controversy and uncertainty exists surrounding the terms "Model verification," "Model validation," and Model calibration." To address this issue, the American Society for Testing and Materials (ASTM, 1984) defined verification as "the examination of the numerical technique in the computer code to ascertain that it truly represents the conceptual model and that there are no inherent numerical problems with obtaining a solution." Validation is "the comparison of model results with numerical data independently derived from experiments or observations of the environment." According to the ASTM, calibration is related to validation because it involves the adjustment of uncertain parameter values to obtain a match between prediction and measurement. The scarcity of data often limits calibration and model validation. In a simpler language, Dent *et al.* (1980) defined verification as the process in model development whereby the computer program of the model is checked for logical consistency while validation is the process of testing for agreement between model-behaviour and behaviour of the real system.

7.2 Literature review

7.2.1 Putu Simulation Model

The initial Putu model, a mechanistic seasonal maize crop growth model, was first developed in 1973. Its initial construction was described by De Jager (1974) and De Jager & King (1974). The computing stages (modules) and partitioning of dry matter were described by De Jager (1974). A version of Putu specifically for wheat, Putu 6 was developed later. All the important functions were described by De Jager *et al.* (1981). Putu 6 was modified for irrigation scheduling and renamed Putu 9. The original version performed an hourly iteration. However, the degree of accuracy attained did not justify the excessive computing time. Therefore, Putu 9 was modified to Putu 9.86 to perform a daily iteration for irrigation purposes. This was also described by De Jager *et al.* (1983).

Then came Putu 12 and the most attractive feature of Putu 12 was its modular construction. The sequence of operations executed were extremely simple to follow and understand. In 1985, the model was completely restructured and simplified. It now became easy to follow computational steps in the model. Since then the model has been continually updated and validated, incorporating the most recent research results. The Putu family of models at present contain crop growth simulation models of most crops, and daily irrigation scheduling models for these crops.

In 1988 the Putu 12.8 maize crop growth model, a refined version of Putu 12.6 was seen to simulate yields at Glen, a semi-arid area, with acceptable accuracy (De Jager & Hensley, 1988). Comparisons between the Putu model and other models has been performed by scientists (Hensley *et al.*, 1997). In comparing DSSAT 3 (Tsuji *et al.,* 1994) and Putu maize and wheat, Hensley *et al.* (1997) reported that these models sometimes gave reliable yield predictions although they were sometimes also unreliable. Both models had better soil water content predictions than those of yield, although the former were also unreliable at times.

The following important weaknesses were found in the models:

(i) the ack of a subroutine to deal with water logging in maize ecotopes,

(ii) the lack of a subroutine for the absence of secondary roots in wheat,

(iii) the inability of Putu to predict high yields on the Bethal/Hutton and Bethal/Avalon ecotopes,

(iv) excessive maize root water extraction rate frequently simulated by DSSAT 3 during the last part of the growing season,

(v) unsatisfactory runoff subroutines for both models,

(vi) unsatisfactory stress prediction subroutines, especially in DSSAT3,

(vii) the lack of subroutine to cater for lateral water movements in the root zone

Putu Model has since undergone some modifications to accommodate the identified weaknesses and improve its performance. The latest, Putu-AnyCrop is available from the Department of Agrometeorology, University of the Orange Free State in computer software packages (De Jager, 1997). Simulation models are developed as tools to help researchers screen innovations and identify those in which confidence can be placed. Simulation does not replace field trials, but supplements them. The Putu model calculates daily plant growth based on temperature, radiation, rainfall, and soil characteristics. The Putu model is now well established and has been used for simulating yields for various crops under mono-cropping systems. Thornton *et al.* (1990) pointed out that the ability of a model to simulate mono-crops as well as inter-crops gives the investigator considerable flexibility in the choice of agronomic strategies. It is in this direction that both the Putu Model and BEWAB Model are heading as they have been successful in mono-crop simulation.

7.2.1.1 Putu theory

Goudriaan & Monteith (1990) proposed an alternative function to describe the growth of crop stands. Its sound physiological basis was developed by assuming that, when light is limiting, growth rate is proportional to intercepted radiation and is therefore an exponential function of leaf area. The function continues by describing the transition from exponential to linear growth, hence the term *expolinear* growth Equation. Expolinear growth functions for both leaf area index development and dry matter accumulation have been incorporated in Putu-AnyCrop which together with its other subroutines, crop evaporation formulae and soil water balance are described in detail by De Jager

(1997). The parameters of the Equation are an initial maximum relative growth rate R_m, (d^{-1}) a maximum absolute growth rate C_m, (g m^{-2} d^{-1}) and a time t_b (days) at which the stand effectively passes from exponential to linear growth.

Leaf growth

For practical purposes, the fraction f of incident radiation intercepted by foliage can be adequately described by Equation 7.1, Beer's function;

$$f = 1 - \exp(-KL) \qquad 7.1$$

where, L is the leaf area index and K is the light extinction coefficient which depends on the average spectral properties of leaves and on their orientation in relation to the spatial distribution of solar radiation.

Goudriaan and Monteith (1990) assumed that crop growth rate $\frac{\delta W}{\delta t}$ is proportional to light interception, increasing at a time-dependent rate C, therefore;

$$\frac{\delta W}{\delta t} = C = f\,C_m = [\,1 - \exp(-KL)\,]\,C_m \qquad 7.2$$

Where, C_m is the maximum crop growth rate achieved when all incident light are intercepted ($f \approx 1$). Assuming that the fraction of growth of total dry matter allocated to new leaves (dynamic leaf weight ratio) is p_l (m^2 g^{-1}) and that the specific leaf area of these leaves is s (m^2 g^{-1}) (Goudriaan & Monteith, 1990). Then from Equation 7.2, it follows that;

$$\frac{\delta L}{\delta t} = f\,C_m\,p_l\,s \qquad 7.3$$

Substituting for $\frac{\delta W}{\delta t}$ in Equation 7.2 resulted in Equation 7.4,

$$\frac{\delta L}{\delta t} = [\,1 - \exp(-KL)\,]\,C_m\,p_l\,s \qquad 7.4$$

Integrating Equation 7.4 lead to the derivation of Equation 7.5, the expolinear function for leaf area development (L);

where L_i is the initial leaf area index and R_m is the maximum relative growth rate given by;

$$R_m = C_m \, p_l \, s \qquad 7.6$$

Leaf area ratio, LAR (m^2 g) is given by;

$$\mathrm{LAR} = \frac{R_m}{C_m} \qquad 7.7$$

Biomass growth

The genetic potential of dry mass growth rate can be limited by either solar and thermal energy input, or by water. Plant growth simulation in Putu can be undertaken in two states, either energy limited, or water limited. Goudriaan and Monteith (1990) substituted the expolinear expression for L (Equation 7.5) into the expression for $\frac{\delta W}{\delta t}$ to produce the differential Equation from which total crop growth rate may be computed;

$$\frac{\delta W}{\delta t} = C_m \frac{\left[\exp(KL_i) - 1\right]\exp\left(\int_0^t KR_m t\right)}{1 + \left[\exp(KL_i) - 1\right]\exp\left(\int_0^t KR_m t\right)} \qquad 7.8$$

integration of Equation 7.8 yields the expolinear crop growth function giving;

$$W = \left(\frac{C_m}{R_m}\right) \ln\left[1 + \exp(R_m(t - t_b))\right] \qquad 7.9$$

The expolinear function describes a crop total dry mass vs. growth curve with an initial exponential growth rate, which gradually decays into a constant maximum growth rate (C_m). From Equation 7.9, the concept 'lost time' (t_b) was introduced. It is defined as the intercept of the linear growth rate curve on the time (x-axis) i.e. time lost before the maximum linear growth rate commences. Further details of the expolinear function as applied in Putu are outlined in De Jager (1997) and Howard (1997). The method on how to determine the input parameters, *LAR*, C_m , t_b and K in practice is explained by De Jager (1997).

7.2.2 BEWAB Model

BEWAB is an irrigation scheduling program developed by Prof. A.T.P. Bennie and co-staff at the University of the Orange Free State (Bennie *et al.*, 1988) based on the soil water balance and is aimed mainly at irrigation scheduling. The program is written in GW-BASIC language which makes it user friendly making it easy to use by irrigation farmers and or extension officers. When using BEWAB, scheduling of irrigation is done for a specific yield target using a soil water balance method. The total amount of irrigation water needed for a target yield, or the crop water demand is calculated from an empirical water production function. The concepts of profile available water capacity (PAWC) and a stress index are also included. The amount of water between the upper and lower limit in the root zone before the onset of mild stress is the profile available water capacity (PAWC) (Hensley & De Jager, 1982). The inputs needed in BEWAB Model are: type of crop, length of the growing season, target yield, depth of soil, silt and clay content for 200 mm depth intervals and selected rain storage capacity. The total consumptive water use over the season is estimated for a selected target yield from the upper boundary water production functions based upon empirically determined water use-yield relationships. The daily crop water demand is estimated from relative crop water demand curves, also based on historic data (Bennie, 1991). The output consists of a printout of a recommended water application schedule (Appendix xviii).

The general objective of this chapter was to improve the dry mattter subroutine of Putu-AnyCrop for maize and beans in mono-crop and inter-crop systems under irrigation, with special reference to accomodate the effect of plantt density. Dry matter components such as leaf, stem and seed yield were included.

7.3 Rationale and specific objectives

In South Africa, arable land is limited and the available irrigable land has to be utilised to maximise production. Since 1994 soon after the new government came into power, one of their promises was to resettle people. In the Free State, the Free State Department of Agriculture intends to resettle more than 3000 farmers, of whom many will be small-scale farmers. The managers charged with the responsibility of resettling small-scale farmers need to have information regarding the areas required, and a decision support system to assist in resettling. Small-scale farming in the new settlements has to be sustainable for food security. Thornton *et al.* (1990) indicated that much work remains to be done before managers and economists will have access to generic inter-cropping models of the important crop associations in the tropics, to generate the information needed in the decision-making process. Inter-cropping models could be operated in a predictive mode (Thornton *et al.*, 1990). It is with this in mind that this research attempted finding solutions regarding decision support systems. Such decision making will entail the use of crop models with weather and soil input data to simulate (i.e. predict) the yields and water use to be expected in a given climate-soil-crop situation. By undertaking a number of " what if " situations, comparing mono-crop and inter-crop yields, decision makers will be able to ascertain the best radiation and water-use efficient crop combination and cultivation practices (including irrigation and dry land). The first step towards this goal is developing expertise in the use of mono-crop and inter-crop models capable of quantifying potential yield and water-use in given circumstances. Hence, the overall objective of this chapter will be to demonstrate that suitable models for this type of decision making:

(i) do exist,

(ii) are reliable enough for the task,

(iii) are easy to use (with few input parameter requirements), and

(iv) come in computer software packages.

This will be achieved in this chapter by aiming specifically to:

(i) use an existing model (Putu) for irrigation scheduling for small-scale irrigation farming systems under inter-cropping

(ii) validate existing crop models (Putu and BEWAB) for small-scale irrigation farming systems which will provide estimates of water demand and potential yield and this will also assist managers planning resettlement.

Although BEWAB is a pre-plant instructive model rather than a response model (Van Rensburg *et al.*, 1991), in this research, the irrigation program was used to test its reliability in irrigation scheduling. This was done by comparing the measured crop water use with the amounts predicted by the BEWAB Model for the actual yields obtained during the 1996/1997 growing season. The following inputs were used:

(i) A maize growing season of 150 days,

(ii) Target yields of 10310, 9010 and 7895 Kg ha^{-1} which were actual experimental yields attained,

(iii) A reserved rain storage capacity of 30mm,

(iv) Overhead irrigation method, and

(v) A 3 day irrigation interval

7.4. Results and discussion

Essentially, serial harvest data from the 1996/1997 growing season were used to evaluate the Putu models, input parameters and test how well the models performed in this season (Appendix xvii for serial harvest data and Appendix xix for input parameters). The input parameters for Putu, C_m, maximum crop growth rate (Goudriaan & Monteith 1990) (also referred to as vegetative growth rate, CGR_v, by Gardner *et al.*, 1990) were determined as explained in Section 2.3.1.1 of Chapter 2. These were found to vary with plant density as well as with the cropping systems. It was found that mono-crops had a higher maximum vegetative crop growth rate than inter-crops at all three plant densities (Table 7.1). Similar results were also obtained for beans. The growth rates obtained agree well with the findings of Gardner *et al.* (1990). These values were used as inputs in the Putu models for simulations. It was found that inter-crop beans took the same time to reach t_b (time taken by the vegetation to effectively pass through the exponential growth rate to linear) but had varying growth rates increasing with plant density (Table 7.1). In both mono-crop and inter-crops, the behaviour of increasing growth rates with density agrees with respect to grain and biomass as reported in Chapter 4.

Table 7.1 Leaf area ratio (LAR), crop growth rate (C_m) and lost time (t_b) for mono-crop and inter-crop maize and bean at three plant densities for 1996/1997 growing seasons.

Crop/Density	Mono-crop			Inter-crop		
Maize	*LAR* (g m^{-2})	C_m (g m^{-2} d^{-1})	t_b (days)	*LAR* (g m^{-2})	C_m (g m^{-2} d^{-1})	t_b (days)
Low	0.0062	25	32	0.0062	20	22
Medium	0.0062	27	29	0.0064	23	27
High	0.0045	42	27	0.0062	32	32
Beans	*LAR* (g m^{-2})	C_m (g m^{-2} d^{-1})	t_b (days)	*LAR* (g m^{-2})	C_m (g m^{-2} d^{-1})	t_b (days)
Low	0.02	10	28	0.0125	6	45
Medium	0.02	14	26	0.0125	7	45
High	0.02	18	24	0.0125	8	45

7.4.1 Putu Model verification

7.4.1.1 Maize Model

The crop physiological and weather data collected during the 1996/1997 and 1997/1998 were used to verify and validate the Putu-AnyCrop model. The parameters for input in Putu-AnyCrop model (*LAR*, C_m , t_b and *K*) determined from the serial harvest as explained in Section 2.3.1.1 of Chapter 2 were entered into Putu and the simulation was run. This was done for mono-crop and inter-crop maize and mono-crop and inter-crop beans. The simulated data and measured values for the three plant densities from mono-crop maize were plotted against time (Figure 7.1 a, b & c). The models were then validated by correlation, regression and tests of simulation accuracy as explained in Section 2.3.1.2 of Chapter 2 (Wilmott, 1982). Outliers were not included in the statistical analysis (Table 7.2). The Wilmott index accounts for errors in the slope and intercept. Generally, a Wilmott index of greater than 0.80 indicates a reliable model accuracy. The 80% accuracy frequency was also determined and was defined as the percentage of simulated values accurate within 80% of the measured values. Only the statistics for total dry matter production and grain yield are shown (Table 7.2) but the graphs contain the remaining yield components including outliers except for root biomass. The statistics show that Putu-AnyCrop model was able to simulate above ground biomass accurately at all three plant densities (Figure 7.1 a, b & c). The high r^2 (0.96) and simulation index (Wilmott, 1982) of 0.98 and 0.72 and 0.85 for total dry matter and grain yield for low plant density respectively, the high r^2 (0.91) and simulation index (Wilmott, 1982) of 0.94 and 0.85 and 0.87 for total dry matter and grain yield for medium plant density respectively and the high r^2 (0.90) and simulation index (Wilmott, 1982) of 0.97 and 0.84 and 0.94 for total dry matter and grain yield for high plant density respectively all testify to this precision (Table 7.2 & Table 7.4). It should be pointed out that the measured value of high density mono-crop maize was lower than the simulated value (Table 7.4). Because the rest of the yield components simulated were within 20% error, it is most likely that there could have been a measurement error in the measured value of high density mono-crop maize leading to a low yield.

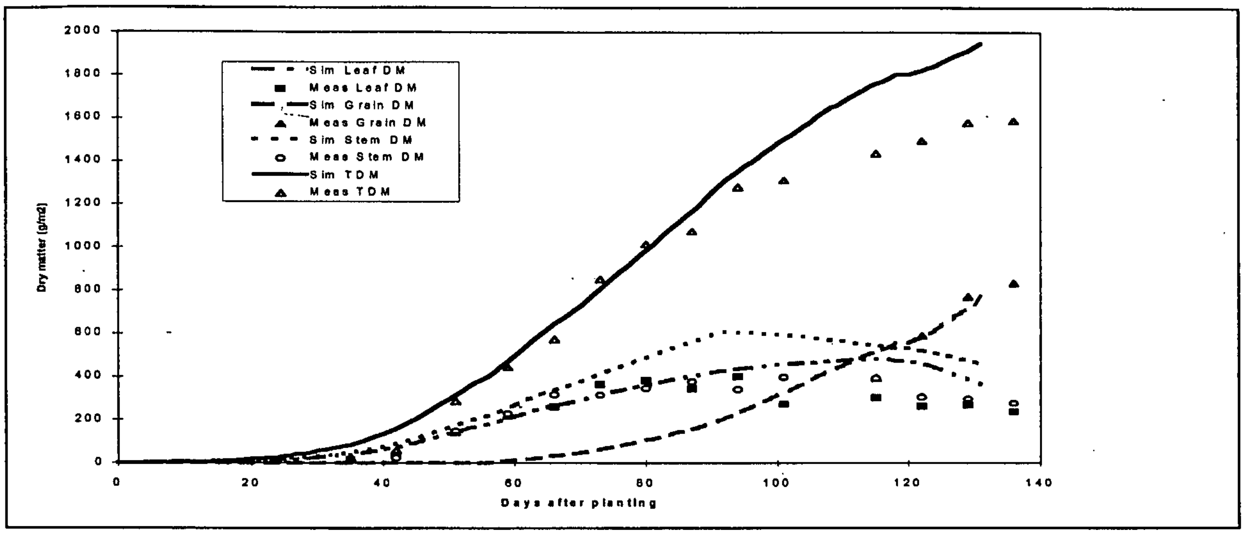

Figure 7.1a Measured and Putu simulated dry matter production for low density mono-crop maize for 1996/1997 growing season.

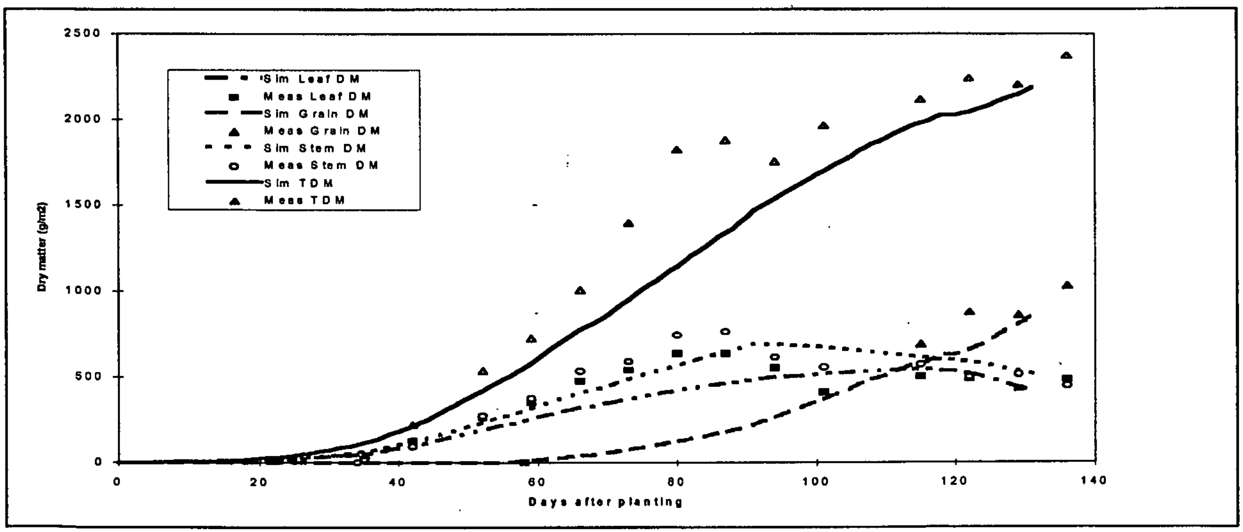

Figure 7.1b Measured and Putu simulated dry matter production for medium density mono-crop maize for 1996/1997 growing season.

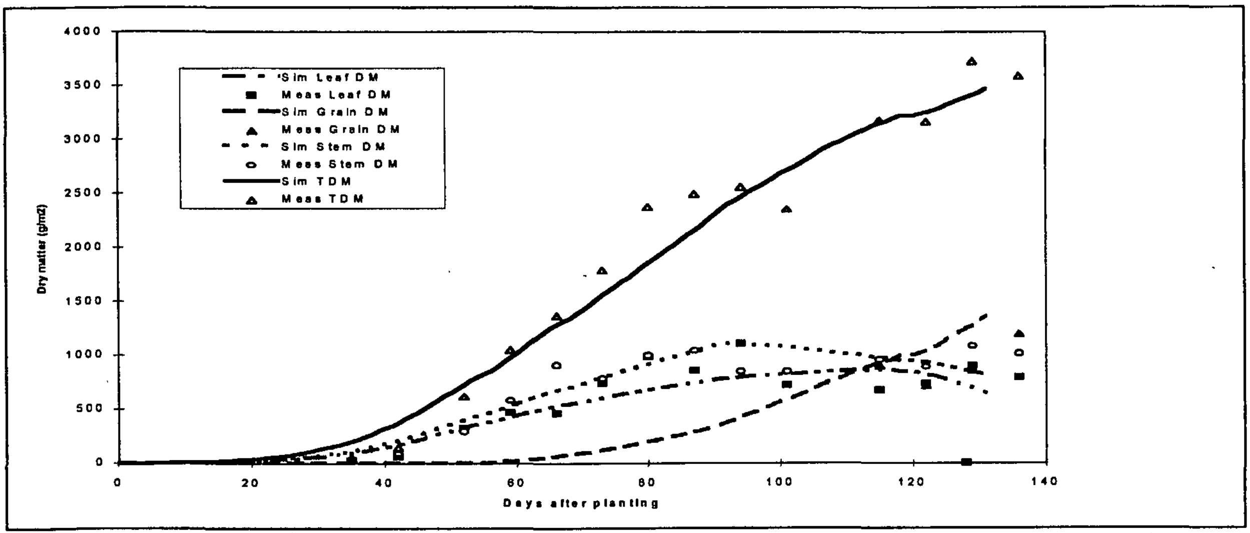

Figure 7.1c Measured and Putu simulated dry matter production for high density mono-crop maize for 1996/1997 growing season.

Table 7.2 Statistical analysis of the data used to verify the Putu models for mono-crop and inter-crop maize total dry matter (g m^{-2}) and seed yield (g m^{-2}) for 1996/1997 growing season.

Mono-crop Maize	Low density		Medium density		High density	
Statistical parameter	Total DM	Grain	Total DM	Grain	Total DM	Grain
Slope	1.1	0.76	0.9	0.73	0.94	0.77
Intercept	-47	96	-107	92	11.2	128
Correlation	0.98	0.85	0.96	0.92	0.95	0.92
R Square	0.96	0.72	0.91	0.85	0.90	0.84
Simulation index	0.98	0.90	0.94	0.87	0.97	0.94
Max. abs difference	191	209	680	221	519	235
Mean abs difference	75.	89	251	99	203	81.7
RMSE	92	113	318	126	258	112
Systematic RMSE	64	62	318	112	108	73
Unsystematic RMSE	65	94	259	57	234	84
80% Accuracy freq.	100%	60%	60%	75%	89%	67%
Number of pairs	7	5	12	4	9	6
Inter-crop Maize						
Slope	0.90	0.78	0.88	0.82	1.0	1.2
Intercept	119	22	118	60	-152	-141
Correlation	0.97	0.88	0.97	0.98	0.96	0.93
R Square	0.95	0.78	0.93	0.97	0.93	0.87
Simulation index	0.98	0.84	0.98	0.97	0.98	0.94
Max. abs difference	193	280	158	112	335	90
Mean abs difference	97	128	91	64	194	68
RMSE	108	156	102	72	215	76
Systematic RMSE	46	135	47	65	99	42
Unsystematic RMSE	97	78	91	31	191	63
80% Accuracy freq.	82%	60%	88%	100%	67%	100%
Number of pairs	11	5	8	4	12	4

Similarly, simulated yields and measured values for inter-crop maize were plotted against time for the three plant densities (Figure 7.2 a, b & c). The statistics (Table 7.2) again showed that Putu-AnyCrop model competently simulated above ground biomass at all three plant densities. Outliers were not included in the statistical analysis but included on the simulation graphs. The high r^2 (0.95) and simulation index (Wilmott, 1982) of 0.98 and 0.78 and 0.84 for total dry matter and grain yield for low plant density respectively, the high r^2 (0.93) and simulation index (Wilmott, 1982) of 0.98 and 0.97 and 0.97 for total dry matter and grain yield for medium plant density respectively and the high r^2

(0.93) and simulation index (Wilmott, 1982) of 0.98 and 0.87 and 0.94 for total dry matter and grain yield for high plant density respectively all testify to this observation (Table 7.2 & Table 7.4).

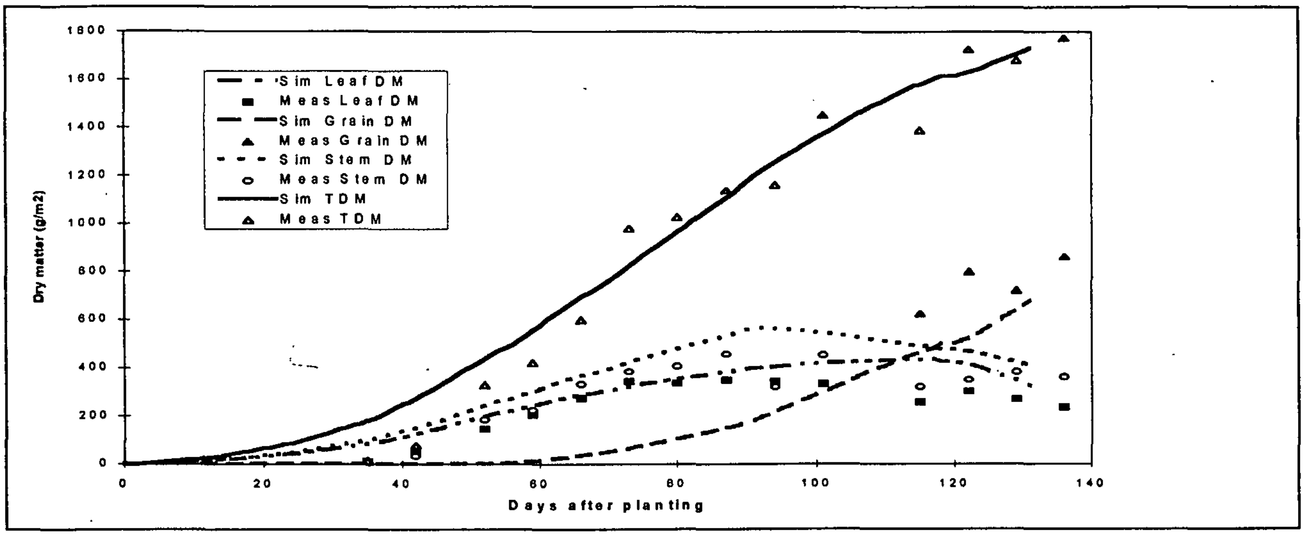

Figure 7.2a Measured and Putu simulated dry matter production for low density inter-crop maize for 1996/1997 growing season.

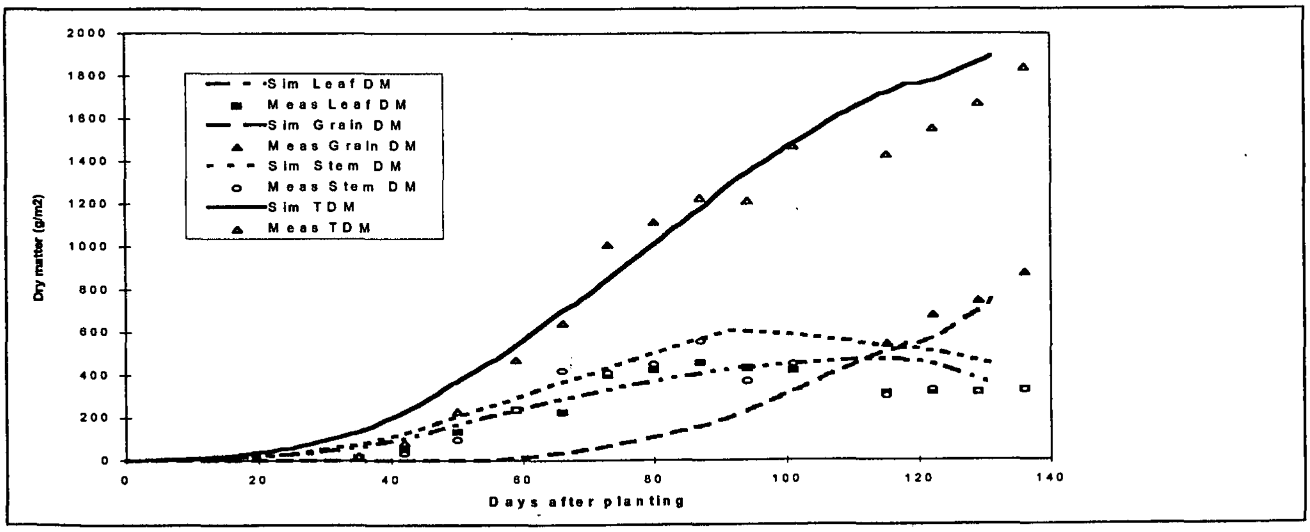

Figure 7.2b Measured and Putu simulated dry matter production for medium density inter-crop maize for 1996/1997 growing season .

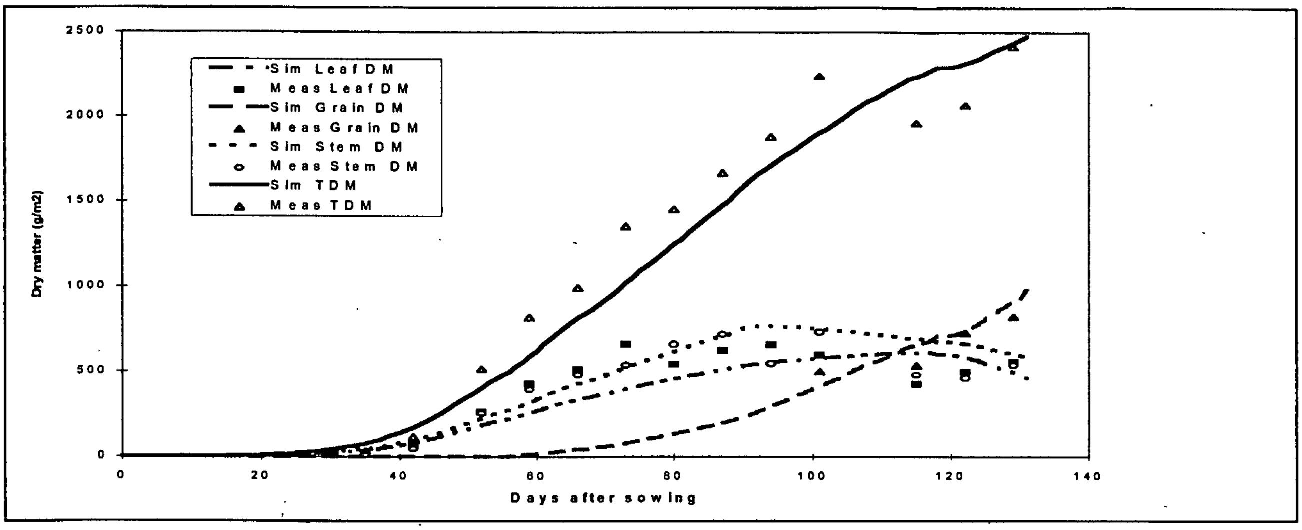

Figure 7.2c Measured and Putu simulated dry matter production for high density inter-crop maize for 1996/1997 growing season .

7.4.1.2 Bean Model

The bean mono-crop simulated and measured values were similarly plotted against time for the three plant densities (Figure 7.3 a, b & c). The statistics (Table 7.3) again showed Putu-AnyCrop simulating above ground biomass reasonably accurately at three plant densities. The high r^2 (1.0) and simulation index (Wilmott, 1982) of 0.99 and 1.0 and 0.86 for total dry matter and grain yield for low plant density respectively, the high r^2 (0.96) and simulation index (Wilmott, 1982) of 0.95 and 0.93 and 0.88 for total dry matter and grain yield for medium plant density respectively and the high r^2 (0.94) and simulation index (Wilmott, 1982) of 0.92 and 0.95 and 0.91 for total dry matter and grain yield for high plant density respectively all testify to this (Table 7.3 & Table 7.4).

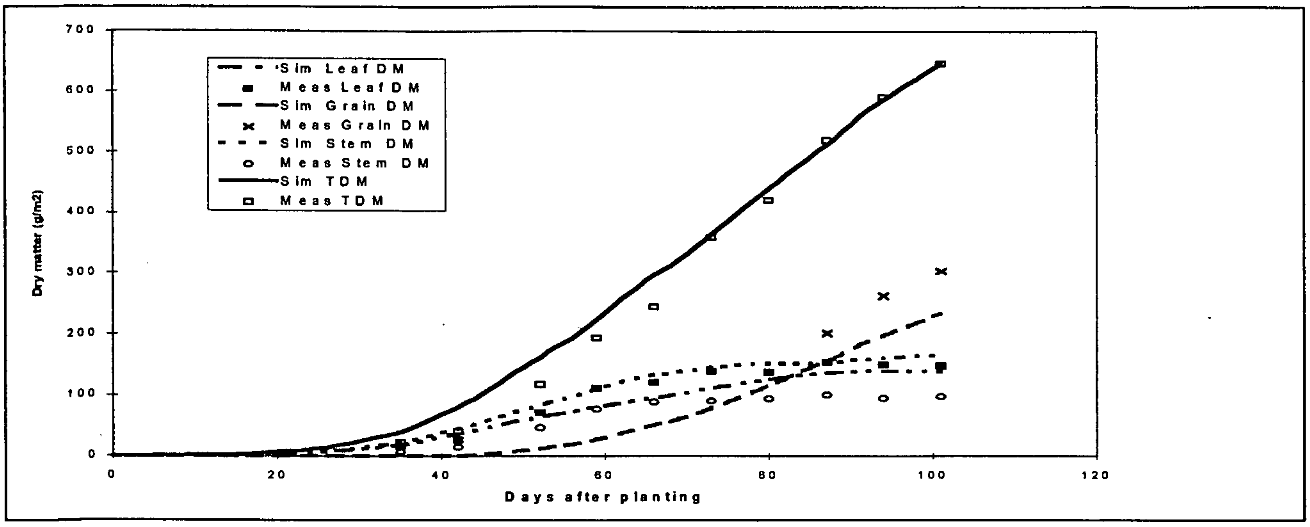

Figure 7.3a Measured and Putu simulated dry matter production for low density mono-crop beans for 1996/1997 growing season.

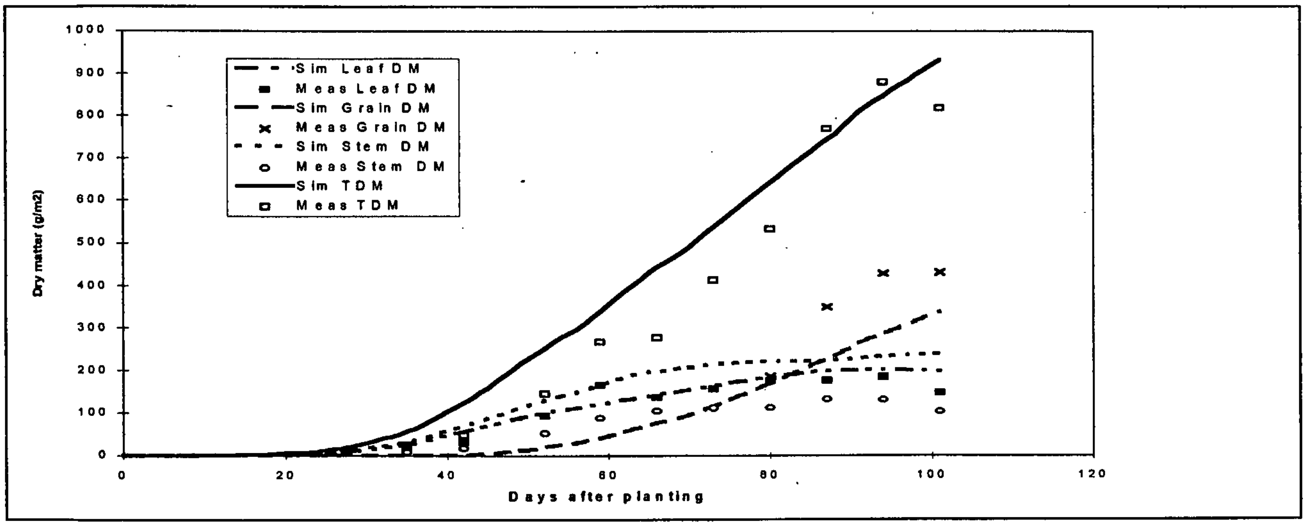

Figure 7.3b Measured and Putu simulated dry matter production for medium density mono-crop beans for 1996/1997 growing season.

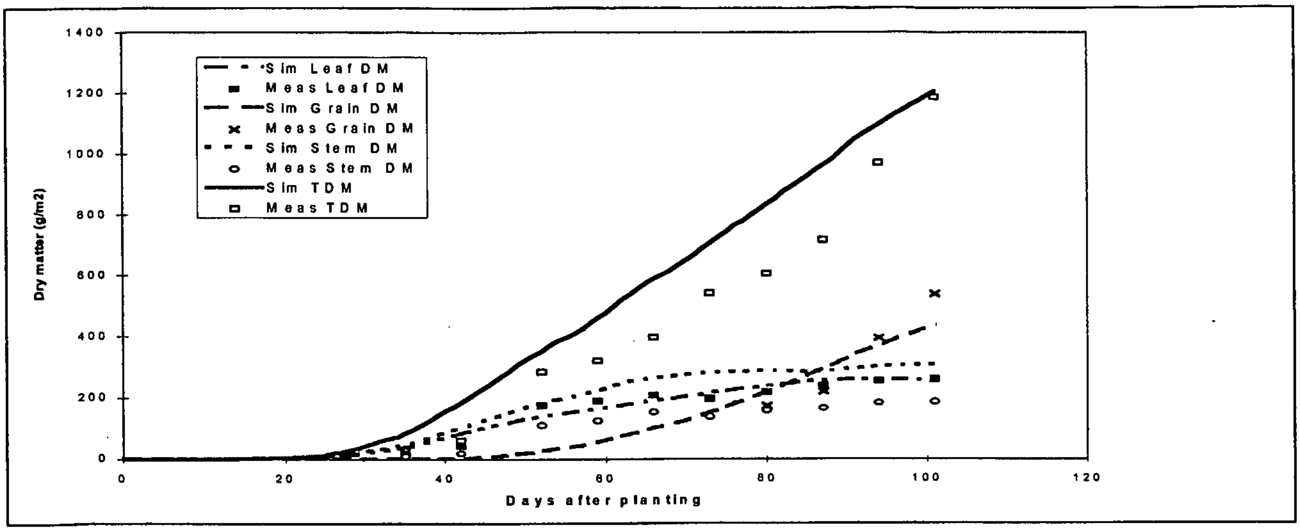

Figure 7.3c Measured and Putu simulated dry matter production for high density mono-crop beans for 1996/1997 growing season.

Table 7. 3 Statistical analysis of the data used to verify the Putu models for mono-crop and inter-crop beans total dry matter (g m^{-2}) and seed yield (g m^{-2}) for 1996/1997 growing season.

Mono-crop Beans	Low density		Medium density		High density	
Statistical parameter	Total DM	Seed	Total DM	Seed	Total DM	Seed
Slope	0.90	0.76	0.77	0.66	0.92	0.55
Intercept	57	2.3	180	32	197	146
Correlation	100	100	0.98	0.97	0.97	0.98
R Square	100	100	0.96	0.93	0.94	0.95
Simulation index	0.99	0.86	0.95	0.88	0.92	0.91
Max. abs difference	53	70	166	123	248	102
Mean abs difference	21	51	91	60	149	61
RMSE	29	54	102	77	165	68
Systematic RMSE	26	54	94	73	151	65
Unsystematic RMSE	11	2	40	22	69	18
80% Accuracy freq.	71%	20%	29%	50%	25%	50%
Number of pairs	7	4	7	4	8	4
Inter-crop Beans						
Slope	1.0	1.0	1.0	1.0	1.1	1.5
Intercept	19	-23	3	-30	-30	-95
Correlation	0.98	0.99	0.98	0.99	0.98	0.96
R Square	0.97	0.98	0.96	0.99	0.96	0.94
Simulation index	0.98	0.87	0.98	0.80	0.98	0.72
Max. abs difference	46	20	48	29	45	42
Mean abs difference	22	15	16	26	26	26
RMSE	26	15	21	26	30	29
Systematic RMSE	21	15	5	26	16	28
Unsystematic RMSE	15	3	20	2	26	7
80% Accuracy freq.	40%	75%	80%	50%	56%	50%
Number of pairs	10	4	10	4	9	4

Bean inter-crops simulations and measured values were equally plotted against time for the three plant densities (Figure 7.4 a, b & c). The statistics (Table 7.3) again showed Putu-AnyCrop simulating above ground biomass reasonably accurately at three plant densities. Similarly, outliers were left out of the statistical analysis. The high r^2 (0.97) and simulation index (Wilmott, 1982) of 0.98 and 0.98 and 0.87 for total dry matter and grain yield for low plant density respectively, the high r^2 (0.96) and simulation index (Wilmott, 1982) of 0.98 and 0.99 and 0.80 for total dry matter and grain yield for medium plant density respectively and the high r^2 (0.96) and simulation index (Wilmott, 1982) of 0.98

and 0.94 and 0.72 for total dry matter and grain yield for high plant density respectively all testify to this (Table 7.3 & Table 7.4).

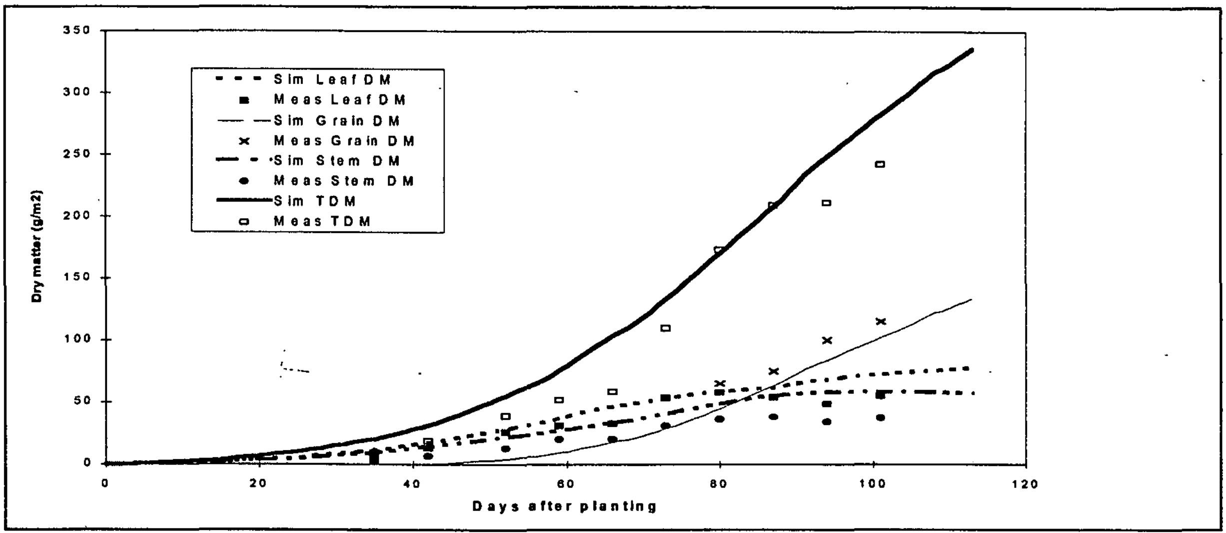

Figure 7.4a Measured and Putu simulated dry matter production for high density inter-crop beans for 1996/1997 growing season.

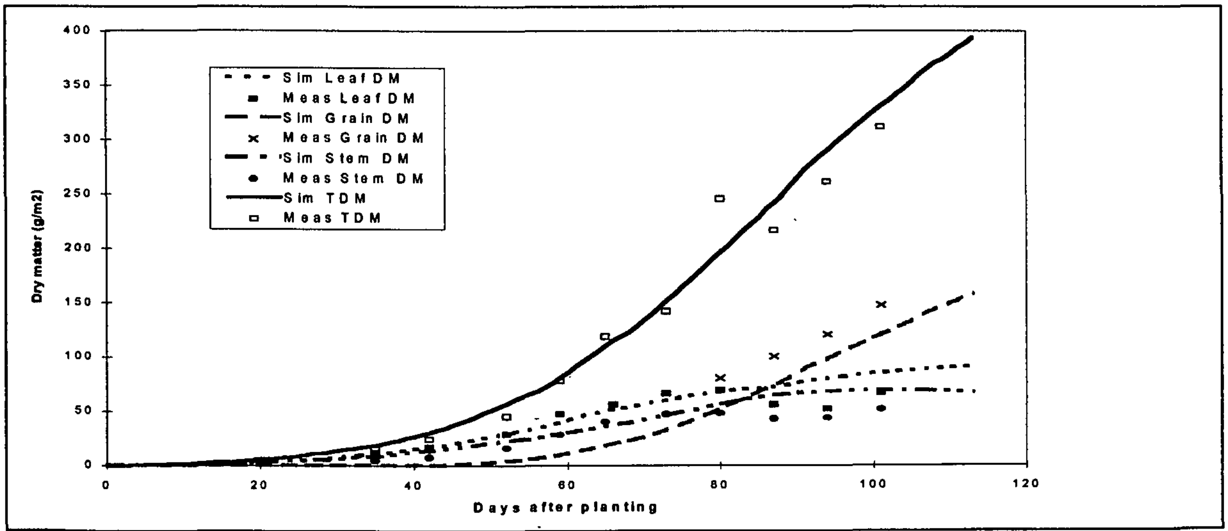

Figure 7.4b Measured and Putu simulated dry matter production for high density inter-crop beans for 1996/1997 growing season .

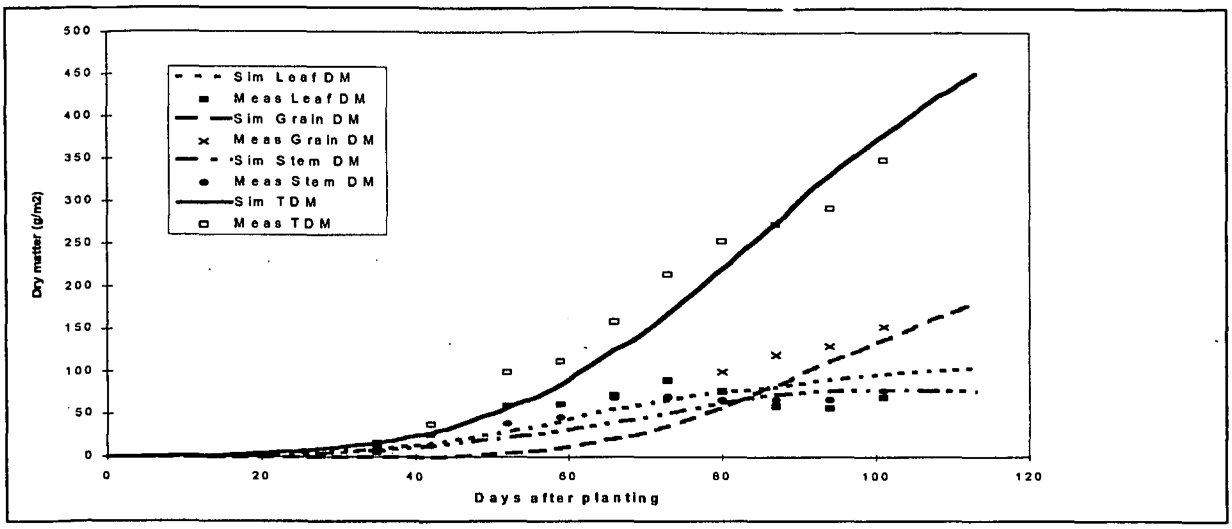

Figure 7.4c Measured and Putu simulated dry matter production for high density inter-crop beans for 1996/1997 growing season.

Table 7.4 Final measured and simulated mono-crop and inter-crop maize and beans standing dry matter production (gm^{-2}) used to verify Putu models for 1996/1997 growing season.

Cropping system		Density (g m^{-2})	Leaves (g m^{-2})	Stem (g m^{-2})	Grain yield (g m^{-2})	Total DM (g m^{-2})
Maize mono-crop	Measured	Low	243	327	789	1742
	Simu Putu		360	454	761	1935
	Measured	Medium	439	458	910	2513
	Simu Putu		403	508	851	2165
	Measured	High	711	829	1031	3673
	Simu Putu		638	805	1348	3430
Maize inter-crop	Measured	Low	202	229	600	1367
	Simu Putu		323	409	684	1740
	Measured	Medium	304	311	831	1698
	Simu Putu		352	445	745	1895
	Measured	High	460	593	899	2269
	Simu Putu		456	576	964	2454
Beans mono-crop	Measured	Low	148	97	281	645
	Simu Putu		138	165	234	646
	Measured	Medium	147	103	430	817
	Simu Putu		198	238	337	930
	Measured	High	260	185	539	1185
	Simu Putu		257	308	436	1204
Beans inter-crop	Measured	Low	55	37	114	242
	Simu Putu		72	59	102	283
	Measured	Medium	66	51	147	312
	Simu Putu		85	69	120	331
	Measured	High	70	77	153	348
	Simu Putu		97	78	137	378

The data used to verify the Putu-AnyCrop models produced accurate estimates of final yield for grain, leaves, stem and total dry matter in both mono-crop and inter-crop maize and beans (Table 7.4 & 7.5). Having produced statistically satisfactory results in 1996/1997, the year in which the input parameters were determined (Table 7.2 & Table 7.3), Putu-AnyCrop model was then validated on completely independent data of inter-crop maize for the 1997/1998 growing season grown under full irrigation. Mono-crop maize was not grown during the 1997/1998 growing season. Putu-AnyCrop performed well in terms of simulating grain yield for 1997/1998 growing season. Biomass data of individual plant organs were not collected during the 1997/1998 growing season (Table 7.4 & Table 7.5).

A stringent validation of the models verified in 1996/1997 growing season were undertaken using independent data collected in 1997/1998 growing season. The input parameters required by Putu were LAR, C_m, t_b and K. Putu-AnyCrop was later tested on full irrigation yield data for 1997/1998 growing season and it was found that Putu was able to simulate final grain yield reasonably accurately (Table 7.5). This is further confirmation as to the reliability of the Putu-AnyCrop models as other researchers have come up with satisfactory results from their simulations (Hensley *et al.* 1997) . Although more tests will be required with regard to inter-cropping, at this stage, Putu model has proved its versatility and is recommended for inter-cropping and mono-cropping use for decision support.

Table 7.5 Measured and simulated inter-crop maize and beans standing dry matter production (gm^{-2}) used to validate Putu model for 1997/1998 growing season.

Cropping system		Density ($g\ m^{-2}$)	Leaves ($g\ m^{-2}$)	Stem ($g\ m^{-2}$)	Grain yield ($g\ m^{-2}$)	Total DM ($g\ m^{-2}$)
Maize inter-crop	Measured	Low	-	-	428	-
	Simu Putu		438	538	389	1511
	Measured	Medium	-	-	504	-
	Simu Putu		475	583	411	1639
	Measured	High	-	-	426	-
	Simu Putu		615	756	532	2123
Beans inter-crop	Measured	Low	-	-	82	-
	Simu Putu		65	57	75	231
	Measured	Medium	-	-	92	-
	Simu Putu		76	66	87	268
	Measured	High	-	-	93	-
	Simu Putu		86	73	99	304

7.4.2 Soil water content simulation

The initial Putu-12 model utilised a double layer root zone (De Jager, *et al.*, 1986). Through extensive research, it became evident however, that a multi-layered root zone was required to improve simulation of water dynamics through a crop system. The modified Putu model now uses a nine-layered root zone. In these experiments, 0.30m layer thickness were chosen for soil water content measurements. As explained in Section 2.2.6.1 of Chapter 2, the experimental site had shallow soils and hence measurements were only taken up to 900mm depth level. The Putu model has been shown to simulate soil water content accurately (De Jager *et al.*, 1986; Anderson, 1997 & Howard, 1997). In this work seasonal variations of profile total soil water content were observed and simulated profile total soil water content were plotted against time for mono-crop maize (Figure 7. 5 a b & c) and mono-crop beans (Figure 7.6 a b & c) as well as inter-crop maize/beans (Figure 7. 7 a b & c). Profile total soil water content was defined as the amount of water contained between field capacity and wilting point in the 900mm profile. In mono-crop maize, Putu was found to simulate soil water content reasonably well at high plant density from 70 DAP where the percentage error was under 18%. The early stages of crop growth up to 70 DAP were observed to have soil water content values higher than the simulated values (Figure 7. 5 a b & c). Non-consistent (without trend) percentage errors were observed in low and medium density mono-crop maize. The percentage error ranged from 2%-26% for both plant densities. These errors being out of the 20% maximum implies that further work is required in these densities and more work on the vegetative stage in high density plants.

In mono-crop beans, Putu did not simulate soil water content reasonably well at low and medium plant density as observed in mono-crop maize (Figure 7. 6 a b & c). Putu was able to simulate profile total soil water content well (<20%) in high plant density and again except in the early stages (up to 70 DAP) of crop growth where the observed profile total soil water content were higher than the simulated values as was observed in mono-crop maize. In inter-crop maize/beans, Putu simulated soil water content reasonably well in high plant density (Figure 7. 7 a b & c) and in the early stages of crop growth (before 70 DAP), the observed profile soil water content were higher than the simulated values. In low and medium plant density, consistent behaviour was observed as was the case in mono-crop maize and mono-crop beans.

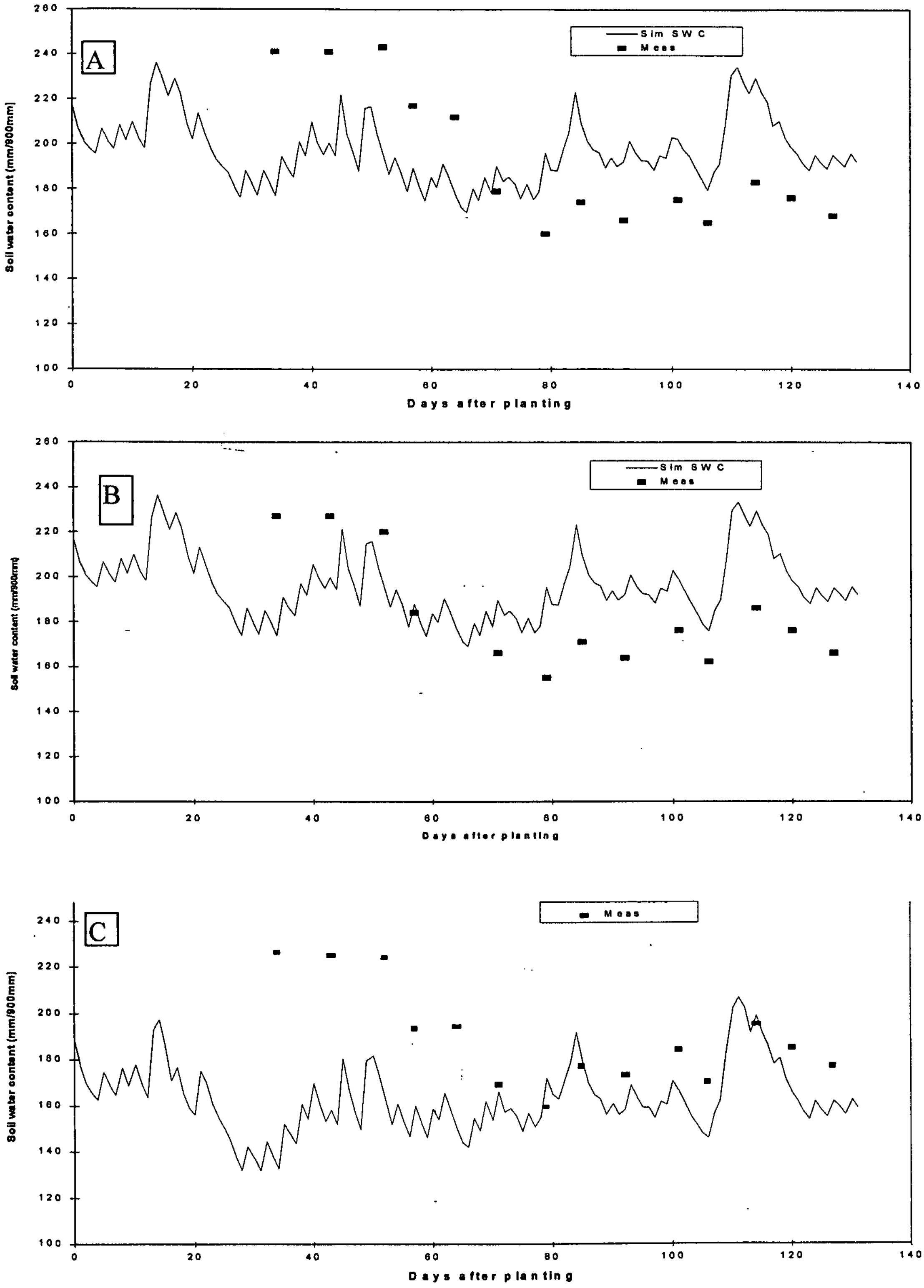

Figure 7.5 Seasonal variation in measured and Putu simulated profile total soil water content for maize monocrop for 1996/1997 growing season. Depicted are (A) low plant density, (B) medium plant density and (C) high plant density.

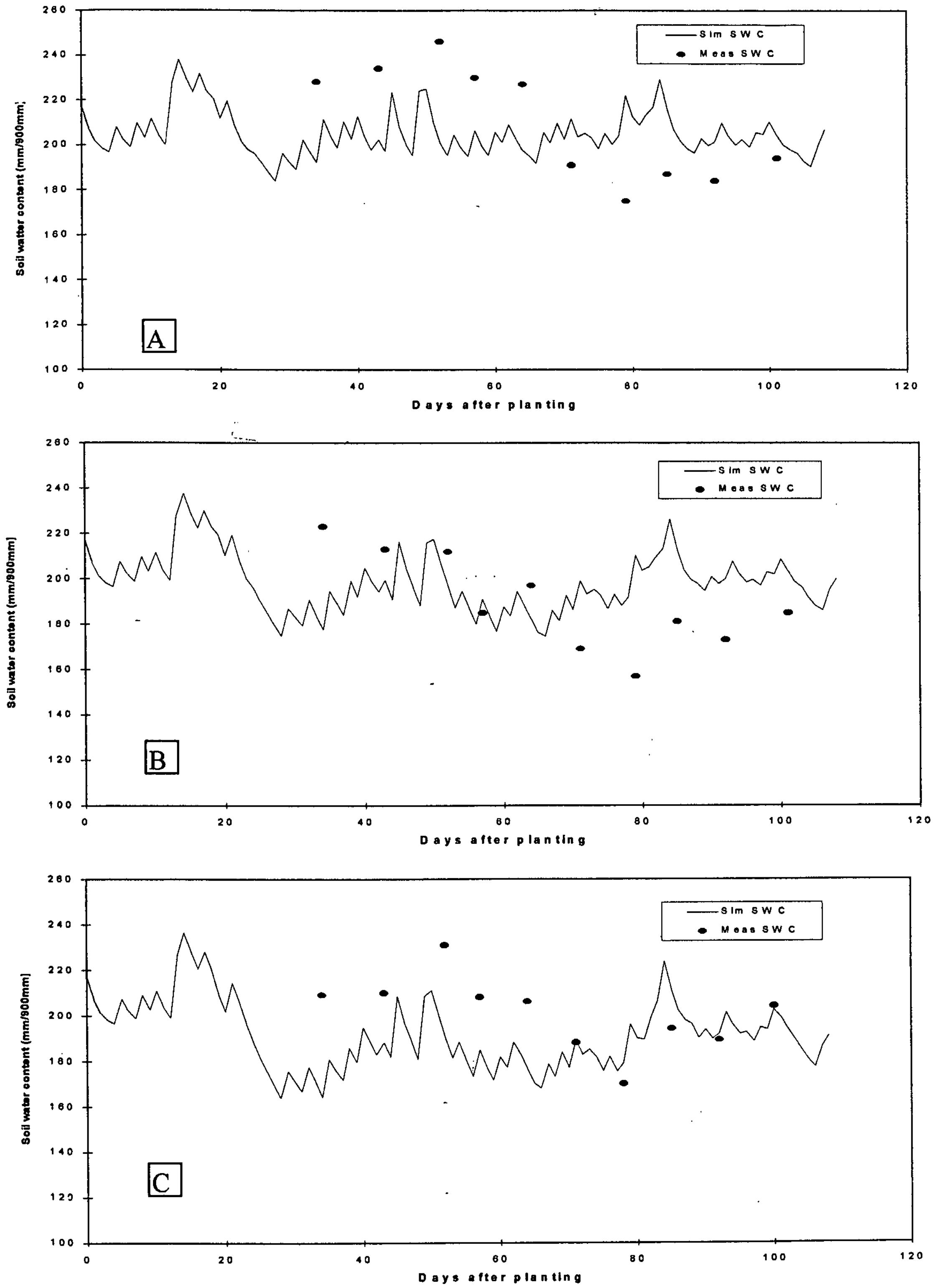

Figure 7.6 Seasonal variation in measured and Putu simulated profile total soil water content for beans monocrop for 1996/1997 growing season. Depicted are (A) low plant density, (B) medium plant density and (C) high plant density.

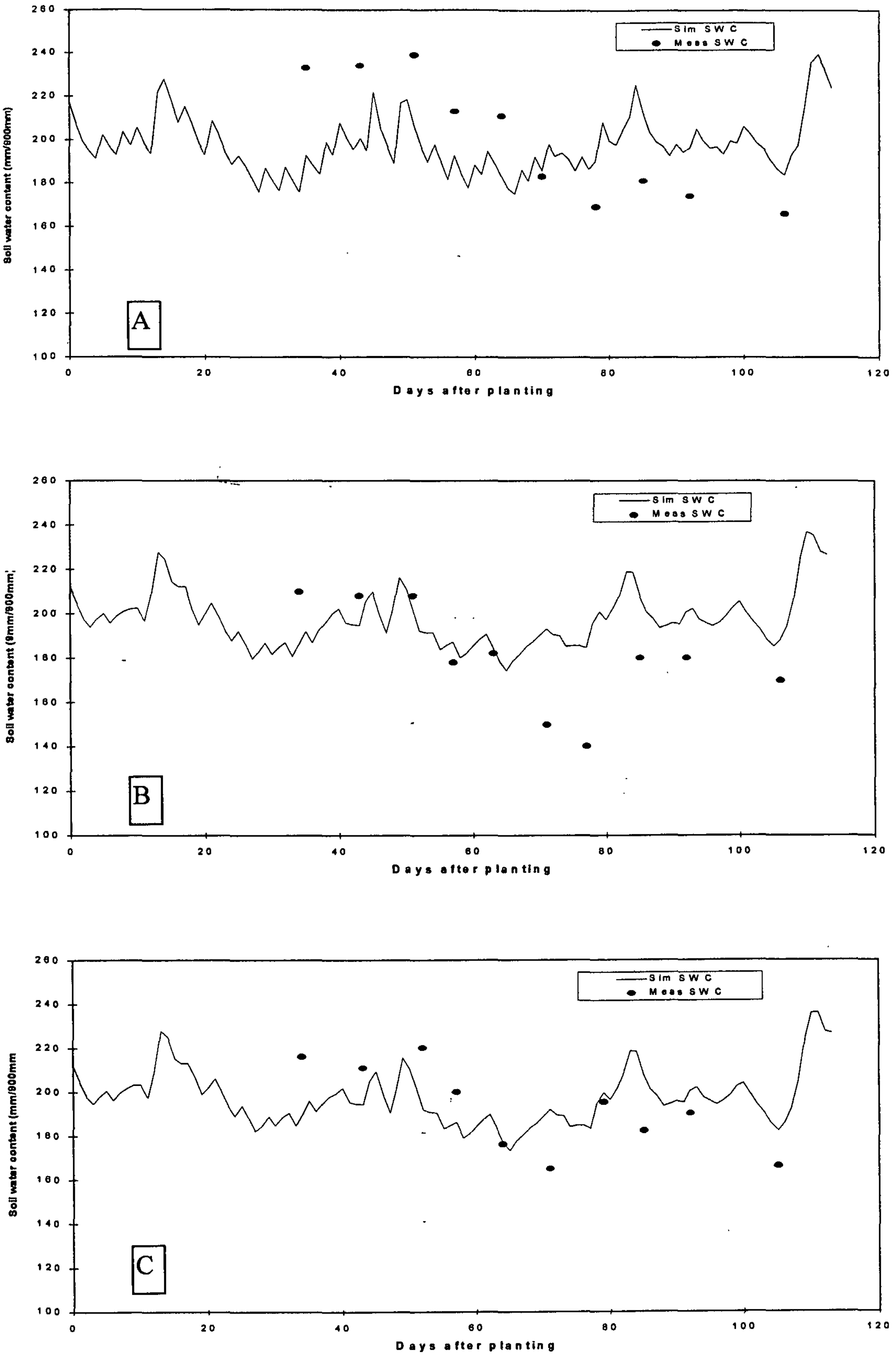

Figure 7.7 Seasonal variation in measured and Putu simulated profile total soil water content for maize/beans inter-crop for 1996/1997 growing season. Depicted are (A) low plant density, (B) medium plant density and (C) high plant density.

7.4.3 BEWAB Model

It was observed that the BEWAB Model was able to predict the water use of mono-crop maize to a reasonable degree. The measured water use values for mono-crop maize were 710, 751 and 694mm for low, medium and high plant densities compared to the water use values from BEWAB Model of 624, 686 and 758mm respectively (Table 7.6). The difference between predicted and observed water use values ranged from 1 - 18 % with the low density having the largest water use difference (Table 7.6). As BEWAB has been developed for maximum plant population, as may be expected it was able to predict water use best at high plant population (Table 7.6).

Table 7.6 Target yield and measured crop water use for mono-crop maize in each plant density with predicted water use values by BEWAB and percentage difference for 1996/1997 growing season

Maize plant density (m^2)	Target yield (Kg ha^{-1})	Crop water use (mm)		
		Observed	BEWAB	% difference of obs
2.2	7895	710	624	12
4.4	9010	751	686	8
6.7	10310	694	758	8

7.5 Conclusion

7.5.1 Putu-AnyCrop Model

Both Putu and BEWAB models were found to be suitably accurate and user friendly for the purpose of decision support for planning small-scale irrigation farming. High r^2 and Wilmott index values show that Putu-AnyCrop was able to simulate above ground biomass with acceptable accuracy. An added advantage of this model is to simulate biomass including leaves, stems, grain and total biomass. Putu-AnyCrop was found to simulate both mono-crop and inter-crop maize biomass and inter-crop beans accurately at three plantt densities. It may be concluded that although further tests need to be done, that Putu-AnyCrop is a reliable tool for decision support. With regard to soil water content, it was observed that Putu-AnyCrop approximated the measured soil water content quite accurately in the high plant densities of inter-crops and mono-crops . While daily simulation of profile total soil water content for low and medium plant density mono-crops and inter-crops proved inaccurate with percentage errors ranging from 2% - 26%. Simulated values of total crop water use for high plant density proved sufficiently accurate for providing decision support for planning small-scale farming while further work needs to be done on low and medium plant densities especially during the early stages of the crop.

It was observed as mentioned earlier on that Putu-AnyCrop model predicted the total biomass well including different plant organs. However, the model for leaf area index under estimates the leaf area index. Putu-AnyCrop also under estimates soil water content. These will have to be addressed in future research and will be corrected by adjusting specific leaf ratio. When Putu is used for scheduling irrigation, level II must be used, where the fractional interception f is inserted in the input parameter file.

7.5.2 BEWAB Model

It is evident that the accuracy of BEWAB model water use estimation in the context of this study was highly sensitive to the target yield selected. The Model BEWAB was able to predict the crop total water use with accuracy better than 20% and hence it was concluded that the model is reliable for scheduling irrigation for small-scale farmers. As indicated, simulations of water use for the BEWAB model are highly sensitive to target yield selected and hence care should be exercised when deciding what apriori values to use.

CHAPTER 8

SUMMARY AND RECOMMENDATIONS

8.1 Summary

The literature review revealed that one of the primary problems with the introduction of new irrigation systems, whether large or small in scale, was the lack of understanding by the agencies involved of the context (physical, social and economic) into which the new irrigation practices were being brought. Lack of knowledge of existing farming systems, marketing constraints, labour limitations, soil properties, and water resources, are just some of the aspects which can lead to the implementation of irrigation systems which in the end prove not viable. Deceived by the apparent simplicity of the technologies involved, development agencies often introduced such systems with inadequate prior understanding of either the farmer and farming system, on the one hand, or the land, water, and crops, on the other.

For the reasons stated this study examined the experiences of small-scale irrigation farmers using participatory rural appraisal (PRA), seeks sustainability for small-scale systems, and addressed the critical problems through field experiments based on experienced problems. The study had the following specific objectives:

(i) To undertake a survey of production practices and strategies at existing small-scale farming irrigation schemes in Free State Province, applying the participatory rural appraisal (PRA) approach.

(ii) To undertake social surveys simultaneously at these sites in order to determine expectations and aspirations of irrigation farmers.

(iii) To evaluate, through field experimentation, the implementation of relevant established small-scale crop production systems within the climatic constraints of the Free State Province.

   (a) To compare soil water use and utilisation efficiency of these production system combinations.

    (b) To compare photosynthetic active radiation utilisation efficiency of these production system combinations.
    (c) To compare inter-cropping and mono-cropping practices in terms of dry matter production and grain yield.
    (d) To examine the effect of different irrigation strategies (supplementary and full).

(iv) To evaluate and quantify the nutrient content in mono-cropping and inter-cropping and determine benefits of inter-cropping in terms of nutrient content.

(v) To improve the dry matter subroutine of Putu-AnyCrop for mono-crop and inter-crop maize and beans with special reference to the effect of plant density.

Results

Small-scale farming has existed for many years in many tropical countries including South Africa. The findings of the socio-economic survey were that traditional farming practices were being neglected and that effort should be made towards supplementing and encouraging rather than replacing existing small-scale irrigation farming practices. Means of improving crop yields, extending the growing season and improving nutrition must be strived for in order to improve the living standards of the rural communities. Unfortunately, the enabling environment with regard to social infrastructure, credit facilities, relevant extension and information services were not sufficient and even when development programmes were carried out either by government or non-governmental organisations, participatory approach has not been applied in the process of addressing the needs of the small-scale farmers and this did not allow small-scale farmers full authority over development programmes including land and water management.

Most sites surveyed had not paid attention to conservation of resources and there was rampant over use and wastage of natural resources. Sustainable and integrated use of land and water resources is essential to prevent soil deterioration and declining water resources. Unfortunately, only limited research has been done, into existing farming systems and social conditions; into new technologies to increase water availability, improve application effectiveness, water use efficiency, and to reduce costs. There was a lack of market incentives, resulting in both low crop prices and lack of co-ordination in production among farmers. Their lack of market information systems often resulted in over supply and under supply of perishable vegetables and fruit during the harvest and off-season, respectively, with corresponding price fluctuations. Lack of storage and transport facilities exacerbated this situation.

Production systems practised by small-scale farmers should be geared for sustainable use of natural resources. Inter-crop maize/beans yielded more nutrient content per hectare in most cases. The number of cobs per plant decreased with increase in plant density (2, 1.66 and 1.2 cobs per plant) in the two cropping systems. A similar trend was observed in the weight of maize cobs where there was no significant difference between mono-crops and inter-crops(453, 236 and 182 grams per plant for mono-crop maize and 444, 226 and 166 for inter-crop maize). Seasonal changes in the photosynthetic active radiation interception for the three inter-cropping plant densities followed the pattern of canopy development. As expected, photosynthetic active radiation (PAR) interception was low in low plant density inter-crop maize/beans. It increased slowly as leaf area index increased, and increased rapidly in medium and high density cropping with an increase in leaf area index up the time to when increasing leaf senescence contributed to a steady decrease.

Dry matter production of inter-crop beans was lower (242, 311 and 348 g m^{-2}) in comparison with mono-crop beans (645, 817 and 1185 g m^{-2}), and the reduction increased as the maize plant density increased. This may be attributed to a reduction in radiation availability to the beans. Radiation use efficiency (RUE) was calculated based on PAR intercepted for a period from 66 to 73 days after planting (DAP) for both mono-crops and inter-crops. In the three plant densities, the mean RUE for mono-crop maize (1.13 - 1.42 g MJ^{-1}) was lower than the mean RUE for maize/beans inter-crop (1.20 -1.59 g MJ^{-1}). There was no significant difference in RUE in mono-crop beans with respect to plant density. In mono-crop maize and inter-crop maize/beans, RUE was positively related to plant density because as plant density increased so did radiation use efficiency. Inter-crop maize/beans utilised radiation more efficiently than mono-crop maize and beans separately.

Comparisons of mono-cropping and inter-cropping were performed with respect to water use at the end of the growing season. Comparison of mean measured cumulative water use in inter-crop maize/beans (705, 730 and 684 mm) and mono-crop maize (710, 751 and 694 mm) showed inconsiderable water use differences which were not significantly different. With regard to full and supplementary irrigation, the analysis of variance showed that there were significant differences in water use between full (639 mm) and supplementary irrigation (level I & II) (541 and 540 mm) at 1% level implying that full irrigation (level II) used up more water than supplementary irrigation (level I & III). Comparison of mean water use in mono-crop maize and mono-crop beans showed significant water use differences and these differences were statistically significant suggesting that there were differences in water use in mono-crop maize (710, 751 and 694 mm) and mono-crop beans (513, 565 and 491 mm). Mono-crop maize used more water than mono-crop beans.

Comparison of water use efficiencies of inter-crop maize/beans with mono-crop maize and inter-crop maize/beans with mono-crop beans, revealed that inter-crop maize/beans produced the various nutrients per hectare per millimetre (mm) of water more efficiently than mono-crop maize and mono-crop beans. Following the findings of Experiment 1, inter-crops were subjected to three irrigation levels to ascertain the water use efficiencies. Comparison of water use efficiencies were done with respect to irrigation applied (full and supplementary irrigation). Water use efficiencies of inter-crop maize/beans in three irrigation levels were in most cases efficient in producing the various nutrients per hectare per millimetre (mm) of water while the water applied in full irrigation (level II) did not raise the water use efficiency, in fact it contributed to lowering the water use efficiency as the grain yield was statistically significantly different in the three irrigation levels.

8.2 Recommendations

8.2.1 Government

Government should adopt a policy where traditional practices should be supplemented and encouraged rather than replaced. Small-scale irrigation farming as a means of improving crop yields, extending the growing season and improving nutrition must be given more emphasis to improve the living standards of the rural communities. Government should support infrastructure, credit facilities, relevant extension and information services and participatory approaches when addressing the needs of the small-scale farmers as this will allow them to maintain full authority over development programmes including land and water management. There should be a deliberate policy for research into existing farming systems and social conditions, and into new technologies to increase water availability, improve application effectiveness, water use and efficiency and reduce costs. Government should use simulation models in their planning activities as these will help in incurring unnecessary costs.

8.2.2 Farmers

Farmers should plant the appropriate density of plants in order to produce a good yield and maximise the natural resources available efficiently.

Training programmes should be developed to pay attention to conservation of resources to avoiding over use and wastage as sustainable and integrated use of land and water resources is essential to prevent soil deterioration and declining water resources.

Small-scale farmers should be encouraged to practice inter-cropping as this will make available a number of nutrients identified as being deficient in many rural communities.

Technology transfer should be conducted in the next phase of the research.

8.2.3 Technical

Extension officers should know the appropriate planting densities for specific conditions of climate and soil to allow the crops to produce to their potential . For conditions similar to those in this study, a density of 4.4 maize plants per m^{-2} is recommended.

Extension officers should know exact amounts of water required for the production of various crops, as applying water more than the required amount will be a waste of resources as it will not improve the yield of the crops and hence reduce the efficiency per millimetre of water used.

There is also need for extension officers to undergo training with respect to the area of specialisation as it was found that extension officers who had animal production training were performing crop extension work.

8.2.4 Modellers

Generic models should be developed for simulation of small-scale production systems which include inter-cropping systems. There should be a multi-disciplinary approach to development of such models. The models developed should be able to simulate total biomass of an inter-crop as the current models only simulate inter-crops separately which makes it difficult to determine how much evapotranspiration or water was used by either crop. Further work should be done on Putu-AnyCrop model to perfect the soil water balance. There should also be further work to separate the evapotranspiration by the crop components in an inter-cropping situation. A suggested methodology would be install some plastic linings to separate the root systems of components in an inter-cropping situation and in that way the water use per crop could be accurately determined.

Abstract

For small-scale irrigation farming systems to be sustainable, knowledge of the nature of these systems, their marketing constraints, labour limitations, crop, soil properties, water and climate, are just some of the aspects which need to be taken into consideration. In the light of this background a research project was started to identify the problems experienced by small-scale farmers using Participatory Rural Appraisal (PRA) approach. The PRA findings were that traditional farming practices were being neglected and that an effort needs to be made towards supplementing and encouraging small-scale irrigation farming practices. Social infrastructure, credit facilities, relevant extension and information services were not sufficient. There was lack of market incentives, market information and co-ordination in production among farmers. Lack of storage and transport facilities exacerbated this situation. Some of the agronomic problems identified with the PRA approach were later investigated through field experimentation at the experimental site of the Agrometeorology Department (University of the Orange Free State).

Production systems practised by small-scale farmers should be geared for optimum use of natural resources. Inter-crop maize/beans yielded more energy and nutrient content per hectare in most cases. The number of cobs per plant decreased with increase in plant density and a similar trend was observed in the weight of maize cobs per plant. There was no significant difference in cob number and weight per plant between inter and mono-cropping systems. Seasonal changes in the photosynthetic active radiation interception for the three inter-cropping plant densities followed the pattern of canopy development. The mean radiation use efficiency for inter-crop was 0.07 - 0.17 g MJ^{-1} higher than mono-crop maize which was 1.13 - 1.42 g MJ^{-1}.

Dry matter production of inter-crop beans was lower in comparison with mono-crop beans and the reduction in inter-crop beans dry matter increased as the maize plant density increased. This was attributed to a reduction in radiation availability. Comparisons of water use at the end of the growing season indicated that mean measured cumulative water use in inter-crop maize/beans and mono-crop maize were in the same order. With regard to full and supplementary irrigation, it was found that full irrigation used 100 mm more water than supplementary irrigation. A comparison of the mean

water use in mono-crop maize and mono-crop beans showed statistically that mono-crop maize used more water than mono-crop beans.

Comparison of water use efficiencies of inter-crop maize/beans with mono-crop maize and beans, revealed that inter-crop maize/beans produced the nutrients per hectare per millimetre (mm) of water more efficiently than mono-crop maize and mono-crop beans. Comparison of water use efficiencies for full and supplementary irrigation levels showed that supplementary irrigation was more efficient.

The Putu and BEWAB models were found to be suitably accurate and user friendly for the purpose of decision support for planning small-scale irrigation farming. Putu was found to simulate both mono-crop and inter-crop maize biomass reasonably accurately. With regard to soil water content, Putu approximated the measured soil water content quite accurately in the high plant densities of inter-crops and mono-crops while further work needs to be done on low and medium plant densities especially during the early growth stages of the crop. BEWAB predicted the crop water use very well with accuracy better than 80% and it was concluded that the model may be used to schedule irrigation for small-scale farmers with reasonable reliability. Putu and BEWAB can now be used for decision support .

OPSOMMING

Kennis oor die aard van kleinskaal besproeiingsboerderystelsels, die bemarkings- en arbeidsbeperkings daarbinne, grond- gewas en klimaatseienskappe asook waterhulpbronne is slegs 'n paar aspekte wat 'n rol speel om kleinskaal besproeiingsboerdery volhoubaar te maak. In die lig teen die agtergrond is 'n navorsingsprojek geloods waarin die probleme wat kleinskaal besproeiingsboere ondervind deur middel van 'n Deelnemende Landelike Evaluasie benadering (DLE) te identifiseer. Vogens die DLE-gebaseerde opname blyk dat die ontwikkeling van tradisionele boerderypraktyke totaal geignoreer en verwaarloos is en dat 'n poging aangewend moet word om die boere en hul praktyke te onderskraag. Daar is verder bevind dat sosiale infrastrukture, krediet fasiliteite, toepaslike voorligting en inligtingsdienste onvoldoende is. Daar is 'n tekort aan bemarkingsaansporing, bemarkingsinligting asook 'n gebrek aan produksie koordinasie tussen boere geidentifiseer. Hierdie situasie is vererger weens 'n gebrek aan stoor- en vervoerfasiliteite. Sommige van die agronomiese probleme wat d.m.v. die DLE benadering geïdentifiseer is, is later in 'n veldproef op die proefterrein van Landbouweerkunde (Universiteit van die Oranje-Vrystaat) ondersoek.

Produksiestelsels wat deur kleinskaal boere beoefen word, behoort gerat te wees om die natuurlike hulpbronne optimaal te benut. Vanuit die veldproewe was dit duidelik dat die mielie/bone intergewasstelsel 'n hoër energie in voedingstofinhoud per hektaar gelewer het as waar die gewasse afsonderlik verbou is. Dit was veral van toepassing by die medium plantdigtheid (4.4 milieplante per m^2) wat gevolglik aanbeveel word as riglynplantestand. Daar was geen betekenisvolle verskil in die getal mieliekoppe per plant asook die kopmassa per plant tussen die intergewas- en monogewasstelsel nie. Seisoenale veranderinge in die fotosintetiese aktiewe stralingsonderskepping by die drie intergewas plantdigthede, het dieselfde patroon as blaardakontwikkeling gevolg. Die gemiddelde stralingsverbruiksdoeltreffendheid van die intergewastelsel was 0.07 – 0.17 g MJ^{-1} hoër as die mielie monogewasstelsel wat tussen 1.13 en 1.42 g MJ^{-1} gewissel het.

Die droëmateriaalproduksie van bone in die intergewasstelsel was deurgaans laer as bone in die monogewasstelsel. Die verskil het groter geword met 'n toename in plantdigtheid weens 'n vermindering in beskikbare straling. 'n Vergelyking van die waterverbruik tussen die mielie/bone intergewasstelsel met die mielie monogewasstelsel, het aangedui dat dit in dieselfde orde was. Wat die vol- en aanvullende besproeiing betref is gevind dat die volbesproeiing 100 mm meer as die aanvullende besproeiing verbruik het. Die mielie monogewasstelsel het betekenisvol meer water as die bone monogewasstelsel verbruik.

Vergelyking van die waterverbuiksdoeltreffendheid tussen die mielie/bone intergewas en die monogewasstelsels het aan die lig gebring dat die intergewasstelsel die voedingstowwe per hektaar per milimeter (mm) water meer doeltreffend as die mielie en bone monogewasstelsels verbruik het. Vergelyking van die waterverbruiksdoeltreffendheid tussen die vol- en aanvullende besproeiing het aangetoon dat die doeltreffendheid van die aanvullende besproeiing beter is as die volbesproeiing.

Weens die akkuraatheid en verbruikersvriendelikheid van die Putu en BEWAB modelle is bevind dat die modelle aangewend kan word vir die beplanning van kleinskaal besproeiingsboerderystelsels. Daar is gevind dat Putu die biomassa akkuraat by mielies in beide 'n monogewas- en intergewasstelsel kan beraam. Wat die grondwaterinhoud betref het dit geblyk dat die Putu-model die grondwaterinhoud redelik akkuraat in die hoë plantdigtheid van die inter- en monogewasstelsel beraam het. Verdere navorsing moet egter op die voorspelling van grondwaterinhoud in die lae en medium plantdigthede, veral in die vroeë groeistadiums van die gewas, gedoen word. Die BEWAB-model het die gewaswaterverbruik met 'n akkuraatheid van 80 % en hoër beraam. Hieruit kan afgelei word dat die model vir besproeiingsskedulering vir kleinskaal boere met redelike vertroue gebruik kan word. Putu en BEWAB kan nou gebruik word vir beplanningsdoeleindes.

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APPENDICES

Appendix i

TERMINOLOGY AND DEFINITIONS

Solar Radiation

A few terms used in the thesis are reviewed for better understanding. When discussing radiation, the terms flux and density are used in most literature. *Flux* is the rate of flow of a substance expressed in units of quantity per unit time while *density* stands for per unit area (Monteith, 1970; Savage, 1988). Therefore, *Flux density* is the flux through a unit surface area (Monteith, 1970; Shibles, 1976). Thus for *radiant flux,* the units used are Watts (W) which is 1 Joule s^{-1}, and for the radiation flux density term, called *irradiance,* the appropriate unit, as set forth in the International System of Units (SI), is Wm^{-2} (Shibles, 1976).

Photosynthetic Active Radiation (PAR) - is radiation found in the 400 to 700 nm waveband in Wm^{-2}.

Photosynthetic Photon Flux Density (PPFD) - The Photon flux density of PAR is the number of photons (400 to 700) incident per unit time on a unit surface area, the unit used is μmol s^{-1} m^{-2} (Shibles, 1976, Savage, 1979; Savage, 1982). Micromole per second per square meter (μmol s^{-1} m^{-2}) is based on the number of photons in a certain wavelength incident per unit time(s) on a unit area (m^{-2}) divided by the avogadro constant (6.022×10^{23} mol^{-1}) commonly used to describe PAR in the 400-700nm waveband (Thimijan and Heins, 1983).

In instances where conversion is required, conversion of μ mol s^{-1} m^{-2} to Wm^{-2} has been documented by Thimijan and Heins (1983) using the expression below with the appropriate constant from the table below.

$$\frac{\mu mol s^{-1} m^{-2}}{Constant} = Wm^{-2}$$

Multiply W m^{-2} by constant to obtain μ mol s^{-1} m^{-2}

Light Source	Constant
Sun and sky, daylight	4.59
blue sky only	4.24
High-pressure sodium	4.98
metal halide	4.59
Mercury deluxe	4.52
Warm-white fluorescent	4.67
Cool-white fluorescent	4.59
Plant growth fluorescent A	4.80
Plant growth fluorescent B	4.69
Incandescent	5.00
Low-pressure sodium	4.92

Ratios from different sources of light used to convert μ mol s^{-1} m^{-2} to W m^{-2} (after McCree, 1972).

Mono-cropping and inter-cropping

Inter-crop maize - implies maize alone from an inter-cropping practice

Inter-crop beans - implies beans alone from an inter-cropping practice

Inter-crop maize/beans - implies maize + beans from an inter-cropping practice

Mono-crop maize - implies maize from a mono-cropping practice

Mono-crop beans - implies beans from a mono-cropping practice

Inter-cropping or multiple cropping is defined as the growing of two or more crop species simultaneously in the same field during a growing season (Beets, 1982, Ofori & Stern, 1987; Francis, 1989).

Mixed cropping is defined as the growing of more than one species on the same piece of land at the same time. The difference with inter-cropping is that plant populations are in an unorganised manner, unevenly distributed over the land (Beets, 1982, Ofori & Stern, 1987; Francis, 1989).

Relay cropping is defined as growing of crops between plants or rows of an already established crop during the growing period of the established crop (Beets, 1982, Ofori & Stern, 1987; Francis, 1989).

Sequential cropping is defined as growing different crops on the same piece of land with each crop during a different time of the year (Beets, 1982, Ofori & Stern, 1987; Francis, 1989).

Strip or lane cropping is defined as growing two or more crops in alternating strips or blocks on the same piece of land at the same time. This system differs from mixed cropping where species are intimately mixed while in strip cropping, only plants on the strips affect each other and permits independent cultivation of each crop (Beets, 1982, Ofori & Stern, 1987; Francis, 1989).

Additive inter-cropping is inter-cropping where mono-culture populations per hectare of the two crops are added together with the aim of producing the usual yield of the dominant crop while obtaining a bonus from the second crop. In some instances, a fraction e.g. 0.25, 0.5 or 0.75 is added to the dominant crop.

Replacement inter-cropping is inter-cropping where part of the mono-culture population of one crop is replaced by an equivalent portion of the second crop to keep the total population pressure constant. An important feature of a replacement series is that a single plant of one species is not necessarily regarded as being equivalent to a single plant of another species e.g. one may replace one maize plant with 3 bean plants.

Appendix ii

Description of Participatory Rural Appraisal (PRA)

Participatory Rural Appraisal (PRA) evolved from the parent methodology Rapid Rural Appraisal (RRA) in the 1980's as a result of moving more towards a participatory approach. The two methodologies still have much in common with basic differences being in the ownership of information, and the nature of the process. During RRA information is more extracted by outsiders as part of data gathering process while in PRA it is more generated, analysed, owned and shared by local people as a process of their empowerment (Chambers, 1992; Chambers, 1994). PRA is basically a practical field-level methodology where actual experience is gained from working with the community. It has been used in several fields including natural resources, agriculture, health, nutrition, food security and programmes for the poor. In the past, outsiders (individuals from an outside locality, including urban educated scientists) have lectured farmers holding "sticks", or have interviewed them, asking rapid questions, interrupting, and not listening beyond immediate replies. PRA approach "hands over the stick" meaning that authority is given to the people who have the information, in this case the farmers. Farmers now perform the roles that the researchers played. The farmers are allowed to dominate, determine more of the agenda to gain, express and analyse information, and to plan (Chambers, 1992). The researchers are merely facilitators, learners and consultants. Their roles are to establish rapport, to convene and catalyse, to enquire and choose and improvise methods for them to use. Effective communication between farmers/respondents and the PRA team is vital for the success of any PRA exercise. In cases where language may be a hindrance, a translator is needed to talk with the farmers. The means of recording any information obtained during PRA is very important and should be determined before commencement of the exercise. This can either be by taking notes or using a tape recorder with permission from the respondents (Nabasa, *et al*, 1995). Like many others, farmers are also suspicious of outsiders and therefore the success of PRA will require a better relationship between the PRA team and farming community than in other forms of research. For this relationship to develop it is important for both groups to get away from the old '*us* and *them*' attitudes which are barriers to effective dialogue. In many cultures, visitors to rural communities are offered seats or chairs which literally '*elevates their importance*' above that of the farming community (who in most cases sit on the ground). This automatically distances them (researchers/visitors) physically and psychologically, from the community. It is extremely important to develop a more informal atmosphere in which the '*us* and *them*' barriers become less pronounced (Nabasa, *et al*, 1995). There are several methods that can be used to conduct PRA (Chambers, 1992) *inter alia* :

- direct observation
- key informants
- semi-structured interviews
- group interviews and discussions
- chains (sequences of interviews) etc.

In order to be successful, PRA excersises should be conducted at a location where the informants feel most confortable. This may be in their community hall or at the field near the crop or the problem being discussed.

Appendix iii

Questionnaire used as a guide to interview small-scale farmers during a socio-economic and agronomic survey

(1) How much land do you have access to for agricultural purposes?
-steps -acres -hectares
-morgan -soccerfields -other

(2) What is it used for?
-livestock -crops -fallow -other

(3) Do you practice dry land farming(rainfed) and/or irrigation farming.
What crop(s) do you grow?
When/what time of the year?
Do you plant by hand or by machine?
What plant spacing do you use? For other crops?

(4) Do you practice intercropping/mixed cropping? Which crops do you intercrop? Why? Pattern?
e.g. one row maize, two rows beans, or maize and beans sowed on same spot

(5) Do you apply fertiliser or organic manure? How much per hectare/acre?

(6) Was the field cropped last season?, Type of crops grown.
-maize -wheat -root vegetables
-surface vegetables -fruit -other

(7) Has your yield been the same over time? No or Yes
Is it going up or down? Why?
What is you yield now?
- kilograms -bags/packets -tins/drums -other

(8) What is the main use of crop
-consumed -gave away -sold to family -sold to neighbours
-sold to local shop -sold at the market -other

(9) After harvest, what fraction do you store for future consumption?

(10) Moneys made during the last year sales? (enter Rand value for the last year)

(11) Are you happy with the Marketing system? If not why?

(12) If you produced a bigger surplus would you sell all of it?
-Don't Know -No -Yes, sometimes -Yes, mostly

(13) If you could not sell all of it, what would the main reason be?
-to far from the market -no transport to reach the market
-transport to market too expensive -people can not afford to buy
-shops sell cheaper than me -other

(14) What are your main sources of drought power for ploughing fields?
-human labour -animal traction
-tractor -other?

(15) If you are involved in ...farming, do you do anything of the following?
-ploughing -planting -weeding
-harvesting -transporting inputs -transporting produce
-selling produce -other?

(16) What is your land used for?
-grazing -cultivation -gardening
-thatching -shack farming -fallow -other

(17) Do you use Pesticide/herbicides yes or no
How?

(18) Do you practice crop rotation? What crops are grown in rotation? Why?
How would you rate your type of soil? Why?

(19) What criteria do you use for selecting seed variety?
-Yield - storability -drought resistance

(20) Is the seed provided? Self or co-operation

(21) Decision making - self or central

(22) Do you irrigate your crop? Amount of water? What type of irrigation?

(23) Do you have enough water to farm with all the time or does it run out
What is the source of water?

(24) Do you have control over the water supply?
Individually or centrally

(25) How long have you been farming?

(26) Knowledge of farming? Training? (Indigenous technical knowledge?)

(27) Is farming better/easier now than it was then? why?

(28) What are the main problems you face as a small scale farmer?

(29) What do you expect from this enterprise (project)?

(30) Tell me something about your aspirations
-economically -socially -environmental sustainability
-expected beneficiaries -the needs of the community -community co-operation

Appendix iv

Supplementary information on survey sites

Thaba Nchu district

Sediba Village

Sediba village is in the district of Thaba nchu, a former part of Bophuthatswana. Small-scale farmers practise dry land farming on land ranging from 0.25 to 3.0 ha. They usually grow maize, wheat and beans, but due to droughts in the recent years, their fields have not been grown. They practise intercropping with maize and wheat. Farmers practising irrigation farming, farm on land ranging from 0.25 to 1.0 ha and usually grow potatoes, cabbage, sorghum, spinach, beetroot, carrots, tomatoes, pumpkin, onion and lucerne. They would also like to grow maize, sunflower, wheat, beans and peanuts. The community has no electricity at the moment.

Bethlehem district

Kopanang village

Kopanang is a village adjacent to Bethlehem where nine farmers practice communal garden farming with water from a nearby dam which is highly polluted with diluted sewage. The garden is being irrigated using buckets and hosepipes. They grow pumpkin, beans, beetroot, potatoes, spinach, maize, tomatoes, onions, carrots and cabbage mainly "to escape from poverty". Daily income ranges from R50 to R70 with an average of less than R10 per farmer. To supplement their income, they sell drinking glasses, candles and mesh wire which they make themselves.

Qwaqwa district

Tsheseng, Makeneng, Makwane and Mangaung

Qwaqwa is situated in the north-eastern Free State on the Free State, KwaZulu-Natal and Lesotho border. This former homeland has been described as "a peri-urban slum in the middle of nowhere". Phuthaditshaba, the capital, with an average annual rainfall of 800mm is surrounded on all sides by small settlements like those mentioned above. High density population patterns and overpopulation, over-utilisation of land, unemployment and general social hardships characterise the whole of Qwaqwa. Botes *et al* (1995) state that there were no available plots left in Qwaqwa for distribution by the early 1970's, and that the homeland administration, by then, "was adamant that farm families had to sell all their livestock before entering the homeland. This resulted in the cramming of families from farms onto urban-size sites in sprawling shack settlements without farmland or cattle. Under these circumstances the dream of many ex-farmers was smashed". As a result, many gardens are utilised for the purpose of vegetable and fruit gardening.

Harrismith district

Tshiame

Tshiame is approximately 10 kilometres from Harrismith in the eastern Free State. It was allocated to Qwaqwa in 1986 but was never officially incorporated into Qwaqwa (Botes *et al*, 1995). Greater Tshiame consists of two residential areas: Tshiame A and Tshiame B. Tshiame B, with a population of approximately 18 000, is lower middle class or lower class residential area with housing provision mainly intended for labourers of the nearby industries. The unemployment rate is high, due to many ex-farmworkers who have flocked to this area. There are 86 plots that have been developed for small-scale irrigation farming. Water is pumped from the Wilge River and the Sterkfontein Dam into a nearby reservoir. Although irrigation pipes cover all plots, only a small number of these plots were being cultivated at the time of the research.

Kroonstad district

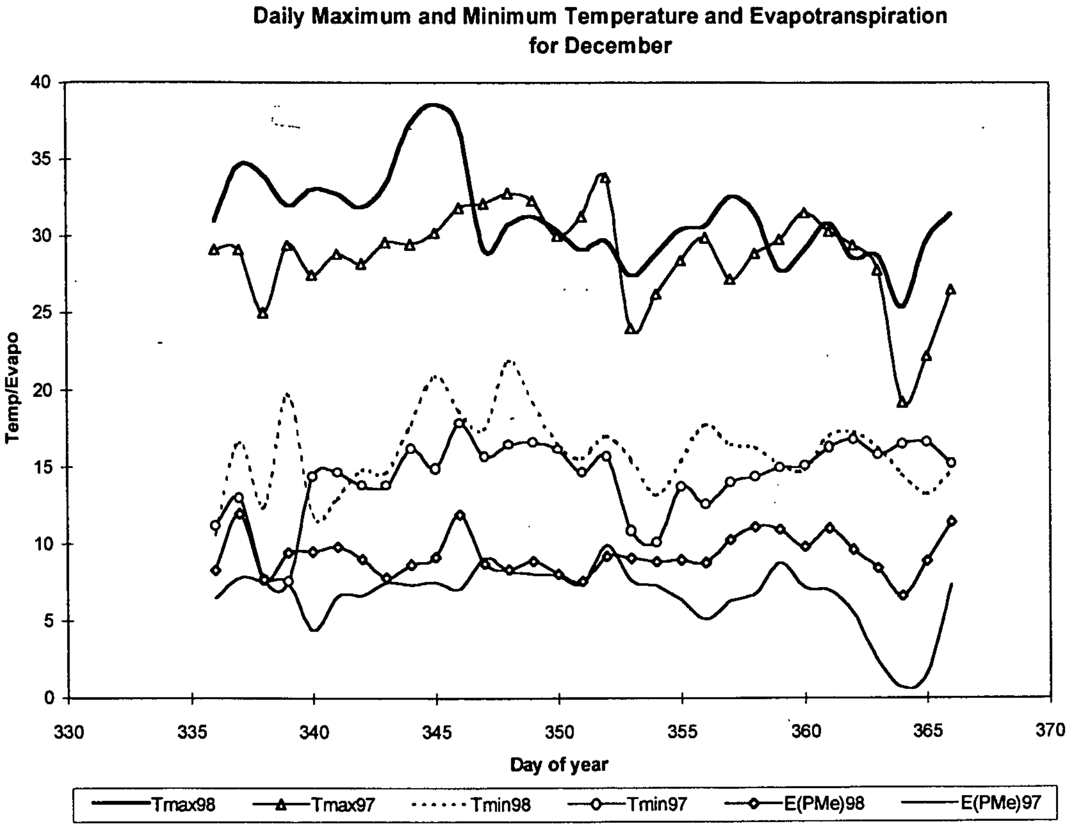
Maokeng and Brentpark

Maokeng and Brentpark are residential areas adjacent to Kroonstad in the northern Free State, where mainly black and coloured people live. Although the majority of the small-scale farmers in these areas are at present still farming in their backyards, considering themselves as being very inexperienced at this stage, there are a few farmers who farm with cattle and poultry. At present, dairy production is being upgraded and officials of the FSDA are supporting farmers from these communities in developing dairy farms.

Appendix v

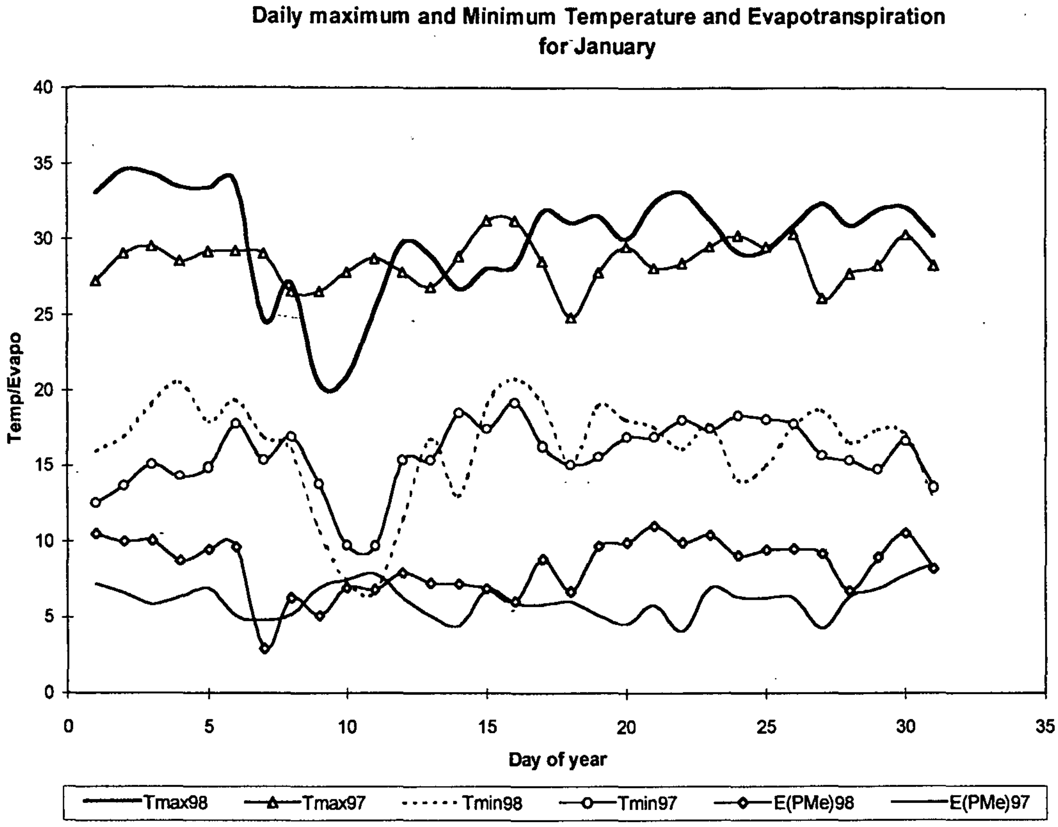
Comparison of maximum and minimum temperature and evapotranspiration during the 1996/1997 and 1997/1998 growing seasons

(a)



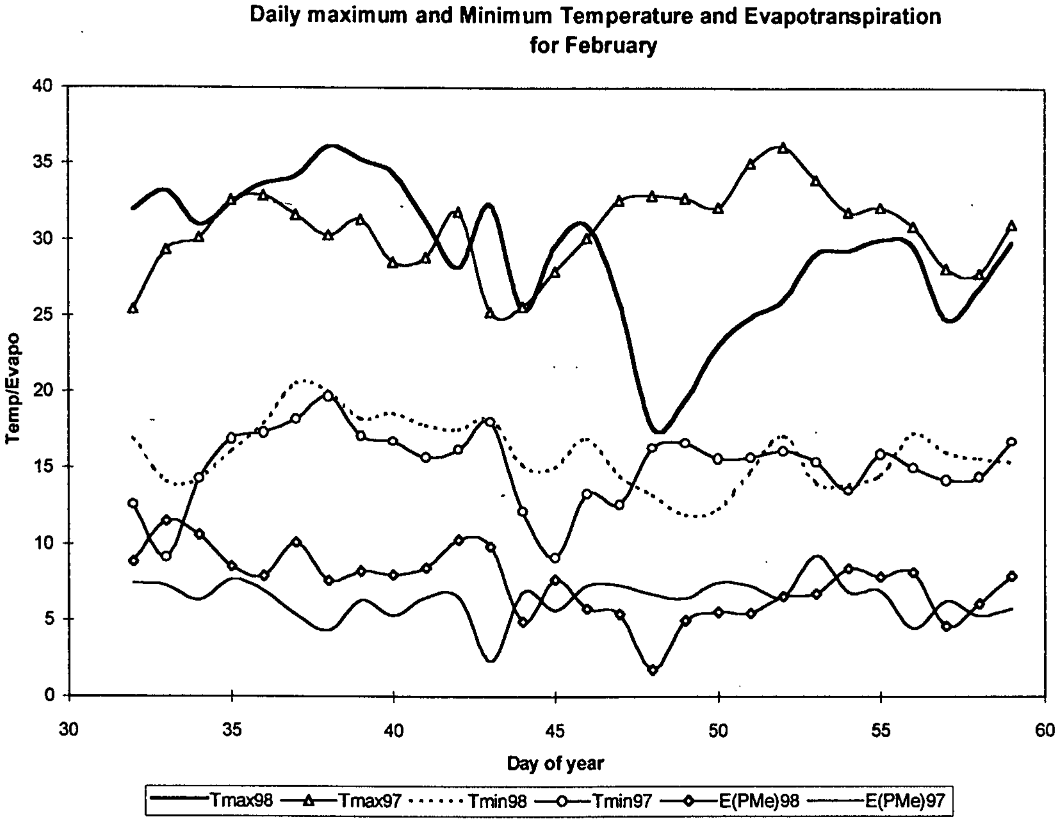
Comparison of 1996/1997 and 1997/1998 growing seasons December daily maximum and minimum temperature (°C) and daily evapotranspiration (mm) calculated with Penman-Monteith equation using PUTU.

(b)



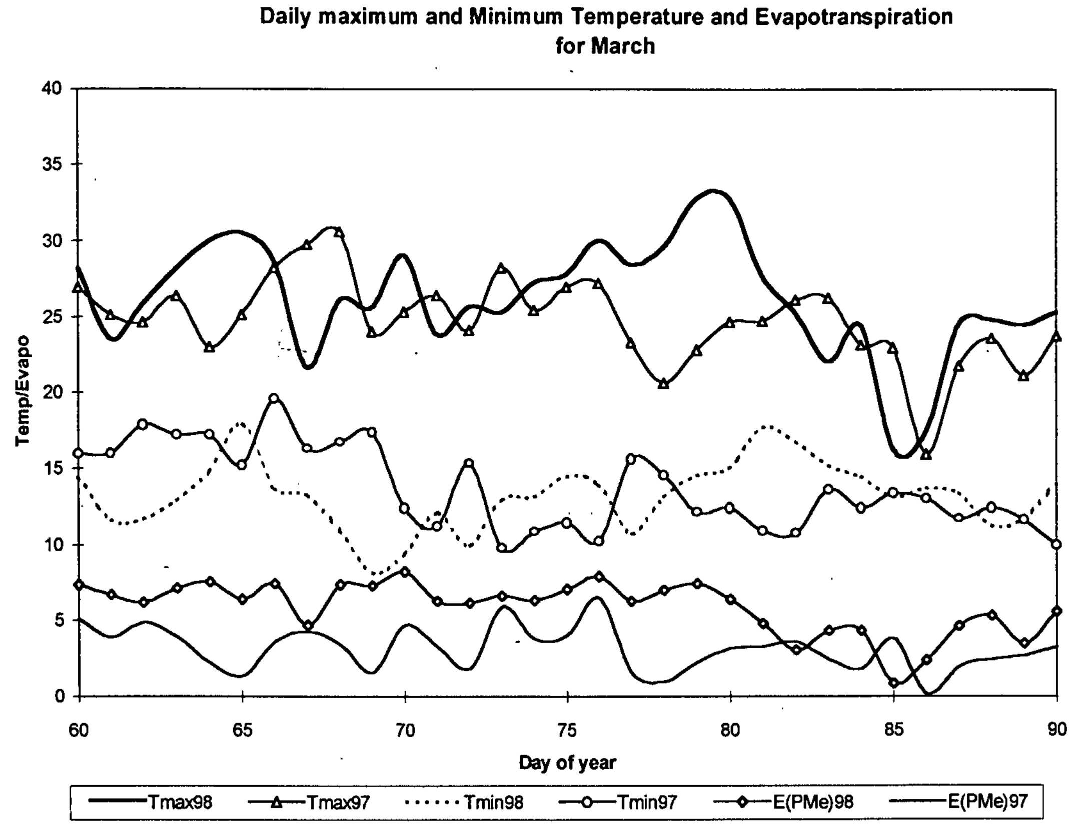
Comparison of 1996/1997 and 1997/1998 growing seasons January daily maximum and minimum temperature (°C) and daily evapotranspiration (mm) calculated with Penman-Monteith equation using PUTU.

(c)



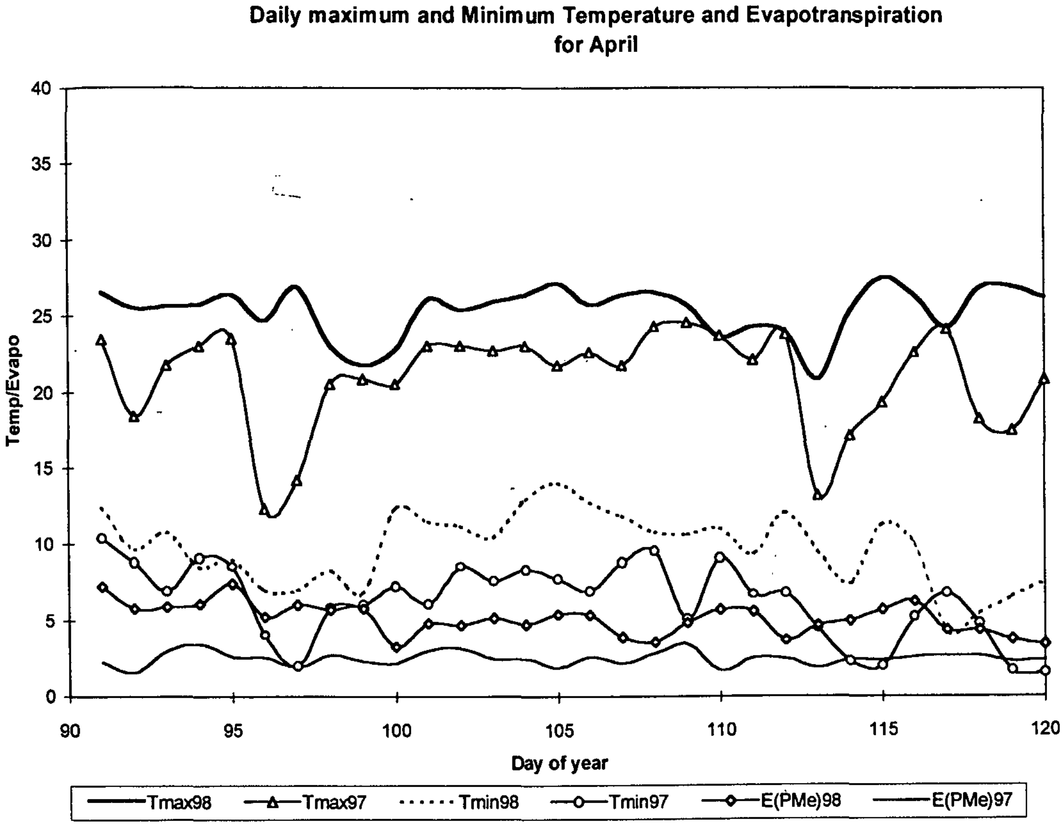
Comparison of 1996/1997 and 1997/1998 growing seasons February daily maximum and minimum temperature (°C) and daily evapotranspiration (mm) calculated with Penman-Monteith equation using PUTU.

(d)



Comparison of 1996/1997 and 1997/1998 growing seasons March daily maximum and minimum temperature (°C) and daily evapotranspiration (mm) calculated with Penman-Monteith equation using PUTU.

(e)



Comparison of 1996/1997 and 1997/1998 growing seasons April daily maximum and minimum temperature (^{o}C) and daily evapotranspiration (mm) calculated with Penman-Monteith equation using PUTU.

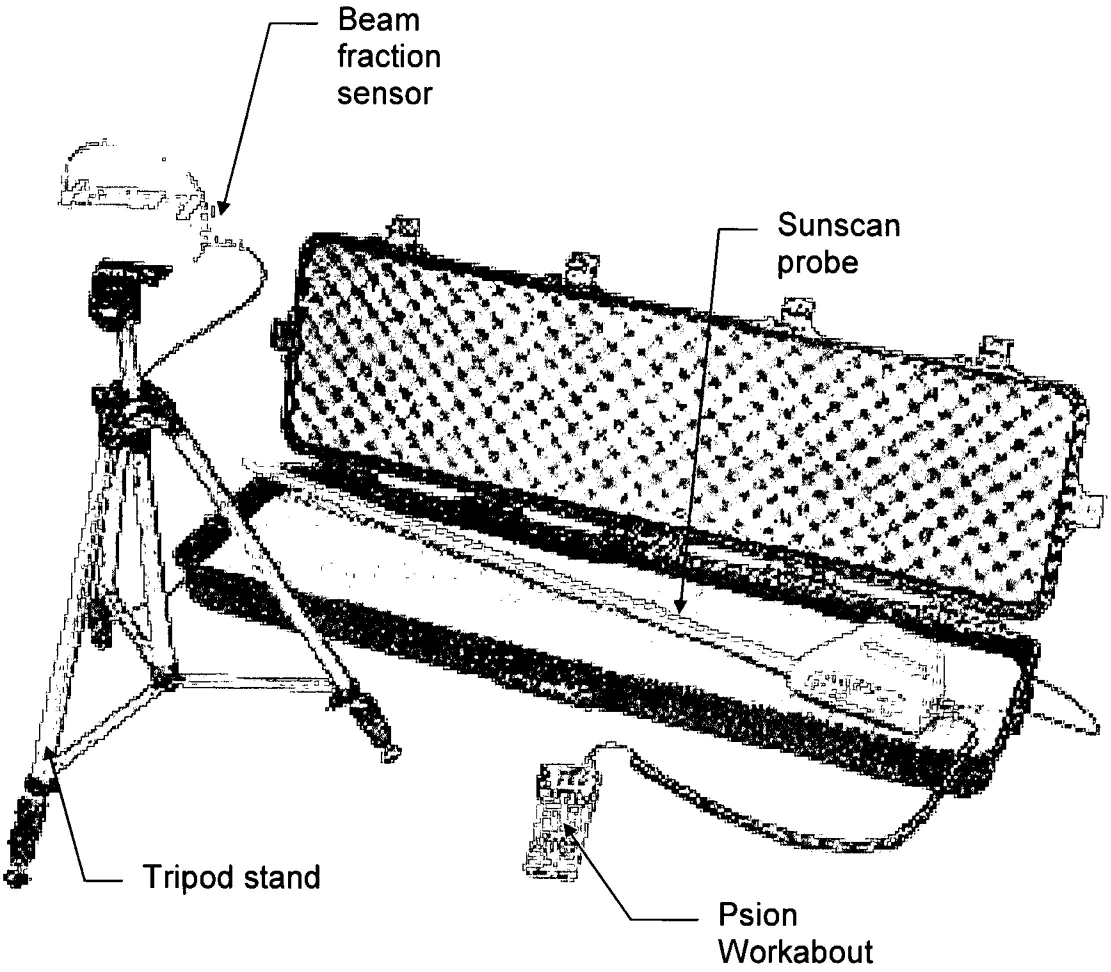
Appendix vi

Description of the Sunscan Canopy Anaysis System (SCAS)

The SunScan uses field measurements of PAR (Photosynthetically Active Radiation) values in crop canopies to provide valuable information about the parameters influencing growth. The SunScan Probe consists of 64 PAR Sensors embedded in a 1m long probe. Whenever a reading is taken, all sensors are scanned and the measurements sent to a portable PC or Data Collection Terminal, type DCT1, via an RS232 interface. The average PAR level from the Probe is read, but all 64 individual readings can be stored for more complete PAR mapping, or making linear transects. Automatic logging can be selected to obtain readings over a period of time at a fixed point. If connected to a data logger the Probe can function as a Linear Quantum Sensor.

The DCT1 Terminal (the Psion Workabout) is a robust, hand-held computer which uses SunData software to collect and analyse readings from the SunScan Probe. Leaf Area Index is immediately displayed and can be stored (on secure, removable flashcards).

The optional Beam Fraction Sensor, type BF1, contains two PAR sensors, one of which is shielded from the direct solar beam by a shade ring. The BF1 Sensor is positioned above (or away from) the canopy to obtain measurements of the relative proportions of incident direct and diffuse light. The simultaneous incident light reading allows SunScan to be used under almost all light conditions.


Beam fraction sensor
Sunscan probe
Tripod stand
Psion Workabout

Appendix vii

Description of neutron probe, Campbell Pacific Nuclear, Model 530

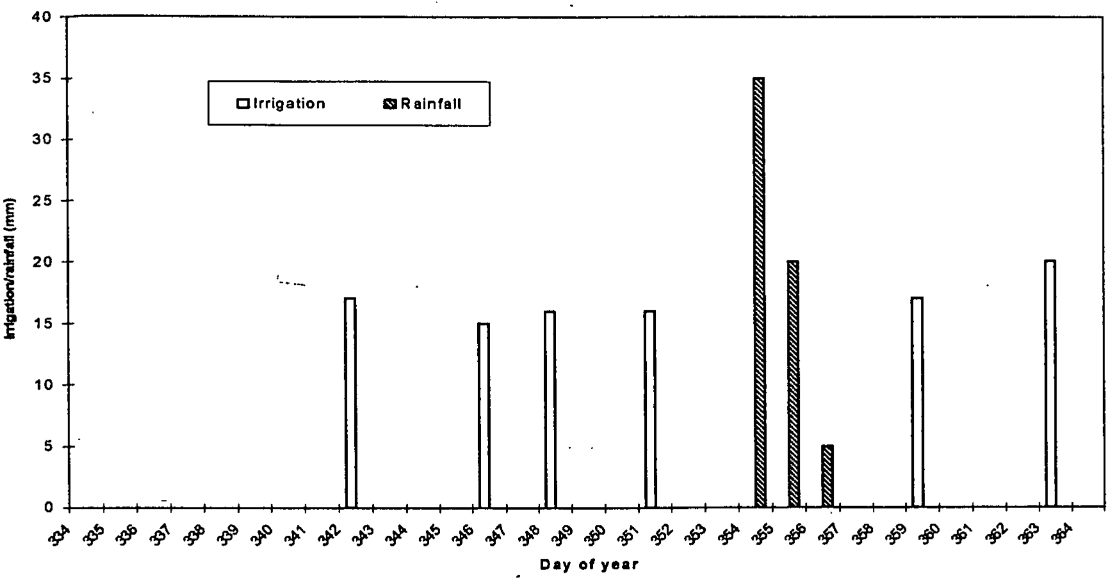
The probe consists of an americium-241:berylium source in annular encapsulated form surrounding a boron trifluoride slow neutron detector, a 2.3kV power unit and a pulse shaping and amplifying unit. The probe is lowered into the access tube using a support cable which also carries a 12v unstabilized power supply to the probe and relays the output from the probe
to a ratescaler at the surface. The ratescaler counts the pulses for four optional time periods of 16 or 60 seconds or minutes and the count rate is displayed as counts per second. The 12V rechargable Ni-Cd batteries are housed within the ratescaler and have an operating life of 10 hours of continuous use.

The probe is accepted throughout research and industry as an accurate instrument for measuring soil water content. Studies on soil water use (WU), water use efficiency (WUE), content have made use of the neutron probe (Hensley, 1980, Kushwaha & De, 1986). The neutron probe measures the sub-surface water content in the soil and other materials by use of a probe containing a source of high energy neutrons (Americium-241:Beryllium) and a slow neutron detector (Helium-3 detector). The detector in the probe is responsive to slow thermal neutrons but not to high energy, fast neutrons. The major source of hydrogen in most soils is water and a soil that is wet will give a high count per time test while a soil that is dry will give a low count for the same period of time. The volume measurement of the probe is approximately spherical with a diameter of 30 cm.

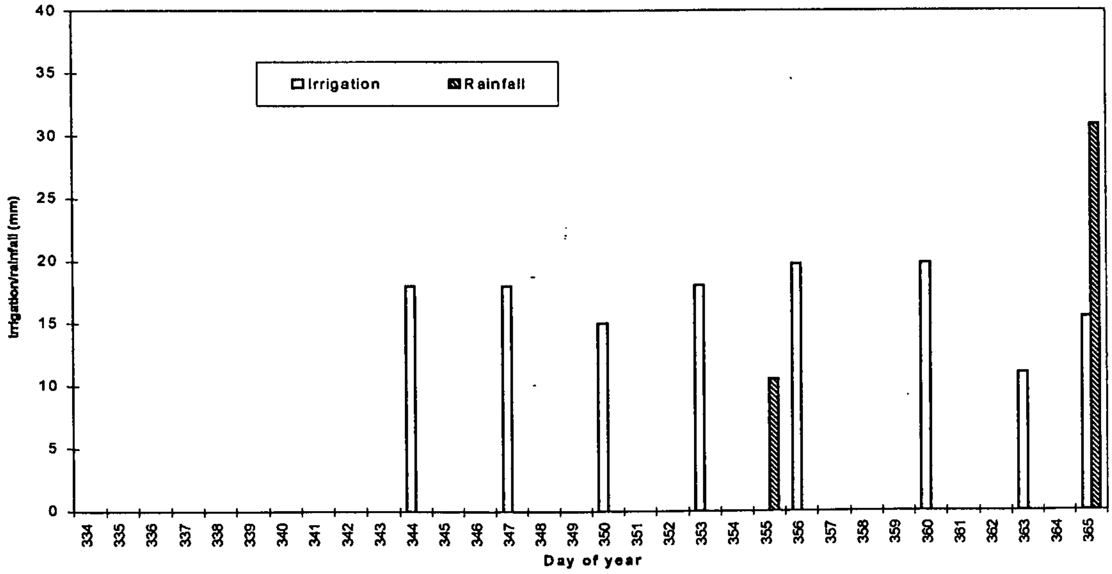
Appendix viii

Comparison of irrigation and rainfall during the 1996/1997 and 1997/1998 growing seasons

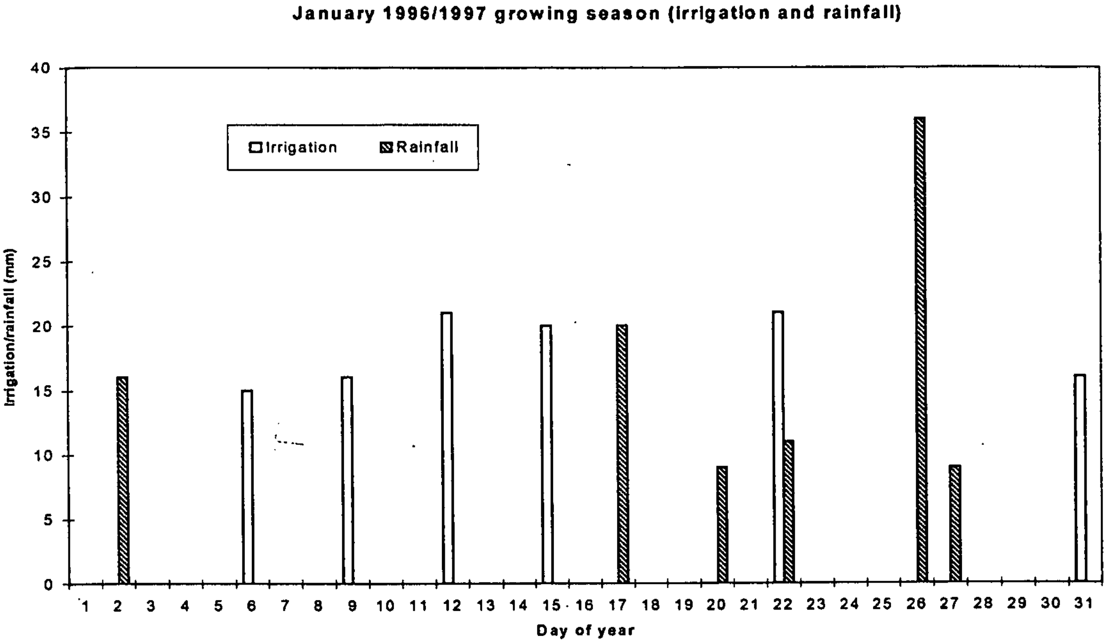
(a)


December 1996/1997 growing season (irrigation and rainfall)

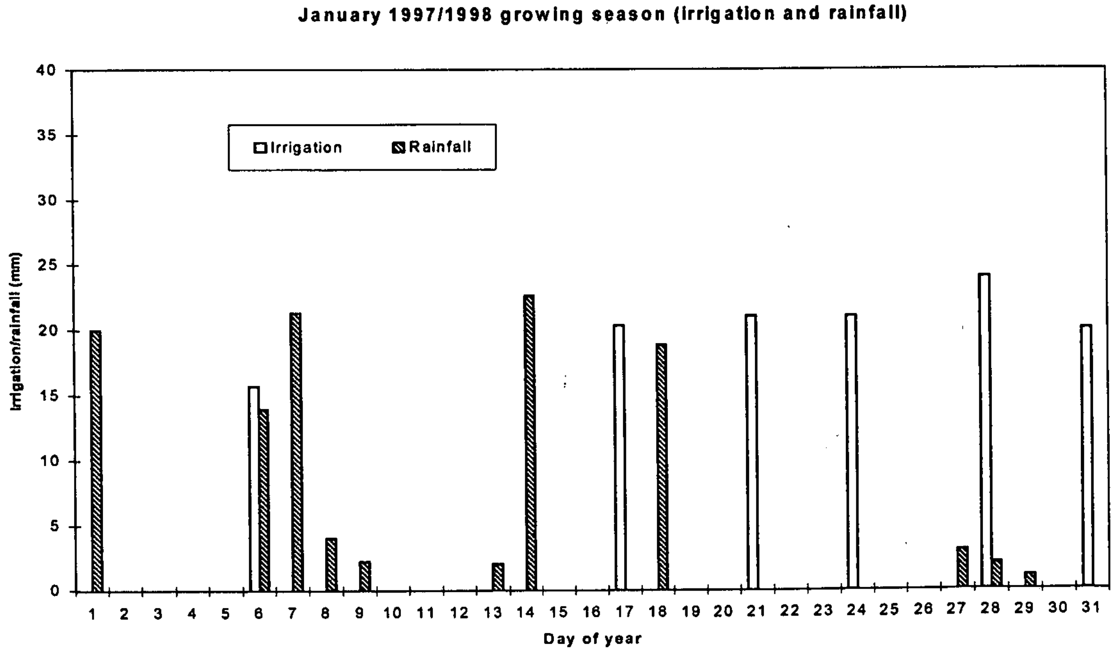
(b)


December 1997/1998 growing season (irrigattion and rainfall)

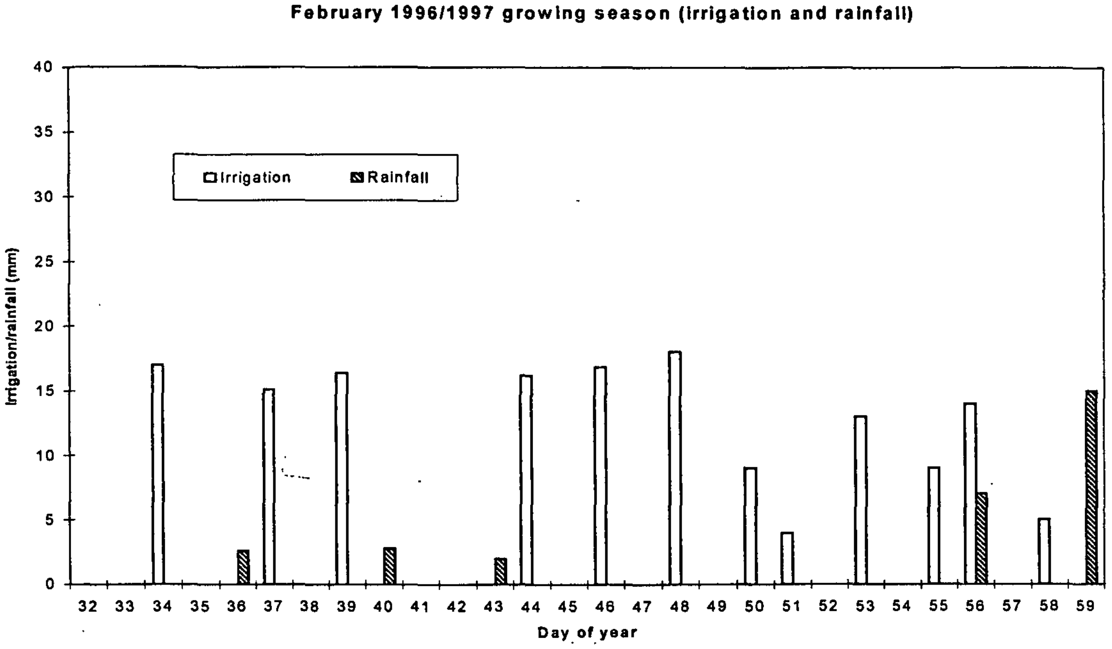
(c)


January 1996/1997 growing season (irrigation and rainfall)
Irrigation
Rainfall
Irrigation/rainfall (mm)
0
5
10
15
20
25
30
35
40
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Day of year

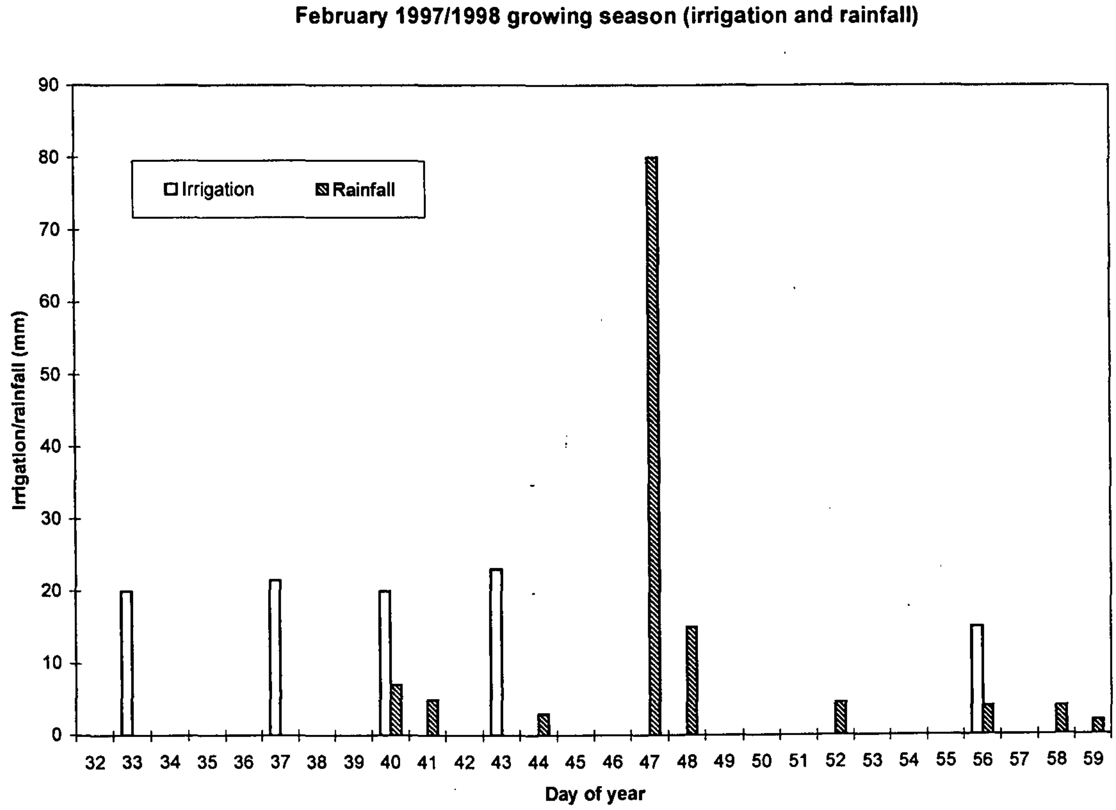
(d)


January 1997/1998 growing season (irrigation and rainfall)
Irrigation
Rainfall
Irrigation/rainfall (mm)
0
5
10
15
20
25
30
35
40
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Day of year

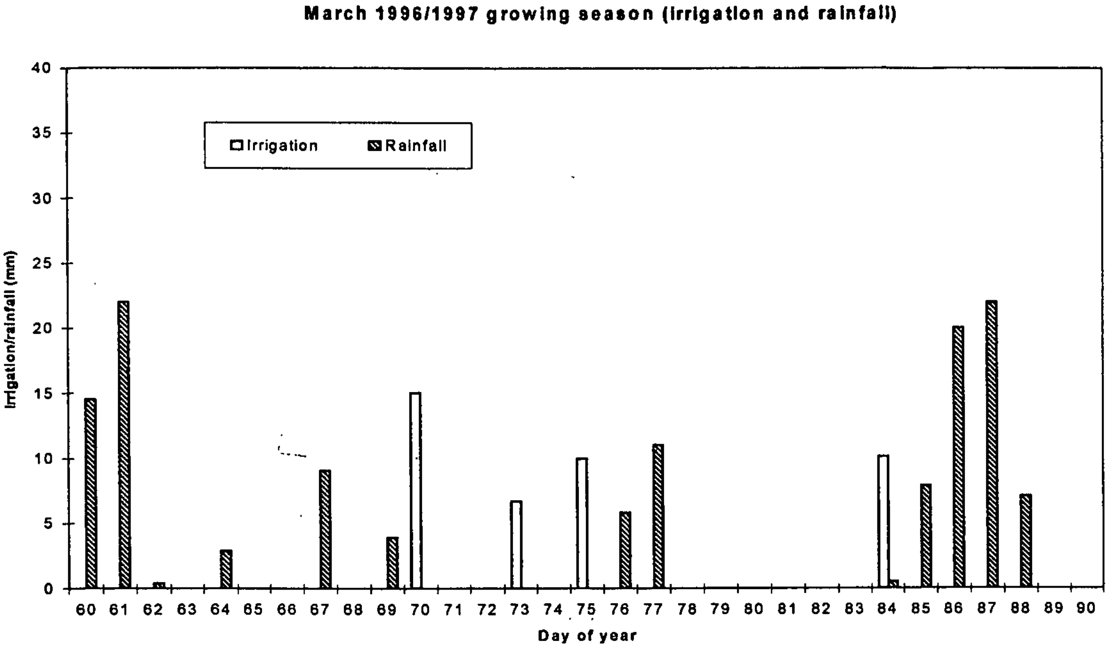
(e)


February 1996/1997 growing season (irrigation and rainfall)

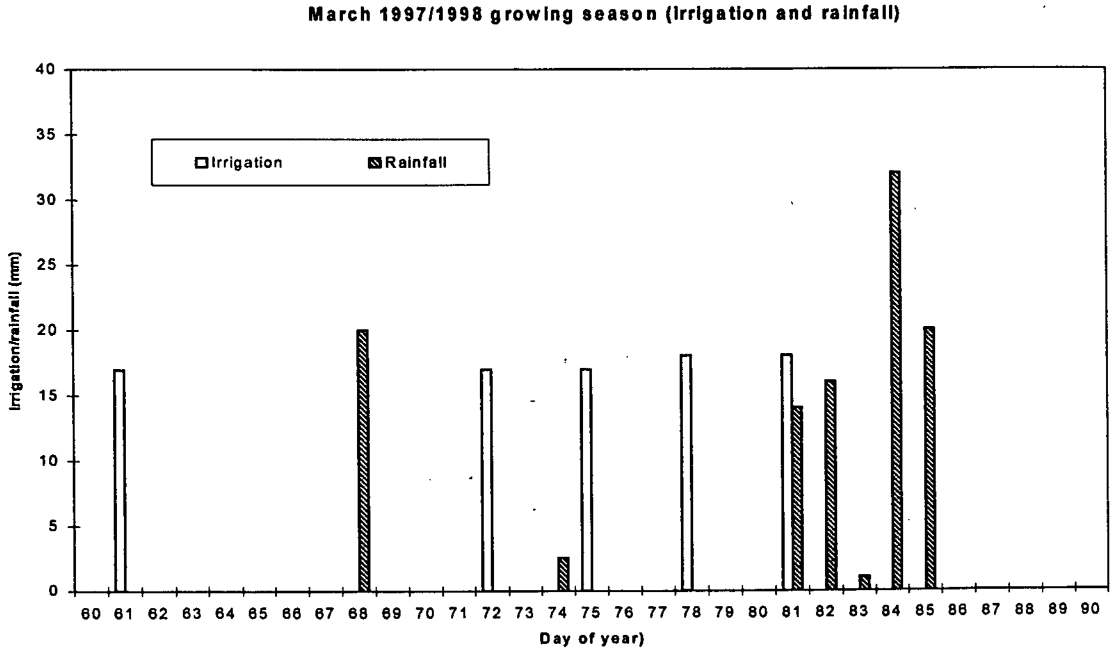
(f)


February 1997/1998 growing season (irrigation and rainfall)

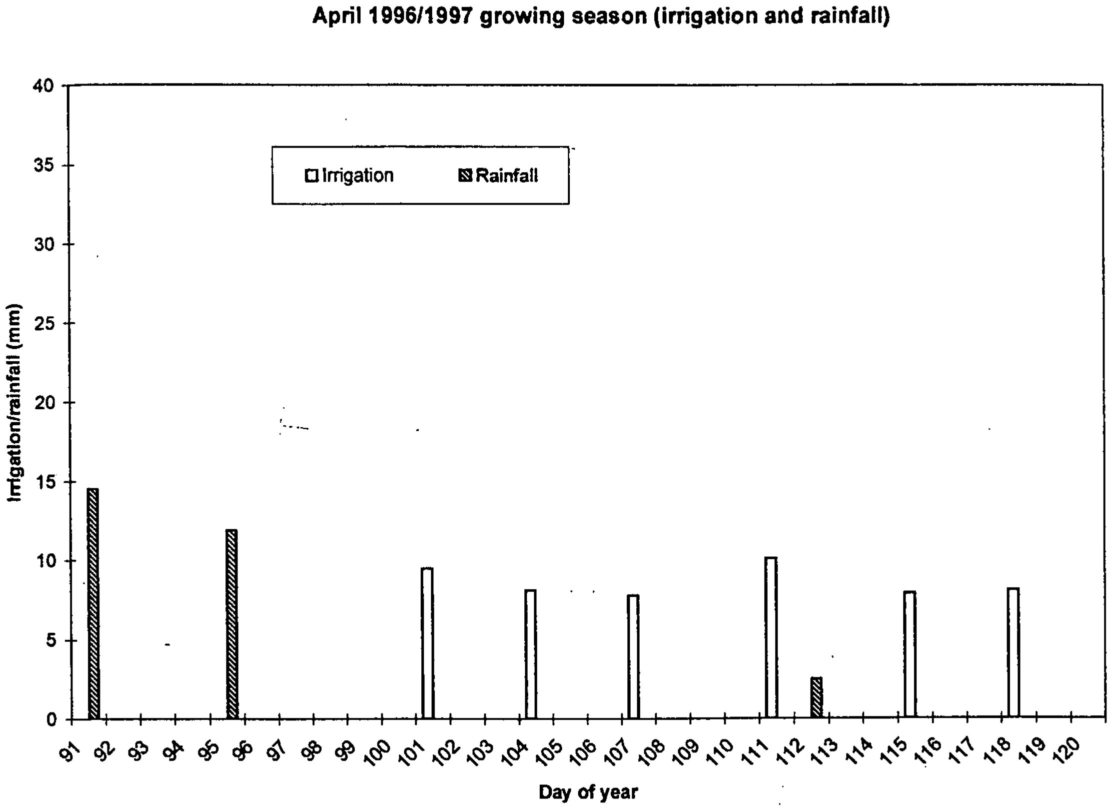
(g)


March 1996/1997 growing season (irrigation and rainfall)
Irrigation
Rainfall
Irrigation/rainfall (mm)
0
5
10
15
20
25
30
35
40
60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90
Day of year

(h)


March 1997/1998 growing season (irrigation and rainfall)
Irrigation
Rainfall
Irrigation/rainfall (mm)
0
5
10
15
20
25
30
35
40
60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90
Day of year)

(l)



April 1996/1997 growing season (irrigation and rainfall)

Appendix ix

1996/1997 Growing season final maize yield data

Density	Rep	Number of plants harvested (area m^{-2})	Number of cobs harvested	Number of cobs per plant	Mean Number of cobs per plant	Maize cob yield (gm^{-2})	Mean Maize cob yield (gm^{-2})	Maize grain yield (gm^{-2})	Mean Maize grain yield (gm^{-2})
Mono-crop	**maize**								
Low	1	50 (22.7)	102	2.04		1014		771.0	
	2	50 (22.7)	104	2.08		1049		797.5	
	3	50 (22.7)	101	2.01	2.04	1053	1038.8	800.0	789.5
Medium	1	80 (18.2)	134	1.68		1213		837.2	
	2	80 (18.2)	138	1.73		1384		955.1	
	3	80 (18.2)	142	1.78	1.73	1320	1305.7	910.6	901.0
High	1	110 (16.4)	132	1.20		1471		1029.5	
	2	110 (16.4)	143	1.30		1420		994.3	
	3	110 (16.4)	138	1.25	1.25	1527	1472.8	1069.1	1031.0
Inter-crop	**maize**								
Low	1	50 (22.7)	110	2.20		666		599.1	
	2	50 (22.7)	100	2.00		630		560.9	
	3	50 (22.7)	120	2.40	2.20	711	669.0	640.1	600.0
Medium	1	70 (15.9)	116	1.65		1043		823.6	
	2	70 (15.9)	105	1.50		1057		831.3	
	3	70 (15.9)	112	1.60	1.58	1061	1053.4	838.1	831.0
High	1	100 (14.9)	118	1.18		1124		877.0	
	2	100 (14.9)	117	1.17		1155		895.0	
	3	100 (14.9)	114	1.14	1.16	1201	1160.2	925.0	899.0

Appendix x

1996/1997 Growing season final beans yield data

Mono-crop	**beans**					
Density	Rep	Number of plants harvested (area m^{-2}))	Beans + Pod wall yield (g m^{-2})	Mean Beans + Pod wall yield (g m^{-2})	Bean seed yield (g m^{-2})	Mean Bean grain yield (g m^{-2})
Low	1	55 (13)	377		267.5	
	2	55 (13)	425		293.0	
	3	55 (13)	400	400.7	281.0	280.5
Medium	1	100 (12)	575		420.0	
	2	100 (12)	570		457.0	
	3	100 (12)	554	566.2	443.0	440.0
High	1	150 (12)	665		530.0	
	2	150 (12)	781		547.0	
	3	150 (12)	771	739.1	540.0	539.0
Inter-crop	**beans**					
Low	1	25 (13)	138		110.0	
	2	25 (13)	175		122.5	
	3	25 (13)	141	151.1	112.5	114.8
Medium	1	50 (12)	183		144.2	
	2	50 (12)	190		148.0	
	3	50 (12)	211	194.6	151.7	147.9
High	1	70 (12)	187		149.5	
	2	70 (12)	199		157.0	
	3	70 (12)	218	201.3	152.5	153.0

Appendix xi

Maize and Bean yields for 1997/1998 growing season

	Plot #	Rep	# of cobs per plant	Maize grain yield (gm^{-2})	Mean Maize grain yield ($g\ m^{-2}$)	Bean grain yield ($g\ m^{-2}$)	Mean Bean grain yield ($g\ m^{-2}$)
BLOCK I	1	Rep 1	1.9	421.0		87.7	
	3	Rep 2	2.0	450.0		87.2	
	5	Rep 3	2.0	418.0	429.8	78.3	84.4
	9	Rep 1	1.2	587.7		90.2	
	7	Rep 2	1.0	543.4		91.2	
	4	Rep 3	1.2	506.4	545.8	86.7	89.4
	6	Rep 1	1.0	546.5		90.1	
	2	Rep 2	1.0	576.3		87.4	
	8	Rep 3	1.0	589.6	570.8	92.8	90.1
BLOCK II	18	Rep 1	1.9	471.2		90.3	
	11	Rep 2	1.5	341.3		79.8	
	15	Rep 3	1.6	361.7	391.4	73.7	81.3
	12	Rep 1	1.6	495.1		97.3	
	13	Rep 2	1.2	554.4		89.0	
	17	Rep 3	1.2	464.1	504.5	90.7	92.3
	16	Rep 1	1.1	672.6		89.8	
	14	Rep 2	1.0	519.7		91.4	
	10	Rep 3	1.0	470.6	554.3	98.1	93.1
	Lys		1.8	453.4			
BLOCK III	22	Rep 1	1.9	458.4		76.8	
	25	Rep 2	1.9	452.2		90.2	
	27	Rep 3	1.7	368.7	426.4	90.5	85.8
	20	Rep 1	1.2	448.9		81.0	
	24	Rep 2	1.2	520.4		90.9	
	26	Rep 3	1.1	367.0	445.4	98.3	90.1
	21	Rep 1	1.0	481.8		90.0	
	19	Rep 2	1.0	489.7		90.2	
	23	Rep 3	1.0	485.2	485.6	95.0	91.7

Appendix xii

Calculation of evapotranspiration (water use) of high plant density mono-crop beans for 1996/1997 growing season using a water balance equation.

Date	*Plot number*	*Days After Sowing (DAS)*	*Rainfall (mm)*	*C/mulative Rainfall (mm)*	*Irrigation (mm)*	*C/mulative Irrigation (mm)*	*Irrigation + Rainfall (mm)*	*C/mulative Irrigation + Rainfall (mm)*	*Change in water content in Profile (mm)*	*Crop total Evap E (mm)*	*Crop total Evap E per day (mm/day)*
11/01/97	2	34	76.0		132.0						
20/01/97	2	43	29.0	105.0	41.0	173.0	70.0	278.0	3.2	66.8	7.4
29/01/97	2	52	56.0	161.0	21.0	194.0	77.0	355.0	16.3	60.7	6.7
5/02/97	2	57	2.6	163.6	33.0	227.0	35.6	390.6	-30.6	66.2	9.5
12/02/97	2	64	4.8	168.4	31.5	258.5	36.3	426.9	-4.8	41.1	5.9
19/02/97	2	71	0.0	168.4	51.0	309.5	51.0	477.9	-3.2	54.2	7.7
27/02/97	2	79	7.0	175.4	49.0	358.5	56.0	533.9	-8.0	64.0	8.0
5/03/97	2	85	54.8	230.2	0.0	358.5	54.8	588.7	23.9	30.9	4.4
12/03/97	2	92	12.9	243.1	0.0	358.5	12.9	601.6	-1.9	14.8	2.1
21/03/97	2	101	16.8	259.9	16.7	375.2	33.5	635.1	11.9	21.6	2.4
								Total	W-use	420.3	

Calculation of evapotranspiration (water use) of medium plant density inter-crop maize/beans for 1996/1997 growing season using a water balance equation.

Date	**Plot number**	**Days After Sowing (DAS)**	**Rainfall (mm)**	**C/mulative Rainfall (mm)**	**Irrigation (mm)**	**C/mulative Irrigation (mm)**	**Irrigation + Rainfall (mm)**	**C/mulative Irrigation + Rainfall (mm)**	**Change in water content in Profile (mm)**	**Crop total Evap E (mm)**	**Crop total Evap E per day (mm/day)**
11/01/97	3	34	76.0		132.0						
20/01/97	3	43	29.0	105.0	41.0	173.0	70.0	278.0	1.1	68.9	7.7
29/01/97	3	52	56.0	161.0	21.0	194.0	77.0	355.0	0.2	76.8	8.5
5/02/97	3	57	2.6	163.6	33.0	227.0	35.6	390.6	-28.9	64.5	9.2
12/02/97	3	64	4.8	168.4	31.5	258.5	36.3	426.9	-6.7	43.0	6.1
19/02/97	3	71	0.0	168.4	51.0	309.5	51.0	477.9	-17.1	68.1	9.7
27/02/97	3	79	7.0	175.4	49.0	358.5	56.0	533.9	-6.6	62.6	7.8
5/03/97	3	85	54.8	230.2	0.0	358.5	54.8	588.7	26.3	28.5	4.1
12/03/97	3	92	12.9	243.1	0.0	358.5	12.9	601.6	-10.6	23.5	3.4
21/03/97	3	101	16.8	259.9	16.7	375.2	33.5	635.1	-1.6	35.1	3.9
26/03/97	3	106	8.4	268.3	10.1	385.3	18.5	653.6	4.6	13.9	2.3
3/04/97	3	114	63.6	331.9	0.0	385.3	63.6	717.2	25.4	38.2	5.5
9/04/97	3	120	11.9	343.8	0.0	385.3	11.9	729.1	-9.6	21.5	3.6
16/04/97	3	127	0.0	343.8	17.6	402.9	17.6	746.7	-11.0	28.6	4.1
23/04/97	3	134	2.5	346.3	17.9	420.8	20.4	767.1	-3.2	23.6	3.4
30/04/97	3	141	0.0	346.3	16.0	436.8	16.0	783.1	-2.8	18.8	2.7
1/05/97	3	142	0.0	346.3	9.5	446.3	9.5	792.6			
								Total	W-use	615.7	

Calculation of evapotranspiration (water use) of high plant density mono-crop maize for 1996/1997 growing season using a water balance equation.

Date	*Plot number*	*Days After Sowing (DAS)*	*Rainfall (mm)*	*C/mulative Rainfall (mm)*	*Irrigation (mm)*	*C/mulative Irrigation (mm)*	*Irrigation + Rainfall (mm)*	*C/mulative Irrigation + Rainfall (mm)*	*Change in water content in Profile (mm)*	*Crop total Evap E (mm)*	*Crop total Evap E per day (mm/day)*
11/01/97	4	34	76.0		132.0						
20/01/97	4	43	29.0	105.0	41.0	173.0	70.0	278.0	8.3	61.7	6.9
29/01/97	4	52	56.0	161.0	21.0	194.0	77.0	355.0	-0.9	77.9	8.7
5/02/97	4	57	2.6	163.6	33.0	227.0	35.6	390.6	-33.7	69.3	9.9
12/02/97	4	64	4.8	168.4	31.5	258.5	36.3	426.9	-6.9	43.2	6.2
19/02/97	4	71	0.0	168.4	51.0	309.5	51.0	477.9	-13.9	64.9	9.3
27/02/97	4	79	7.0	175.4	49.0	358.5	56.0	533.9	-8.6	64.6	8.1
5/03/97	4	85	54.8	230.2	0.0	358.5	54.8	588.7	12.0	42.8	6.1
12/03/97	4	92	12.9	243.1	0.0	358.5	12.9	601.6	-1.0	13.9	2.0
21/03/97	4	101	16.8	259.9	16.7	375.2	33.5	635.1	10.4	23.1	2.6
26/03/97	4	106	8.4	268.3	10.1	385.3	18.5	653.6	-14.4	32.9	5.5
3/04/97	4	114	63.6	331.9	0.0	385.3	63.6	717.2	23.2	40.4	5.8
9/04/97	4	120	11.9	343.8	0.0	385.3	11.9	729.1	-10.3	22.2	3.7
16/04/97	4	127	0.0	343.8	17.6	402.9	17.6	746.7	-7.0	24.6	3.5
23/04/97	4	134	2.5	346.3	17.9	420.8	20.4	767.1	-2.2	22.6	3.2
30/04/97	4	141	0.0	346.3	16.0	436.8	16.0	783.1	-4.1	20.1	2.9
1/05/97	4	142	0.0	346.3	9.5	446.3	9.5	792.6			
								Total	W-use	624.2	

Calculation of evapotranspiration (water use) of low plant density mono-crop beans for 1996/1997 growing season using a water balance equation.

Date	**Plot number**	**Days After Sowing (DAS)**	**Rainfall (mm)**	**C/mulative Rainfall (mm)**	**Irrigation (mm)**	**C/mulative Irrigation (mm)**	**Irrigation + Rainfall (mm)**	**C/mulative Irrigation + Rainfall (mm)**	**Change in water content in Profile (mm)**	**Crop total Evap E (mm)**	**Crop total Evap E per day (mm/day)**
11/01/97	5	34	76.0		132.0						
20/01/97	5	43	29.0	105.0	41.0	173.0	70.0	278.0	1.9	68.1	7.6
29/01/97	5	52	56.0	161.0	21.0	194.0	77.0	355.0	8.5	68.5	7.6
5/02/97	5	57	2.6	163.6	33.0	227.0	35.6	390.6	-20.9	56.5	8.1
12/02/97	5	64	4.8	168.4	31.5	258.5	36.3	426.9	-6.9	43.2	6.2
19/02/97	5	71	0.0	168.4	51.0	309.5	51.0	477.9	-30.7	81.7	11.7
27/02/97	5	79	7.0	175.4	49.0	358.5	56.0	533.9	-14.5	70.5	8.8
5/03/97	5	85	54.8	230.2	0.0	358.5	54.8	588.7	8.4	46.4	6.6
12/03/97	5	92	12.9	243.1	0.0	358.5	12.9	601.6	-2.0	14.9	2.1
21/03/97	5	101	16.8	259.9	16.7	375.2	33.5	635.1	10.2	23.3	2.6
								Total	W-use	473.0	

Calculation of evapotranspiration (water use) of medium plant density mono-crop maize for 1996/1997 growing season using a water balance equation.

Date	***Plot number***	***Days After Sowing (DAS)***	***Rainfall (mm)***	***C/mulative Rainfall (mm)***	***Irrigation (mm)***	***C/mulative Irrigation (mm)***	***Irrigation + Rainfall (mm)***	***C/mulative Irrigation + Rainfall (mm)***	***Change in water content in Profile (mm)***	***Crop total Evap E (mm)***	***Crop total Evap E per day (mm/day)***
11/01/97	6	34	76.0		132.0						
20/01/97	6	43	29.0	105.0	41.0	173.0	70.0	278.0	1.0	69.0	7.7
29/01/97	6	52	56.0	161.0	21.0	194.0	77.0	355.0	-5.3	82.3	9.1
5/02/97	6	57	2.6	163.6	33.0	227.0	35.6	390.6	-39.5	75.1	10.7
12/02/97	6	64	4.8	168.4	31.5	258.5	36.3	426.9	-9.9	46.2	6.6
19/02/97	6	71	0.0	168.4	51.0	309.5	51.0	477.9	-26.9	77.9	11.1
27/02/97	6	79	7.0	175.4	49.0	358.5	56.0	533.9	-9.6	65.6	8.2
5/03/97	6	85	54.8	230.2	0.0	358.5	54.8	588.7	22.1	32.7	4.7
12/03/97	6	92	12.9	243.1	0.0	358.5	12.9	601.6	-12.7	25.6	3.7
21/03/97	6	101	16.8	259.9	16.7	375.2	33.5	635.1	15.6	17.9	2.0
26/03/97	6	106	8.4	268.3	10.1	385.3	18.5	653.6	-15.3	33.8	5.6
3/04/97	6	114	63.6	331.9	0.0	385.3	63.6	717.2	27.3	36.3	5.2
9/04/97	6	120	11.9	343.8	0.0	385.3	11.9	729.1	-9.3	21.2	3.5
16/04/97	6	127	0.0	343.8	17.6	402.9	17.6	746.7	-11.6	29.2	4.2
23/04/97	6	134	2.5	346.3	17.9	420.8	20.4	767.1	-7.4	27.8	4.0
30/04/97	6	141	0.0	346.3	16.0	436.8	16.0	783.1	-7.5	23.5	3.4
1/05/97	6	142	0.0	346.3	9.5	446.3	9.5	792.6			
								Total	W-use	663.9	

Calculation of evapotranspiration (water use) of low plant density inter-crop maize/beans for 1996/1997 growing season using a water balance equation.

Date	***Plot number***	***Days After Sowing (DAS)***	***Rainfall (mm)***	***C/mulative Rainfall (mm)***	***Irrigation (mm)***	***C/mulative Irrigation (mm)***	***Irrigation + Rainfall (mm)***	***C/mulative Irrigation + Rainfall (mm)***	***Change in water content in Profile (mm)***	***Crop total Evap E (mm)***	***Crop total Evap E per day (mm/day)***
11/01/97	7	34	76.0		132.0						
20/01/97	7	43	29.0	105.0	41.0	173.0	70.0	278.0	2.1	67.9	7.5
29/01/97	7	52	56.0	161.0	21.0	194.0	77.0	355.0	1.2	75.8	8.4
5/02/97	7	57	2.6	163.6	33.0	227.0	35.6	390.6	-29.4	65.0	9.3
12/02/97	7	64	4.8	168.4	31.5	258.5	36.3	426.9	-6.6	42.9	6.1
19/02/97	7	71	0.0	168.4	51.0	309.5	51.0	477.9	-21.2	72.2	10.3
27/02/97	7	79	7.0	175.4	49.0	358.5	56.0	533.9	-11.8	67.8	8.5
5/03/97	7	85	54.8	230.2	0.0	358.5	54.8	588.7	11.4	43.4	6.2
12/03/97	7	92	12.9	243.1	0.0	358.5	12.9	601.6	-5.9	18.8	2.7
21/03/97	7	101	16.8	259.9	16.7	375.2	33.5	635.1	10.6	22.9	2.5
26/03/97	7	106	8.4	268.3	10.1	385.3	18.5	653.6	-7.8	26.3	4.4
3/04/97	7	114	63.6	331.9	0.0	385.3	63.6	717.2	13.3	50.3	7.2
9/04/97	7	120	11.9	343.8	0.0	385.3	11.9	729.1	-3.0	14.9	2.5
16/04/97	7	127	0.0	343.8	17.6	402.9	17.6	746.7	-11.4	29.0	4.1
23/04/97	7	134	2.5	346.3	17.9	420.8	20.4	767.1	18.3	2.1	0.3
30/04/97	7	141	0.0	346.3	16.0	436.8	16.0	783.1	-18.9	34.9	5.0
1/05/97	7	142	0.0	346.3	9.5	446.3	9.5	792.6			
								Total	W-use	634.2	

Calculation of evapotranspiration (water use) of low density mono-crop maize for 1996/1997 growing season using a water balance equation.

Date	Plot number	Days After Sowing (DAS)	Rainfall (mm)	C/mulative Rainfall (mm)	Irrigation (mm)	C/mulative Irrigation (mm)	Irrigation + Rainfall (mm)	C/mulative Irrigation + Rainfall (mm)	Change in water content in Profile (mm)	Crop total Evap E (mm)	Crop total Evap E per day (mm/day)
11/01/97	8	34	76.0		132.0						
20/01/97	8	43	29.0	105.0	41.0	173.0	70.0	278.0	0.3	69.7	7.7
29/01/97	8	52	56.0	161.0	21.0	194.0	77.0	355.0	2.9	74.1	8.2
5/02/97	8	57	2.6	163.6	33.0	227.0	35.6	390.6	-27.7	63.3	9.0
12/02/97	8	64	4.8	168.4	31.5	258.5	36.3	426.9	-7.2	43.5	6.2
19/02/97	8	71	0.0	168.4	51.0	309.5	51.0	477.9	-30.7	81.7	11.7
27/02/97	8	79	7.0	175.4	49.0	358.5	56.0	533.9	-20.1	76.1	9.5
5/03/97	8	85	54.8	230.2	0.0	358.5	54.8	588.7	14.0	40.8	5.8
12/03/97	8	92	12.9	243.1	0.0	358.5	12.9	601.6	-7.9	20.8	3.0
21/03/97	8	101	16.8	259.9	16.7	375.2	33.5	635.1	8.4	25.1	2.8
26/03/97	8	106	8.4	268.3	10.1	385.3	18.5	653.6	-11.7	30.2	5.0
3/04/97	8	114	63.6	331.9	0.0	385.3	63.6	717.2	19.1	44.5	6.4
9/04/97	8	120	11.9	343.8	0.0	385.3	11.9	729.1	-7.1	19.0	3.2
16/04/97	8	127	0.0	343.8	17.6	402.9	17.6	746.7	-9.1	26.7	3.8
23/04/97	8	134	2.5	346.3	17.9	420.8	20.4	767.1	1.3	19.1	2.7
30/04/97	8	141	0.0	346.3	16.0	436.8	16.0	783.1	7.9	8.1	1.2
1/05/97	8	142	0.0	346.3	9.5	446.3	9.5	792.6			
								Total	W-use	642.7	

Calculation of evapotranspiration (water use) of medium plant density mono-crop beans for 1996/1997 growing season using a water balance equation.

Date	Plot number	Days After Sowing (DAS)	Rainfall (mm)	C/mulative Rainfall (mm)	Irrigation (mm)	C/mulative Irrigation (mm)	Irrigation + Rainfall (mm)	C/mulative Irrigation + Rainfall (mm)	Change in water content in Profile (mm)	Crop total Evap E (mm)	Crop total Evap E per day (mm/day)
11/01/97	9	34	76.0		132.0						
20/01/97	9	43	29.0	105.0	41.0	173.0	70.0	278.0	-16.3	86.3	9.6
29/01/97	9	52	56.0	161.0	21.0	194.0	77.0	355.0	-0.9	77.9	8.7
5/02/97	9	57	2.6	163.6	33.0	227.0	35.6	390.6	-23.1	58.7	8.4
12/02/97	9	64	4.8	168.4	31.5	258.5	36.3	426.9	8.9	27.4	3.9
19/02/97	9	71	0.0	168.4	51.0	309.5	51.0	477.9	-23.4	74.4	10.6
27/02/97	9	79	7.0	175.4	49.0	358.5	56.0	533.9	-8.2	64.2	8.0
5/03/97	9	85	54.8	230.2	0.0	358.5	54.8	588.7	19.9	34.9	5.0
12/03/97	9	92	12.9	243.1	0.0	358.5	12.9	601.6	-6.3	19.2	2.7
21/03/97	9	101	16.8	259.9	16.7	375.2	33.5	635.1	15.9	17.6	2.0
								Total	W-use	460.7	

Calculation of evapotranspiration (water use) of medium density mono-crop beans for 1996/1997 growing season using a water balance equation.

Date	*Plot number*	*Days After Sowing (DAS)*	*Rainfall (mm)*	*C/mulative Rainfall (mm)*	*Irrigation (mm)*	*C/mulative Irrigation (mm)*	*Irrigation + Rainfall (mm)*	*C/mulative Irrigation + Rainfall (mm)*	*Change in water content in Profile (mm)*	*Crop total Evap E (mm)*	*Crop total Evap E per day (mm/day)*
11/01/97	10	34	76.0		132.0						
20/01/97	10	43	29.0	105.0	41.0	173.0	70.0	278.0	-3.1	73.1	8.1
29/01/97	10	52	56.0	161.0	21.0	194.0	77.0	355.0	-2.2	79.2	8.8
5/02/97	10	57	2.6	163.6	33.0	227.0	35.6	390.6	-30.3	65.9	9.4
12/02/97	10	64	4.8	168.4	31.5	258.5	36.3	426.9	13.5	22.8	3.3
19/02/97	10	71	0.0	168.4	51.0	309.5	51.0	477.9	-32.3	83.3	11.9
27/02/97	10	79	7.0	175.4	49.0	358.5	56.0	533.9	-16.2	72.2	9.0
5/03/97	10	85	54.8	230.2	0.0	358.5	54.8	588.7	28.3	26.5	3.8
12/03/97	10	92	12.9	243.1	0.0	358.5	12.9	601.6	-8.1	21.0	3.0
21/03/97	10	101	16.8	259.9	16.7	375.2	33.5	635.1	7.3	26.2	2.9
								Total	W-use	470.1	

Calculation of evapotranspiration (water use) of high plant density mono-crop maize for 1996/1997 growing season using a water balance equation.

Date	Plot number	Days After Sowing (DAS)	Rainfall (mm)	C/mulative Rainfall (mm)	Irrigation (mm)	C/mulative Irrigation (mm)	Irrigation + Rainfall (mm)	C/mulative Irrigation + Rainfall (mm)	Change in water content in Profile (mm)	Crop total Evap E (mm)	Crop total Evap E per day (mm/day)
11/01/97	11	34	76.0		132.0						
20/01/97	11	43	29.0	105.0	41.0	173.0	70.0	278.0	-6.8	76.8	8.5
29/01/97	11	52	56.0	161.0	21.0	194.0	77.0	355.0	-1.4	78.4	8.7
5/02/97	11	57	2.6	163.6	33.0	227.0	35.6	390.6	-30.3	65.9	9.4
12/02/97	11	64	4.8	168.4	31.5	258.5	36.3	426.9	9.6	26.7	3.8
19/02/97	11	71	0.0	168.4	51.0	309.5	51.0	477.9	-36.5	87.5	12.5
27/02/97	11	79	7.0	175.4	49.0	358.5	56.0	533.9	-10.6	66.6	8.3
5/03/97	11	85	54.8	230.2	0.0	358.5	54.8	588.7	22.7	32.1	4.6
12/03/97	11	92	12.9	243.1	0.0	358.5	12.9	601.6	-6.7	19.6	2.8
21/03/97	11	101	16.8	259.9	16.7	375.2	33.5	635.1	12.4	21.1	2.3
26/03/97	11	106	8.4	268.3	10.1	385.3	18.5	653.6	-14.7	33.2	5.5
3/04/97	11	114	63.6	331.9	0.0	385.3	63.6	717.2	27.7	35.9	5.1
9/04/97	11	120	11.9	343.8	0.0	385.3	11.9	729.1	-8.2	20.1	3.4
16/04/97	11	127	0.0	343.8	17.6	402.9	17.6	746.7	-11.3	28.9	4.1
23/04/97	11	134	2.5	346.3	17.9	420.8	20.4	767.1	-6.5	26.9	3.8
30/04/97	11	141	0.0	346.3	16.0	436.8	16.0	783.1	-7.2	23.2	3.3
1/05/97	11	142	0.0	346.3	9.5	446.3	9.5	792.6			
								Total	W-use	643.0	

Calculation of evapotranspiration (water use) of low plant density inter-crop maize/beans for 1996/1997 growing season using a water balance equation.

Date	***Plot*** number	***Days*** After Sowing (DAS)	***Rainfall*** (mm)	***C/mulative*** Rainfall (mm)	***Irrigation*** (mm)	***C/mulative*** Irrigation (mm)	***Irrigation*** + Rainfall (mm)	***C/mulative*** Irrigation + Rainfall (mm)	***Change in*** water content in Profile (mm)	***Crop total*** Evap E (mm)	***Crop total*** Evap E per day (mm/day)
11/01/97	12	34	76.0		132.0						
20/01/97	12	43	29.0	105.0	41.0	173.0	70.0	278.0	0.1	69.9	7.8
29/01/97	12	52	56.0	161.0	21.0	194.0	77.0	355.0	7.7	69.3	7.7
5/02/97	12	57	2.6	163.6	33.0	227.0	35.6	390.6	-21.9	57.5	8.2
12/02/97	12	64	4.8	168.4	31.5	258.5	36.3	426.9	-0.1	36.4	5.2
19/02/97	12	71	0.0	168.4	51.0	309.5	51.0	477.9	-34.9	85.9	12.3
27/02/97	12	79	7.0	175.4	49.0	358.5	56.0	533.9	-16.0	72.0	9.0
5/03/97	12	85	54.8	230.2	0.0	358.5	54.8	588.7	14.7	40.1	5.7
12/03/97	12	92	12.9	243.1	0.0	358.5	12.9	601.6	-7.4	20.3	2.9
21/03/97	12	101	16.8	259.9	16.7	375.2	33.5	635.1	10.0	23.5	2.6
26/03/97	12	106	8.4	268.3	10.1	385.3	18.5	653.6	-5.1	23.6	3.9
3/04/97	12	114	63.6	331.9	0.0	385.3	63.6	717.2	14.2	49.4	7.1
9/04/97	12	120	11.9	343.8	0.0	385.3	11.9	729.1	-9.0	20.9	3.5
16/04/97	12	127	0.0	343.8	17.6	402.9	17.6	746.7	-6.3	23.9	3.4
23/04/97	12	134	2.5	346.3	17.9	420.8	20.4	767.1	-1.4	21.8	3.1
30/04/97	12	141	0.0	346.3	16.0	436.8	16.0	783.1	-5.0	21.0	3.0
1/05/97	12	142	0.0	346.3	9.5	446.3	9.5	792.6			
								Total	W-use	635.5	

Calculation of evapotranspiration (water use) of medium density mono-crop maize for 1996/1997 growing season using a water balance equation.

Date	***Plot number***	***Days After Sowing (DAS)***	***Rainfall (mm)***	***C/mulative Rainfall (mm)***	***Irrigation (mm)***	***C/mulative Irrigation (mm)***	***Irrigation + Rainfall (mm)***	***C/mulative Irrigation + Rainfall (mm)***	***Change in water content in Profile (mm)***	***Crop total Evap E (mm)***	***Crop total Evap E per day (mm/day)***
11/01/97	13	34	76.0		132.0						
20/01/97	13	43	29.0	105.0	41.0	173.0	70.0	278.0	-1.4	71.4	7.9
29/01/97	13	52	56.0	161.0	21.0	194.0	77.0	355.0	-6.5	83.5	9.3
5/02/97	13	57	2.6	163.6	33.0	227.0	35.6	390.6	-34.6	70.2	10.0
12/02/97	13	64	4.8	168.4	31.5	258.5	36.3	426.9	7.5	28.8	4.1
19/02/97	13	71	0.0	168.4	51.0	309.5	51.0	477.9	-47.3	98.3	14.0
27/02/97	13	79	7.0	175.4	49.0	358.5	56.0	533.9	-11.4	67.4	8.4
5/03/97	13	85	54.8	230.2	0.0	358.5	54.8	588.7	10.1	44.7	6.4
12/03/97	13	92	12.9	243.1	0.0	358.5	12.9	601.6	-2.3	15.2	2.2
21/03/97	13	101	16.8	259.9	16.7	375.2	33.5	635.1	9.0	24.5	2.7
26/03/97	13	106	8.4	268.3	10.1	385.3	18.5	653.6	-13.2	31.7	5.3
3/04/97	13	114	63.6	331.9	0.0	385.3	63.6	717.2	20.9	42.7	6.1
9/04/97	13	120	11.9	343.8	0.0	385.3	11.9	729.1	-9.8	21.7	3.6
16/04/97	13	127	0.0	343.8	17.6	402.9	17.6	746.7	-8.4	26.0	3.7
23/04/97	13	134	2.5	346.3	17.9	420.8	20.4	767.1	-1.6	22.0	3.1
30/04/97	13	141	0.0	346.3	16.0	436.8	16.0	783.1	-6.3	22.3	3.2
1/05/97	13	142	0.0	346.3	9.5	446.3	9.5	792.6			
								Total	W-use	670.2	

Calculation of evapotranspiration (water use) of low plant density mono-crop beans for 1996/1997 growing season using a water balance equation.

Date	**Plot number**	**Days After Sowing (DAS)**	**Rainfall (mm)**	**C/mulative Rainfall (mm)**	**Irrigation (mm)**	**C/mulative Irrigation (mm)**	**Irrigation + Rainfall (mm)**	**C/mulative Irrigation + Rainfall (mm)**	**Change in water content in Profile (mm)**	**Crop total Evap E (mm)**	**Crop total Evap E per day (mm/day)**
11/01/97	14	34	76.0		132.0						
20/01/97	14	43	29.0	105.0	41.0	173.0	70.0	278.0	9.4	60.6	6.7
29/01/97	14	52	56.0	161.0	21.0	194.0	77.0	355.0	16.4	60.6	6.7
5/02/97	14	57	2.6	163.6	33.0	227.0	35.6	390.6	-11.2	46.8	6.7
12/02/97	14	64	4.8	168.4	31.5	258.5	36.3	426.9	0.9	35.4	5.1
19/02/97	14	71	0.0	168.4	51.0	309.5	51.0	477.9	-41.1	92.1	13.2
27/02/97	14	79	7.0	175.4	49.0	358.5	56.0	533.9	-17.7	73.7	9.2
5/03/97	14	85	54.8	230.2	0.0	358.5	54.8	588.7	15.3	39.5	5.6
12/03/97	14	92	12.9	243.1	0.0	358.5	12.9	601.6	-3.9	16.8	2.4
21/03/97	14	101	16.8	259.9	16.7	375.2	33.5	635.1	9.8	23.7	2.6
								Total	W-use	449.1	

Calculation of evapotranspiration (water use) of low plant density mono-crop maize for 1996/1997 growing season using a water balance equation.

Date	***Plot number***	***Days After Sowing (DAS)***	***Rainfall (mm)***	***C/mulative Rainfall (mm)***	***Irrigation (mm)***	***C/mulative Irrigation (mm)***	***Irrigation + Rainfall (mm)***	***C/mulative Irrigation + Rainfall (mm)***	***Change in water content in Profile (mm)***	***Crop total Evap E (mm)***	***Crop total Evap E per day (mm/day)***
11/01/97	15	34	76.0		132.0						
20/01/97	15	43	29.0	105.0	41.0	173.0	70.0	278.0	0.5	69.5	7.7
29/01/97	15	52	56.0	161.0	21.0	194.0	77.0	355.0	1.9	75.1	8.3
5/02/97	15	57	2.6	163.6	33.0	227.0	35.6	390.6	-26.0	61.6	8.8
12/02/97	15	64	4.8	168.4	31.5	258.5	36.3	426.9	-2.0	38.3	5.5
19/02/97	15	71	0.0	168.4	51.0	309.5	51.0	477.9	-35.8	86.8	12.4
27/02/97	15	79	7.0	175.4	49.0	358.5	56.0	533.9	-18.0	74.0	9.3
5/03/97	15	85	54.8	230.2	0.0	358.5	54.8	588.7	13.3	41.5	5.9
12/03/97	15	92	12.9	243.1	0.0	358.5	12.9	601.6	-8.4	21.3	3.0
21/03/97	15	101	16.8	259.9	16.7	375.2	33.5	635.1	11.3	22.2	2.5
26/03/97	15	106	8.4	268.3	10.1	385.3	18.5	653.6	-9.5	28.0	4.7
3/04/97	15	114	63.6	331.9	0.0	385.3	63.6	717.2	16.9	46.7	6.7
9/04/97	15	120	11.9	343.8	0.0	385.3	11.9	729.1	-6.6	18.5	3.1
16/04/97	15	127	0.0	343.8	17.6	402.9	17.6	746.7	-6.0	23.6	3.4
23/04/97	15	134	2.5	346.3	17.9	420.8	20.4	767.1	-3.8	24.2	3.5
30/04/97	15	141	0.0	346.3	16.0	436.8	16.0	783.1	-7.0	23.0	3.3
1/05/97	15	142	0.0	346.3	9.5	446.3	9.5	792.6			
								Total	W-use	654.4	

Calculation of evapotranspiration (water use) of medium density inter-crop maize/beans for 1996/1997 growing season using a water balance equation.

Date	Plot number	Days After Sowing (DAS)	Rainfall (mm)	C/mulative Rainfall (mm)	Irrigation (mm)	C/mulative Irrigation (mm)	Irrigation + Rainfall (mm)	C/mulative Irrigation + Rainfall (mm)	Change in water content in Profile (mm)	Crop total Evap E (mm)	Crop total Evap E per day (mm/day)
11/01/97	16	34	76.0		132.0						
20/01/97	16	43	29.0	105.0	41.0	173.0	70.0	278.0	-4.4	74.4	8.3
29/01/97	16	52	56.0	161.0	21.0	194.0	77.0	355.0	-4.0	81.0	9.0
5/02/97	16	57	2.6	163.6	33.0	227.0	35.6	390.6	-31.3	66.9	9.6
12/02/97	16	64	4.8	168.4	31.5	258.5	36.3	426.9	14.9	21.4	3.1
19/02/97	16	71	0.0	168.4	51.0	309.5	51.0	477.9	-47.9	98.9	14.1
27/02/97	16	79	7.0	175.4	49.0	358.5	56.0	533.9	-11.7	67.7	8.5
5/03/97	16	85	54.8	230.2	0.0	358.5	54.8	588.7	24.9	29.9	4.3
12/03/97	16	92	12.9	243.1	0.0	358.5	12.9	601.6	-2.5	15.4	2.2
21/03/97	16	101	16.8	259.9	16.7	375.2	33.5	635.1	11.6	21.9	2.4
26/03/97	16	106	8.4	268.3	10.1	385.3	18.5	653.6	-13.1	31.6	5.3
3/04/97	16	114	63.6	331.9	0.0	385.3	63.6	717.2	26.8	36.8	5.3
9/04/97	16	120	11.9	343.8	0.0	385.3	11.9	729.1	-7.6	19.5	3.2
16/04/97	16	127	0.0	343.8	17.6	402.9	17.6	746.7	-11.4	29.0	4.1
23/04/97	16	134	2.5	346.3	17.9	420.8	20.4	767.1	-4.0	24.4	3.5
30/04/97	16	141	0.0	346.3	16.0	436.8	16.0	783.1	-6.3	22.3	3.2
1/05/97	16	142	0.0	346.3	9.5	446.3	9.5	792.6			
								Total	W-use	641.2	

Calculation of evapotranspiration (water use) of high plant density mono-crop beans for 1996/1997 growing season using a water balance equation.

Date	***Plot number***	***Days After Sowing (DAS)***	***Rainfall (mm)***	***C/mulative Rainfall (mm)***	***Irrigation (mm)***	***C/mulative Irrigation (mm)***	***Irrigation + Rainfall (mm)***	***C/mulative Irrigation + Rainfall (mm)***	***Change in water content in Profile (mm)***	***Crop total Evap E (mm)***	***Crop total Evap E per day (mm/day)***
11/01/97	17	34	76.0		132.0						
20/01/97	17	43	29.0	105.0	41.0	173.0	70.0	278.0	-0.1	70.1	7.8
29/01/97	17	52	56.0	161.0	21.0	194.0	77.0	355.0	25.3	51.7	5.7
5/02/97	17	57	2.6	163.6	33.0	227.0	35.6	390.6	-15.8	51.4	7.3
12/02/97	17	64	4.8	168.4	31.5	258.5	36.3	426.9	2.2	34.1	4.9
19/02/97	17	71	0.0	168.4	51.0	309.5	51.0	477.9	-32.8	83.8	12.0
27/02/97	17	79	7.0	175.4	49.0	358.5	56.0	533.9	-28.5	84.5	10.6
5/03/97	17	85	54.8	230.2	0.0	358.5	54.8	588.7	23.1	31.7	4.5
12/03/97	17	92	12.9	243.1	0.0	358.5	12.9	601.6	-7.8	20.7	3.0
21/03/97	17	101	16.8	259.9	16.7	375.2	33.5	635.1	17.5	16.0	1.8
								Total	W-use	444.0	

Appendix xviii

Calculated water use in intercrop maize/beans in three plant densities for the 1997/1998 growing season in block I of the experiment with limited irrigation application.

Block 1				
	Water use (mm)			
Density	rep 1	rep 2	rep 3	Mean
Low	559.7	532.6	535.3	542.5 a
Medium	529.7	535.0	544.6	536.4 a
High	526.5	547.8	555.6	543.3 a

Means with the same letter are not significantly different at 5% level by Tukey's Studentized Range (HSD) Test.

Calculated water use in intercrop maize/beans in three plant densities for the 1997/1998 growing season in block II of the experiment with full irrigation application.

Block 2				
Density	rep 1 Water use (mm)	rep 2 Water use (mm)	rep 3 Water use (mm)	Mean Water use (mm)
Low	625.4	631.0	632.2	629.5 a
Medium	630.9	641.5	661.1	644.5 a
High	630.7	638.5	656.3	641.8 a

Means with the same letter are not significantly different at 5% level by Tukey's Studentized Range (HSD) Test.

Calculated water use in intercrop maize/beans in three plant densities for the 1997/1998 growing season in block III of the experiment with limited irrigation application.

Block 3				
Density	rep 1 Water use (mm)	rep 2 Water use (mm)	rep 3 Water use (mm)	Mean Water use (mm)
Low	524.9	534.4	526.0	528.4 a
Medium	534.9	551.1	526.6	537.5 a
High	544.2	547.5	569.6	553.8 a

Means with the same letter are not significantly different at 5% level by Tukey's Studentized Range (HSD) Test.

Appendix xiv

Comparison of weight of maize cobs per plant for three plant densities under full irrigation for 1996/1997 growing season.

	Mean weight of maize cobs per plant (grams)		
Cropping system	low density	medium density	high density
Monocropping	452.7	235.6	182.1
Intercropping	444.5	285.7	165.5
mean	448.6 a	260.7 b	173.8 c

Means with the same letter are not significantly different at 1% level by Tukey's Studentized Range (HSD) Test.

Comparison of number of maize cobs per plant for three plant densities under full irrigation for 1996/1997 growing season.

	Mean number of maize cobs per plant		
Cropping system	low density	medium density	high density
Monocropping	2.04	1.73	1.25
Intercropping	2.02	1.58	1.16
mean	2.03 a	1.66 b	1.20 c

Means with the same letter are not significantly different at 1% level by Tukey's Studentized Range (HSD) Test.

Appendix xv

Comparison of intercrop maize plant height (cm) and monocrop maize plant height (cm) for three plant densities under full irrigation for 1996/1997 growing season.

Days after planting	Mono LD	Inter LD	Mono MD	Inter MD	Mono HD	Inter HD
36	51.8	52.0	52.8	50.0	43.3	54.8
43	63.8	70.3	68.5	59.3	51.5	64.5
53	138.0	135.0	145.0	101.3	147.5	157.3
57	179.8	165.8	179.0	153.8	184.5	192.8
60	210.0	205.0	212.5	181.3	230.0	212.5
74	230.0	240.0	251.3	215.0	245.0	243.8
81	232.5	240.0	252.5	217.5	253.8	247.5
88	225.0	235.0	235.0	225.0	260.0	250.0
95	235.0	228.8	227.5	222.5	255.0	242.5

Comparison of intercrop beans plant height (cm) and monocrop beans plant height (cm) for three plant densities under full irrigation for 1996/1997 growing season.

Days after planting	Mono LD	Inter LD	Mono MD	Inter MD	Mono HD	Inter HD
43	22.5	22.8	23.3	23.0	24.3	22.5
53	32.3	33.0	31.8	35.0	34.3	36.3
57	34.0	35.5	34.5	37.3	35.8	37.5
60	38.0	38.3	38.8	39.5	38.3	39.5
74	37.5	38.3	37.5	38.3	38.3	40.3
81	37.0	38.5	38.5	39.8	39.0	41.0
88	37.2	38.3	37.8	39.0	39.3	39.5
95	38.0	39.3	39.3	40.0	39.5	39.5

Appendix xvi

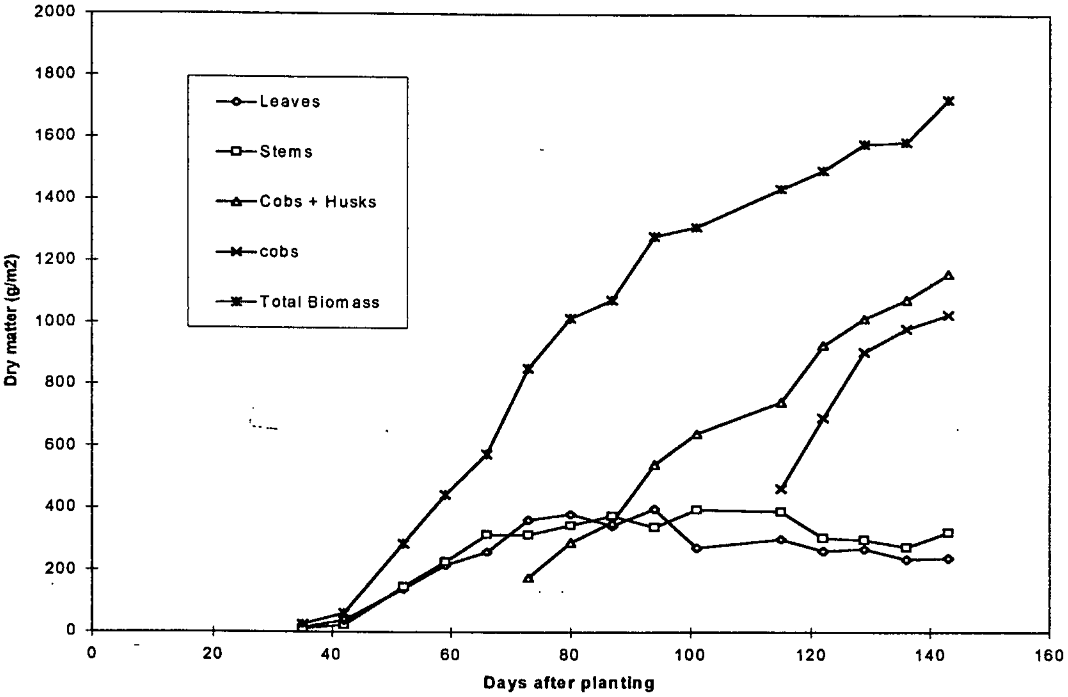
Measured leaf area index in mono-crop maize in three plant densities for 1996/1997 growing season.

	Mono-crop maize plant density leaf area index		
Days after planting	High	Medium	Low
36	1.0	1.1	1.0
43	1.9	1.5	1.4
60	2.6	2.5	1.8
63	2.8	2.8	2.5
67	3.5	3.1	1.7
74	5.3	5.1	2.8
81	3.9	4.6	3.5
89	3.5	2.3	2.0

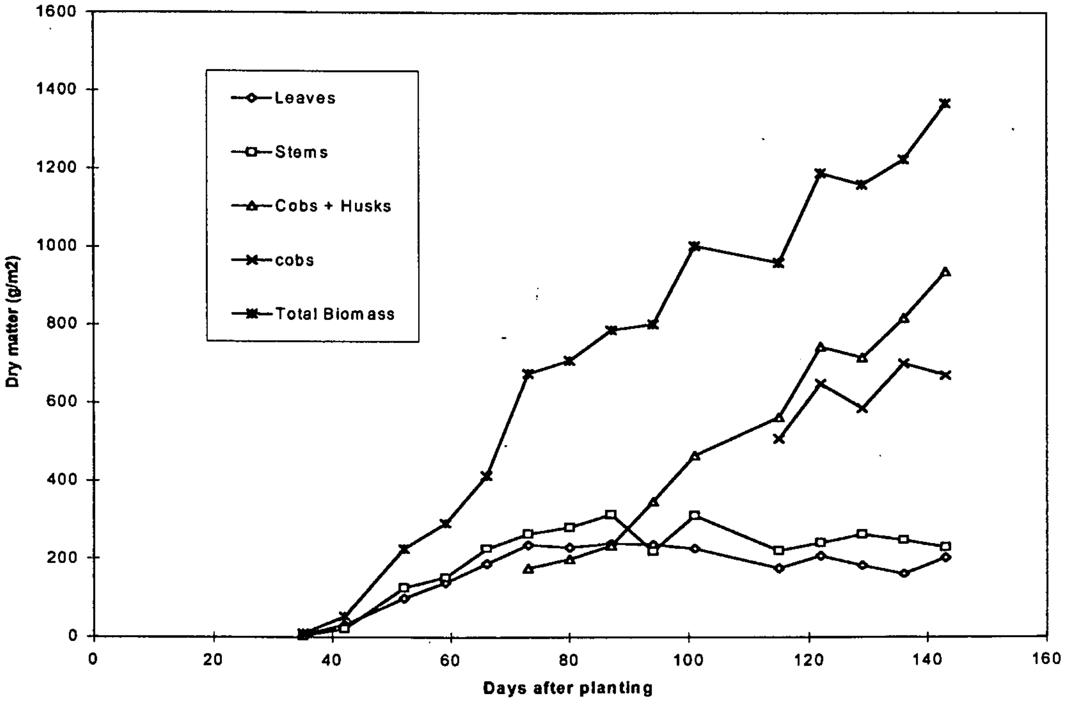
Measured leaf area index in inter-crop maize/beans in three plant densities for 1996/1997 growing season.

	Inter-crop maize/beans plant density leaf area index		
Days after planting	High	Medium	Low
35	1.3	0.8	0.5
42	2.6	1.7	1.2
52	3.6	2.7	1.1
56	4.4	3.1	1.7
63	5.6	4.0	2.2
66	6.7	5.2	3.0
70	5.0	3.2	1.5
73	4.3	4.0	3.4
80	3.4	2.6	1.9
88	2.9	2.7	1.3

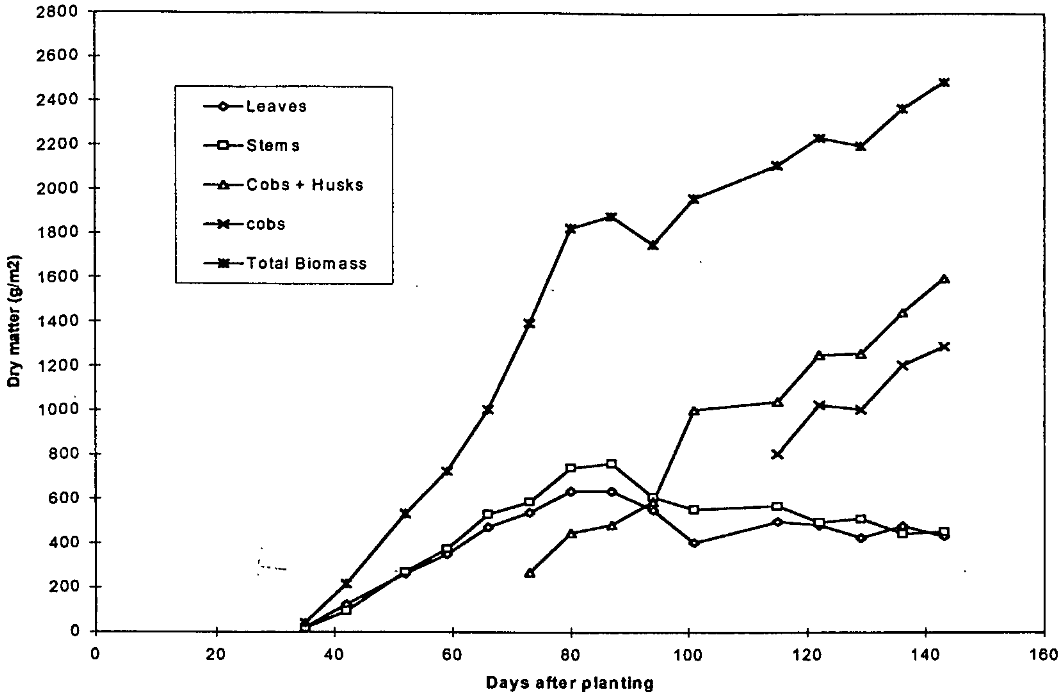
Appendix xvii



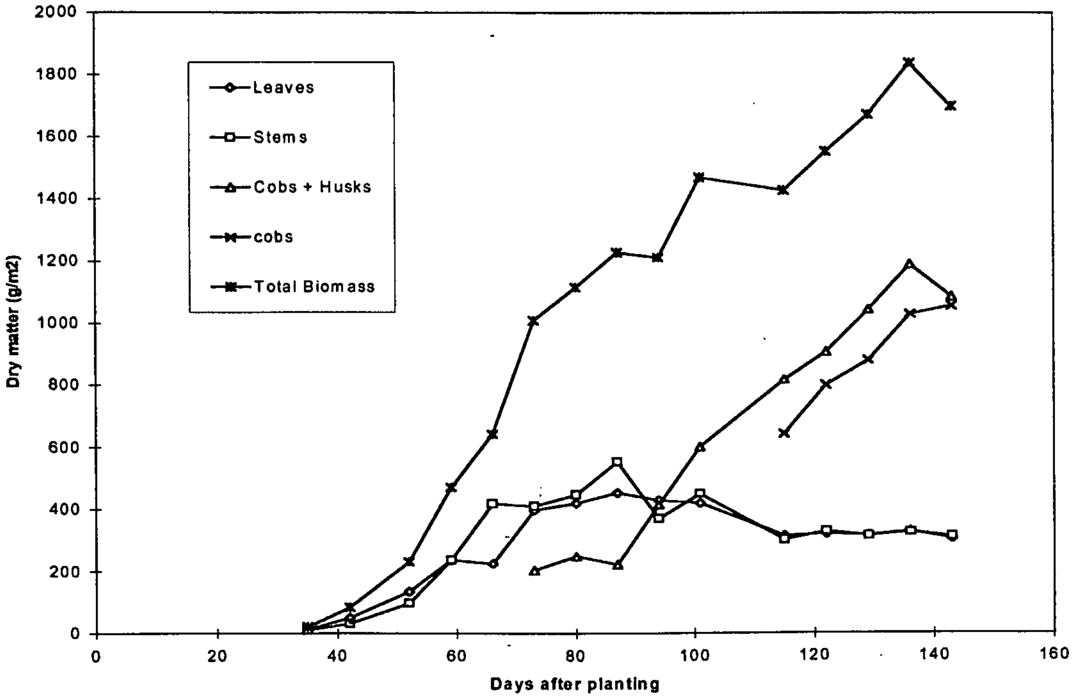
Low density mono-crop maize standing dry matter production of leaves, stems, cobs + husks, cobs and total dry matter for the 1996/1997 growing season.



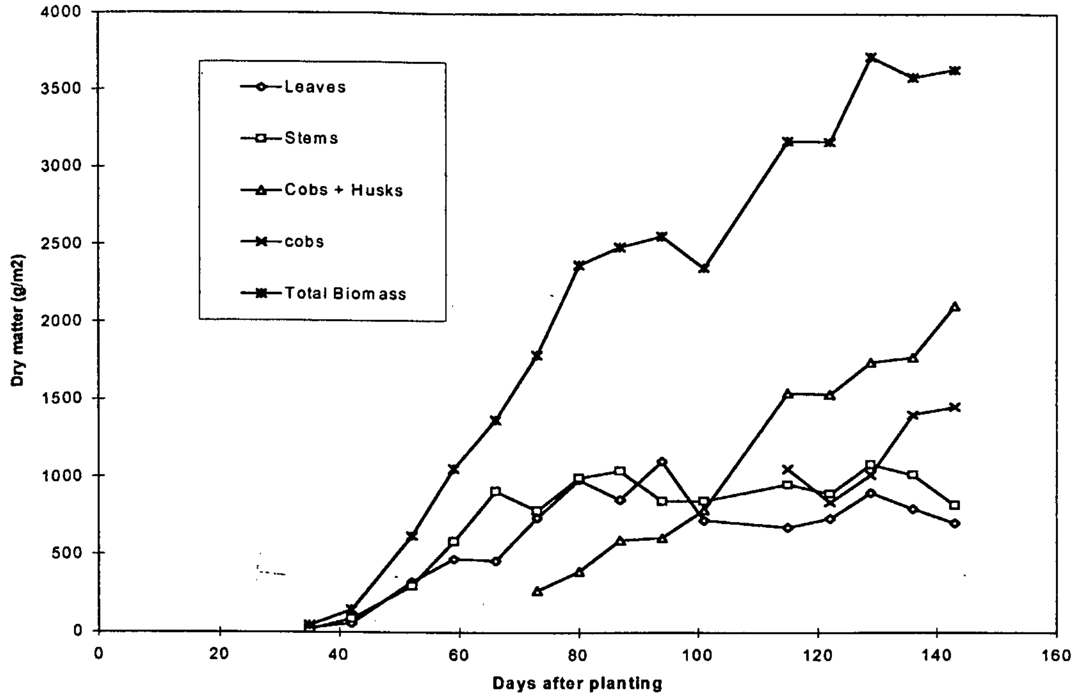
Low density inter-crop maize standing dry matter production of leaves, stems, cobs + husks, cobs and total dry matter for the 1996/1997 growing season.



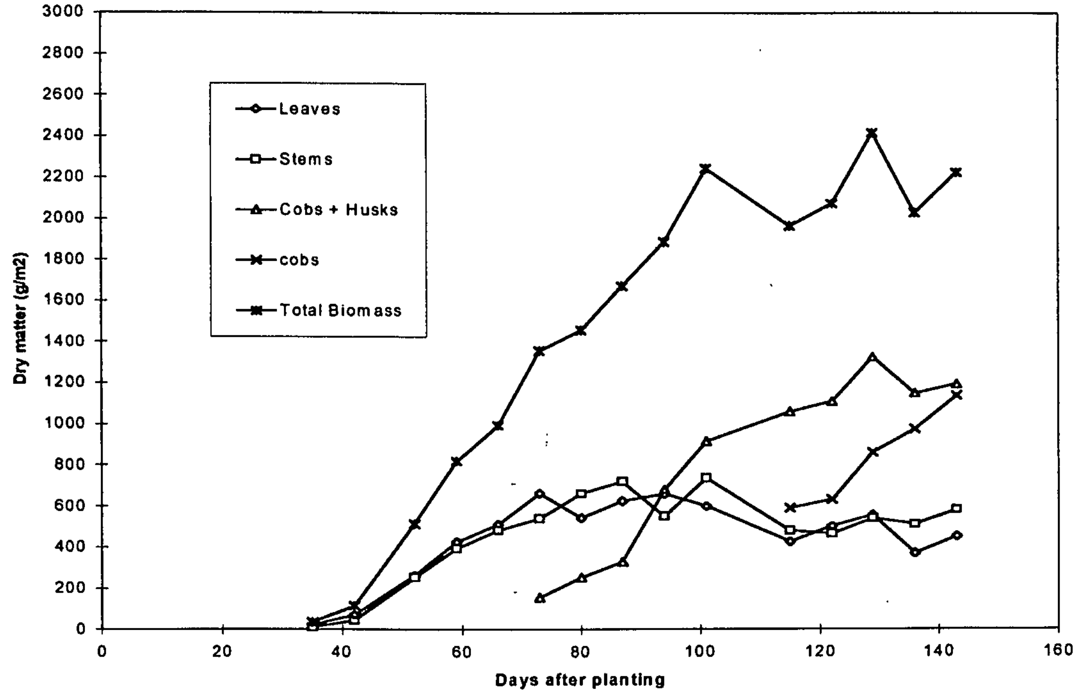
Medium density mono-crop maize standing dry matter production of leaves, stems, cobs + husks, cobs and total dry matter for the 1996/1997 growing season.



Medium density inter-crop maize standing dry matter production of leaves, stems, cobs + husks, cobs and total dry matter for the 1996/1997 growing season.



High density mono-crop maize standing dry matter production of leaves, stems, cobs + husks, cobs and total dry matter for the 1996/1997 growing season.



High density inter-crop maize standing dry matter production of leaves, stems, cobs + husks, cobs and total dry matter for the 1996/1997 growing season.

Low density mono-crop beans standing biomass production

	gms/m^2	gms/m^2	gms/m^2	gms/m^2
DAP	Leaves	Stems	Seeds + Pod Walls	Total Biomass
	LD Sole Beans	LD Sole Beans	LD Sole Beans	LD Sole beans
35	15.1	6.2		21.3
42	26.3	14.3		40.6
52	71.5	45.8		117.3
59	110.9	76.8	6.5	194.2
66	120.6	88.5	35.6	244.7
73	138.9	90.1	130.4	359.4
80	137.1	94.1	189.5	420.7
87	154	100.1	265.9	520.0
94	150.4	94.3	346.1	590.8
101	148.2	97.0	400.7	645.9
		Grain Yield	280.5	HI 0.43

Medium density mono-crop beans standing biomass production

DAP	Leaves (gm^{-2})	Stems (gm^{-2})	Seeds + Pod Walls (gm^{-2})	Total Biomass (gm^{-2})
35	17.3	7.1		24.4
42	30.8	16.2		47.1
52	92.5	51.7		144.2
59	165.4	87.3	13.5	266.2
66	136.0	104.0	37.1	277.1
73	156.5	111.0	145.2	412.7
80	175.4	112.5	244.4	532.3
87	175.8	131.9	460.8	768.5
94	184.2	130.0	564.6	878.7
101	147.5	103.3	566.2	817.1
		Grain Yield	440.0	HI 0.54

High density mono-crop beans standing biomass production

DAP	Leaves (gm^{-2})	Stems (gm^{-2})	Seeds + Pod Walls (gm^{-2})	Total Biomass (gm^{-2})
35	17.5	8.4		25.9
42	42.2	17.8		60.0
52	175.0	110.9		285.9
59	190.3	125.3	4.7	320.3
66	207.5	152.8	36.6	396.9
73	196.3	136.9	208.1	541.3
80	219.1	158.4	228.8	606.3
87	238.1	165.6	312.8	716.6
94	255.0	182.2	532.2	969.4
101	260.6	185.3	739.1	1185.0
		Grain Yield	539.5	HI 0.46

Low density inter-crop beans standing biomass production

DAP	Leaves (gm^{-2})	Stems (gm^{-2})	Seeds + Pod Walls (gm^{-2})	Total Biomass (gm^{-2})
35	6.3	2.5		8.8
42	12.5	6.2		18.6
52	25.7	12.5		38.2
59	30.5	20.1	0.8	51.3
66	32.3	20.0	6.2	58.4
73	53.1	30.8	25.8	109.7
80	57.8	36.2	79.1	173.1
87	53.5	37.9	117.9	209.2
94	48.2	33.7	129.9	211.7
101	54.7	36.8	151.1	242.5
110		Grain Yield	114.8	HI 0.47

Medium density inter-crop beans standing biomass production

DAP	Leaves (gm^{-2})	Stems (gm^{-2})	Seeds + Pod Walls (gm^{-2})	Total Biomass (gm^{-2})
35	11.3	3.9		15.2
42	16.3	7.2		23.5
52	28.6	16.0		44.6
59	46.7	27.6	3.1	77.4
66	55.8	39.6	22.8	118.2
73	35.7	26.2	29.4	91.3
80	68.4	47.6	128.7	244.7
87	55.5	42.3	118.4	216.2
94	51.7	43.3	166.0	261.0
101	66.0	50.9	194.6	311.5
		Grain Yield	147.9	HI 0.47

High density inter-crop beans standing biomass production

DAS	Leaves (gm^{-2})	Stems (gm^{-2})	Seeds + Pod Walls (gm^{-2})	Total Biomass (gm^{-2})
35	11.3	5.1		16.4
42	26.0	12.9		38.9
52	60.2	38.9		99.0
59	60.9	46.7	4.4	111.9
66	71.4	68.7	18.6	158.7
73	89.6	70.4	54.0	213.9
80	76.4	66.3	110.6	253.2
87	59.3	67.5	146.6	273.3
94	57.2	67.1	168.0	292.2
101	69.6	77.4	201.3	348.3
		Grain Yield	153.0	HI 0.44

Low density mono-crop maize standing dry matter production for 1996/1997 growing season.

DAP	Leaves (gm^{-2})	Stems (gm^{-2})	Cobs + Husks (gm^{-2})	cobs (gm^{-2})	Total Biomass (gm^{-2})
35	14.7	11.0			25.7
42	36.5	23.3			59.8
52	139.3	145.9			285.1
59	216.3	227.9			444.2
66	259.8	315.9			575.7
73	362.3	314.2	176.7		853.2
80	381.3	344.7	289.7		1015.7
87	343.6	375.5	354.6		1073.8
94	398.4	339.9	542.5		1280.8
101	272.8	397.1	640.9		1310.8
115	300.7	390.7	743.8	465.1	1435.3
122	262.7	304.7	928.6	694.5	1496.0
129	268.0	297.0	1014.9	907.5	1579.8
136	236.5	275.2	1076.0	981.2	1587.7
143	240.5	323.4	1160.9	1027.8	1724.8

Low density inter-crop maize standing dry matter production for 1996/1997 growing season.

DAP	Leaves (gm^{-2})	Stems (gm^{-2})	Cobs + Husks (gm^{-2})	cobs (gm^{-2})	Total Biomass (gm^{-2})
35	6.4	3.7			10.1
42	31.5	21.9			53.4
52	99.1	125.6			224.8
59	138.6	151.9			290.5
66	186.7	226.3			412.9
73	235.2	263.6	176.3		675.0
80	229.5	279.7	198.4		707.6
87	237.9	313.5	233.6		785.0
94	235.3	218.8	346.1		800.2
101	226.3	310.0	464.5		1000.8
115	175.2	220.8	561.7	507.0	957.6
122	206.4	240.2	742.2	648.7	1188.8
129	183.1	261.9	713.4	585.4	1158.5
136	161.3	247.6	814.3	699.4	1223.1
143	202.9	228.7	935.4	668.6	1367.1

Medium density mono-crop maize standing dry matter production for 1996/1997 growing season.

DAP	Leaves (gm^{-2})	Stems (gm^{-2})	Cobs + Husks (gm^{-2})	cobs (gm^{-2})	Total Biomass (gm^{-2})
35	23.1	18.2			41.3
42	124.9	95.1			220.0
52	267.1	272.9			539.9
59	353.3	378.2			731.5
66	477.3	536.4			1013.7
73	544.8	593.3	272.0		1410.1
80	641.7	749.3	451.5		1842.5
87	641.3	768.8	488.4		1898.5
94	557.7	616.8	595.5		1770.0
101	408.4	558.2	1015.0		1981.6
115	505.7	575.5	1053.7	815.0	2134.9
122	490.6	501.7	1267.9	1037.7	2260.2
129	431.5	517.3	1273.7	1019.5	2222.4
136	484.0	448.8	1461.2	1222.1	2394.0
143	438.6	457.7	1616.3	1306.1	2512.6

Medium density inter-crop maize standing dry matter production for 1996/1997 growing season.

DAP	Leaves (gm^{-2})	Stems (gm^{-2})	Cobs + Husks (gm^{-2})	cobs (gm^{-2})	Total Biomass (gm^{-2})
35	11.7	9.3			21.0
42	50.7	32.1			82.8
52	132.9	96.6			229.5
59	234.6	235.2			469.8
66	223.8	417.6			641.4
73	396.6	408.3	201.9		1006.8
80	419.7	446.7	247.2		1113.6
87	452.7	553.5	219.9		1226.1
94	428.4	368.4	413.7		1210.5
101	418.5	448.8	600.3		1467.6
115	312.3	299.4	816.0	641.4	1427.7
122	318.6	328.5	904.5	798.9	1551.6
129	315.3	313.5	1041.6	878.7	1670.4
136	327.6	324.9	1185.6	1027.5	1838.1
143	304.5	310.8	1082.4	1053.3	1697.7

High density mono-crop maize standing dry matter production for 1996/1997 growing season.

DAP	Leaves (gm^{-2})	Stems (gm^{-2})	Cobs + Husks (gm^{-2})	cobs (gm^{-2})	Total Biomass (gm^{-2})
35	27.3	16.7			44.0
42	57.3	87.3			144.7
52	326.6	299.3			625.9
59	474.6	589.9			1064.6
66	465.3	916.6			1381.9
73	743.3	791.9	272.0		1807.2
80	992.6	1006.6	397.3		2396.4
87	863.2	1051.9	597.9		2513.1
94	1113.9	855.2	613.9		2583.1
101	726.6	853.2	795.3		2375.1
115	683.3	961.9	1559.8	1063.9	3205.0
122	742.6	902.6	1553.2	848.6	3198.3
129	910.6	1091.9	1759.2	1025.2	3761.6
136	803.3	1027.9	1793.8	1419.9	3625.0
143	711.3	829.3	2132.5	1473.2	3673.0

High density inter-crop maize standing dry matter production for 1996/1997 growing season.

DAP	Leaves (gm^{-2})	Stems (gm^{-2})	Cobs + Husks (gm^{-2})	cobs (gm^{-2})	Total Biomass (gm^{-2})
35	23.4	12.2			35.6
42	73.8	44.6			118.4
52	267.8	258.8			526.5
59	435.6	401.0			836.6
66	522.0	491.9			1013.9
73	675.9	550.4	159.8		1386.0
80	554.0	675.0	258.8		1487.7
87	636.8	733.5	336.6		1706.9
94	672.3	559.4	692.1		1923.8
101	609.8	748.4	932.9		2291.0
115	435.2	491.0	1079.6	602.1	2005.7
122	510.8	473.4	1131.3	644.0	2115.5
129	567.0	549.9	1351.8	877.5	2468.7
136	378.0	520.2	1171.4	993.2	2069.6
143	459.9	592.7	1216.8	1160.6	2269.4

Appendix xviii

Partitioning factors for daily new growth (mass) of maize to the different plant parts.

Growth stage	Store	Stem	Leaf	Grain / fruit
Sow	70	10	20	0
Emergence	0	40	60	0
Establish	0	50	50	0
Vegetative	0	55	45	0
Anthesis	0	55	45	0
Reproductive 1	5	47	33	15
Reproductive 2	13	30	27	30
Maturity	19	23	18	40
Fallow	0	0	0	0

Partitioning factors for daily new growth (mass) of beans to the different plant parts.

Growth stage	Store	Stem	Leaf	Grain / fruit
Sow	70	20	10	0
Emergence	0	60	40	0
Establish	0	50	50	0
Vegetative	0	45	55	0
Anthesis	0	45	55	0
Reproductive 1	5	33	47	15
Reproductive 2	13	27	30	30
Maturity	19	18	23	40
Fallow	0	0	0	0

Sandy-Loam soil used in the PUTU simulations

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Layer 6
Thickness (m)	0.15	0.15	0.15	0.15	0.15	0.15
Porosity (mm/m)	358	358	340	340	320	320
SWUL (K/Pa)	- 7	- 7	- 7	- 7	- 7	- 7
SWUL (mm/m)	265	265	340	340	390	390
V10 (mm/m)	250	250	300	300	380	380
DUL (mm/m)	183	183	267	267	360	360
V1500 (mm/m)	60	60	80	80	100	100

Water application programme and minimum effective irrigation demands (IRR.mm) per cycle for MAIZE with a seed yield target of 7895 kg/ha

Days after planting	Complete CWD addition during peak		Profile completely wet when planted		Profile partially wet when planted		Profile dry when planted	
	IRR	Total	IRR	Total	IRR	Total	IRR	Total
10	1	1	1	1	4	4	5	5
13	5	6	5	6	13	17	14	19
16	6	12	6	12	13	30	14	34
19	7	19	7	19	13	42	14	48
22	8	27	8	27	13	55	14	63
25	9	35	9	35	13	68	14	77
28	10	45	10	45	13	81	14	92
31	10	55	10	55	13	93	14	106
34	11	66	11	66	13	106	14	121
37	12	78	12	78	13	119	14	135
40	13	91	13	91	13	132	14	150
43	13	104	13	104	13	144	14	164
46	14	118	14	118	13	157	14	179
49	14	132	14	132	14	171	14	193
52	15	147	14	146	14	185	14	208
55	15	162	14	160	14	199	14	222
58	16	178	14	174	14	213	14	237
61	16	194	14	188	14	227	14	251
64	17	211	14	202	14	241	14	266
67	17	228	14	216	14	255	14	280
70	17	245	14	230	14	269	14	295
73	17	262	14	244	14	283	14	309
76	18	280	14	258	14	297	14	324
79	18	298	14	272	14	311	14	338
82	18	316	14	286	14	325	14	353
85	18	334	14	300	14	339	14	367
88	18	352	14	314	14	353	14	382
91	18	370	14	328	14	367	14	396
94	18	388	14	342	14	381	14	411
97	18	406	14	356	14	395	14	425
100	18	424	14	370	14	409	14	440
103	18	442	14	384	14	423	14	454
106	17	459	14	398	14	437	14	469
109	17	476	14	412	14	451	14	483
112	17	493	14	426	14	465	14	497
115	16	509	14	440	14	479	14	512
118	16	525	14	454	14	493	14	526
121	16	541	14	468	14	507	14	541
124	15	556	14	482	14	521	14	555
127	15	571	14	496	14	535	14	570
130	14	585	14	510	14	549	14	584
133	14	599	14	523	14	563	14	598
136	13	612	13	536	13	576	13	611
139	12	**624**	12	548	12	588	12	623

Water application programme and minimum effective irrigation demands (IRR.mm) per cycle for MAIZE with a seed yield target of 9010 kg/ha

Days after planting	Complete CWD addition during peak		Profile completely wet when planted		Profile partially wet when planted		Profile dry when planted	
	IRR	Total	IRR	Total	IRR	Total	IRR	Total
10	2	2	2	2	5	5	5	5
13	5	7	5	7	14	19	16	21
16	6	13	6	13	14	33	16	37
19	8	21	8	21	14	42	16	53
22	9	29	9	29	14	56	16	69
25	10	39	10	39	14	70	16	85
28	10	49	10	49	14	84	16	101
31	11	61	11	61	14	93	16	117
34	12	73	12	73	14	107	16	132
37	13	86	13	86	14	121	16	148
40	14	100	14	100	14	135	16	164
43	15	114	15	114	14	144	16	180
46	15	130	15	130	14	158	16	196
49	16	145	16	145	15	173	16	212
52	16	162	16	161	16	189	16	228
55	17	179	16	176	16	205	16	244
58	17	196	16	192	16	221	16	260
61	18	214	16	207	16	237	16	275
64	18	232	16	223	16	253	16	291
67	19	251	16	239	16	269	16	307
70	19	270	16	254	16	285	16	323
73	19	289	16	270	16	301	16	339
76	19	308	16	285	16	317	16	355
79	20	328	16	301	16	333	16	371
82	20	348	16	316	16	349	16	387
85	20	368	16	332	16	365	16	403
88	20	387	16	348	16	381	16	418
91	20	407	16	363	16	397	16	434
94	20	427	16	379	16	413	16	450
97	20	447	16	394	16	429	16	466
100	19	466	16	410	16	445	16	482
103	19	485	16	425	16	461	16	498
106	19	504	16	441	16	477	16	514
109	19	523	16	457	16	493	16	530
112	18	541	16	472	16	509	16	545
115	18	559	16	488	16	525	16	561
118	18	577	16	503	16	541	16	577
121	17	594	16	519	16	557	16	593
124	17	611	16	534	16	573	16	609
127	16	627	16	550	16	589	16	625
130	16	643	16	566	16	605	16	641
133	15	658	15	580	15	620	15	656
136	14	672	14	594	14	634	14	670
139	14	**686**	14	608	14	648	14	684

Water application programme and minimum effective irrigation demands (IRR.mm) per cycle for MAIZE with a seed yield target of 10310 kg/ha.

Days after planting	Complete CWD addition during peak		Profile completely wet when planted		Profile partially wet when planted		Profile dry when planted	
	IRR	Total	IRR	Total	IRR	Total	IRR	Total
10	2	2	2	2	5	5	6	6
13	6	8	6	8	15	20	18	24
16	7	15	7	15	15	35	18	41
19	8	23	8	23	15	50	18	59
22	9	32	9	32	15	65	18	77
25	11	43	11	43	15	80	18	94
28	12	55	12	55	15	95	18	112
31	13	67	13	67	15	110	18	130
34	14	81	14	81	15	126	18	147
37	14	95	14	95	15	141	18	165
40	15	110	15	110	15	156	18	183
43	16	127	16	127	15	171	18	200
46	17	143	17	143	15	186	18	218
49	18	161	18	161	15	201	18	236
52	18	179	18	179	18	219	18	254
55	19	198	18	196	18	236	18	271
58	19	217	18	214	18	254	18	289
61	20	237	18	231	18	271	18	307
64	20	257	18	249	18	289	18	324
67	21	278	18	267	18	307	18	342
70	21	298	18	284	18	324	18	360
73	21	320	18	302	18	342	18	377
76	21	341	18	320	18	360	18	395
79	22	363	18	337	18	377	18	413
82	22	385	18	355	18	395	18	430
85	22	406	18	373	18	413	18	448
88	22	428	18	390	18	430	18	466
91	22	450	18	408	18	448	18	484
94	22	472	18	426	18	466	18	501
97	22	494	18	443	18	483	18	519
100	22	515	18	461	18	501	18	537
103	21	537	18	479	18	519	18	554
106	21	558	18	496	18	536	18	572
109	21	578	18	514	18	554	18	590
112	20	599	18	532	18	572	18	607
115	20	619	18	549	18	589	18	625
118	20	638	18	567	18	607	18	643
121	19	657	18	585	18	625	18	660
124	18	676	18	602	18	642	18	678
127	18	694	18	620	18	660	18	696
130	17	711	17	637	17	677	17	713
133	17	728	17	654	17	694	17	730
136	16	743	16	670	16	710	16	745
139	15	**758**	15	685	15	725	15	760

Appendix xix

Input parameters for mono-crop maize snk 2147 for three plant densities

Parameter	Low density	Medium density	High density
T maximum	30	30	30
T anthesis	845	845	845
T maturity	1500	1500	1500
f	1	1	1
fw	1	1	1
fr	1	1	1
K	0.85	0.85	0.85
LAR	0.0062	0.0062	0.0045
Cm	20	20	20
Tb	22	22	22
Plant density	2.2	2.2	2.2
LAI.i	0.04	0.04	0.04
Gamma20	0.045	0.045	0.045

Input parameters for inter-crop maize snk 2147 for three plant densities

Parameter	Low density	Medium density	High density
T maximum	30	30	30
T anthesis	845	845	845
T maturity	1500	1500	1500
f	1	1	1
fw	1	1	1
fr	1	1	1
K	0.85	0.85	0.85
LAR	0.0062	0.0064	0.0062
Cm	20	20	20
Tb	22	22	22
Plant density	2.2	2.2	2.2
LAI.i	0.04	0.04	0.04
Gamma20	0.045	0.045	0.045

Input parameters for mono-crop beans Pan127 for three plant densities

Parameter	Low density	Medium density	High density
T maximum	30	30	30
T anthesis	489	489	489
T maturity	1268	1268	1268
f	1	1	1
fw	1	1	1
fr	1	1	1
K	0.85	0.85	0.85
LAR	0.02	0.02	0.02
Cm	10	14	18
Tb	45	45	45
Plant density	4.2	8.3	12.5
LAI.i	0.04	0.04	0.04
Gamma20	0.045	0.045	0.045

Input parameters for inter-crop beans Pan 127 for three plant densities

Parameter	Low density	Medium density	High density
T maximum	30	30	30
T anthesis	489	489	489
T maturity	1268	1268	1268
f	1	1	1
fw	1	1	1
fr	1	1	1
K	0.85	0.85	0.85
LAR	0.0125	0.0125	0.0125
Cm	6	6	6
Tb	45	45	45
Plant density	2.1	4.4	6.7
LAI.i	0.04	0.04	0.04
Gamma20	0.045	0.045	0.045

Appendix xx

Putu AnyCrop

```
COMMON SHARED DPLcrit, LPREV
DECLARE SUB ResetSub ()
DECLARE SUB BiomassGrowth ()
DECLARE SUB WaterStressPhenology ()
DECLARE SUB LeafAreaDevelopment ()
DECLARE SUB WriteResults ()
DECLARE FUNCTION CHANTER! (CHANTERa!, CHANTERb!, CHANTERc!, CHANTERd!, TTmat!, TIMEthml!)
DECLARE SUB Partitioning ()
DECLARE SUB EnvironmentalVar ()
DECLARE SUB RootDevelopment ()
DECLARE SUB DayLength ()
DECLARE SUB Calendar ()
DECLARE SUB EffectiveTemp ()
DECLARE SUB WeatherDataInput ()
DECLARE SUB AdjustSimulation ()
DECLARE SUB Callendar ()
DECLARE SUB AdjustInseasonData ()
'$INCLUDE: 'COMMON.BAS'
COMMON SHARED CUTFS(), CUTF(), PercTrash, Lamda, GAMMA, Biomass, BIOMprev
COMMON SHARED Tsvap, TtransT, Srain, Sirrig, Srunoff, WatEnd, QTOT

DEF FNRADUE (Fv) = 1.3 * Fv                        'INSERTED 20/8/92
'OPEN "f:\test.var" FOR OUTPUT AS #9

    DIM PARTD(10), PSISSAT(10), PORO(10), KSOILSAT(10), KSOIL(10), IAW(10)
    DIM X(367, 9), GMT(12), GMR(12), GMS(12), GME(12), Doymnd(20), Daypm(13), DOYMES(12)
    DIM JC(10), FI(10), CRITthmlperd(10), Ky(10), green(10), trsh(10), ST$(10), standing(10), senesced(10)
    DIM sensesced(10)

    DIM Store(10), Stem(10), Leaf(10), GrainFruit(10)
    DIM DZRT(10), DUL(10), VINIT(10), LL(10), V15(10), CLAYFRAC(10), SILTFRAC(10), BULKDENS(10)
    DIM V(10), W(10), mends(12), mlens(12)
    DIM PERC(10), SANDFRAC(10), V0(10), V01(10), PSIS(10)
    DIM VCON(10), M(10), V1600(10), P0(10), W01(10), W15(10), W16(10), KSPO(10)
    DIM PAW(9), RPROP(10), ZBOTT(10), Vdummy(10)
    DIM KSP(9), TS(9), AW(9), PAWL(9), DEFICIT(9), FAW(9), Yred(10)
    DIM DOYHAIL(10), HAILP(10), CUTD(10)
    DIM MeasValue(367, 11), VCS(3, 20)
    DIM CUTFS(6, 20)
    DIM CUTF(20)

    DIM SWULpress(9), SWULcont(9), V1500(9), PSIS1500(9), B(9)

    CALL hdatum
    CALL Heading
65   CALL MeanD
66   CALL InitialConditions
    'CALL Weathsummary

    CALL CultivarCharacter
    CALL InitialWater
    ' CALL ReadInseasonData
67   CALL OPENoutputfiles
    'CALL Grassparameter

80   CALL Zero
85   CALL TitlePage
    CALL TableHeading
```

```
90    '*************************
100   'BEGINNING OF CALCULATION
101   '*************************
130
140   FLAGprint = 0
150   FLAGrest = 0

'     START LOOPING THROUGH THE SEASONS
'     ***********************************************************************


      FOR SEASONcounter = 1 TO Nseasons
            CALL Calendar
            CALL WeatherDataInput
        FOR DOY = 1 TO LENGTHyear
          IF Stge <> 10 THEN
           PRINT USING "### ##.# ##.# ##   ##   ##   ###   ###   #####   ####     #.# ####  ##.# ###"; DOY; FW;
Laist; X(DOY, 6); X(DOY, 3); PERC; PPAW; TDEFICIT; PSIL; TIMEthml; kc; AEDplot; Eo; FID
           ELSE
           GOTO 532
          END IF
        IF DOY = MeasValue(DOY, 1) THEN
          'CALL AdjustSimulation
        END IF


180      CALL EnvironmentalVar
        CALL LeafAreaDevelopment
        CALL BiomassGrowth

        ' CALL ScheduleIrrig
192       CALL RootDevelopment
194       ' SoilwaterPot
        FOR L = 1 TO 9
           PSIS(L) = -1500 * (V(L) / V1500(L)) ^ B(L)
        NEXT L

      CALL ReWetSoil
      CALL SoilRootCond

230       IF Stge = 1 OR Stge = 10 THEN            'REST PERIOD
          CALL TriggerS1
          CALL Zero
250        ELSE
         GOTO 260
        END IF
        GOTO 520

260       IF Stge <= 2 THEN               'STAGE TWO
          CALL TriggerS2
280        ELSE
          GOTO 290
        END IF

290       IF Stge <= 3 THEN                         'STAGE THREE
          CALL TriggerS3

         ELSE
          GOTO 320
        END IF

        GOTO 500

320       IF Stge <= 4 THEN                   'STAGE FOUR
          CALL TriggerS4
```

```
     ELSE
      GOTO 350
     END IF

     GOTO 500

350   IF Stge <= 5 THEN              'STAGE FIVE
       CALL TriggerS5
      ELSE
       GOTO 380
     END IF

     GOTO 500

380   IF Stge <= 6 THEN                    'STAGE SIX
       CALL TriggerS6
      ELSE
       GOTO 410
     END IF

     GOTO 500

410   IF Stge <= 7 THEN              'STAGE SEVEN
       CALL TriggerS7
420      IF LAI < 0 THEN LAI = 0
      ELSE
       GOTO 470
     END IF

     GOTO 500

470   IF Stge <= 8 THEN                    'STAGE eight
       CALL TriggerS8
       IF FLAGstg8 = 1 THEN
        'CALL RECORDseason
       END IF
      ELSE
       GOTO 480
     END IF

     GOTO 500

480   IF Stge <= 9 THEN                    'STAGE eight

       CALL TriggerS9
       GOTO 520

       IF FLAGstg8 = 1 THEN
         'CALL RECORDseason
       END IF
      ELSE
       GOTO 490
     END IF

     GOTO 500

490          ' tenth stage is a rest stage

'    **********************************************************************
500  '* Commence simulation of daily crop growth
'    **********************************************************************

     CALL PsicLeaf
     CALL Partitioning
```

```
      'CALL HailS
      CALL CropHeight
      'CALL Translocation

520     CALL Totals

      IF JX = InVIPrn OR FLAGprint = 1 THEN
        GOTO 528
       ELSE
        GOTO 532
     END IF
528   CALL Means
     CALL ScheduleIrrig
     CALL WriteResultP
     CALL WriteResults

     FLAGprint = 0: JX = 0
532

     TAW = 0
     FOR L = 1 TO 9
      AW(L) = W(L) - W16(L)
      TAW = TAW + AW(L)  'Total available soilwater and maximum available water in the root zone
     NEXT L

   IF DOG >= 1 THEN
      IF DOG = 1 THEN
            ITAW = 0: SOILVAP = 0
            FOR L = 1 TO 9
                 ITAW = ITAW + (W(L) - W16(L))
            NEXT L
       END IF

   END IF

   RUNOF = 0
    PERC(10) = 0
  NEXT DOY
      Fweadat = LEFT$(Fweadat, 24) + RIGHT$(STR$(Yrcrnt), 2)
'     YrCrnt = YrCrnt + 1
'************************
' END OF DAILY SIMULATION
'************************

  NEXT SEASONcounter
   CLOSE #9
END
 'CALL Update

   CLOSE #20, #6, #3, #5, #24
   WWeight = WM
   WM = WWeight
   'Wm = WWeight

'  CUTFS(5, YrStart - 76) = WWeight
'

'   W = 0: WM = 0: WWeight = 0: DOG = 0: HU = 0: TU = 0
'   Stge = 1:
'   DayDev = 0: SeasTFv = 0: SeasMFv = 0
'   Tpgrowth = 0: Tpgrowtho = TTanthesis:
'   LAI1 = 0: LAI2 = 0: LAI3 = 0
'
   CLOSE #1
'  OPEN "LOC" FOR OUTPUT AS #1
```

```
'  PRINT #1, USING "#####.##"; YrB; YrStart + 1; YrEnd; WM; VeldT
'  CLOSE #1

'  ns$ = "A" + LTRIM$(STR$(YrStart)) + ".DAT"
'  OPEN ns$ FOR OUTPUT AS #1
'  PRINT #1, USING "######.##"; CUTFS(5, YrStart - 76); CUTFS(1, YrStart - 76)
'  CLOSE #1
'
'  CLEAR
'  OPEN "LOC" FOR INPUT AS #1
'  INPUT #1, YrB, YrStart, YrEnd, WM, VeldT
'  CLOSE #1
'
   END

SUB AdjustSimulation

4000 '*****************************************************************
4001 '    SUBROUTINE TO TEST FOR VARIABLES THAT CHANGE
4005 '    DURING THE SEASON
4010 '*****************************************************************
        K = 0
        FOR K = 2 TO 10
          IF MeasValue(DOY, K) <> 0 THEN
            V(K - 1) = MeasValue(DOY, K)
            W(K - 1) = V(K - 1) * DZRT(K - 1)
          END IF
        NEXT K
        IF MeasValue(DOY, 11) <> 0 THEN
          LAI = Var
        END IF
END SUB

SUB BiomassGrowth

'GROWTHRATEmax = 130
'ExtCoef = .7
'TIMElost = 30
'LAR = .0013
'LAinitial = .002
Lamda = 2

     DMGWeight = 0
     IF TIMEthml < TTmat THEN
     IF DOG <> 0 THEN
       Biomass = FuNEXPOLIN(GROWTHRATEmax, ExtCoef, TIMEphysio, TIMElost, LAR) -
FuNEXPOLIN(GROWTHRATEmax, ExtCoef, 0, TIMElost, LAR)
       DMGWeight = (Biomass - BIOMprev)
       DMG = DMGWeight * Fv
       WWeight = WWeight + DMG
       BIOMprev = Biomass
     END IF

      Wprev = WWeight
      gain = DMGWeight: loss = Lamda * GAMMA * W1

      W1 = W1 + gain - loss
      IF TIMEthml > TTanthesis THEN
        W1 = W1 - gain + loss
      END IF
      gain = loss
      loss = GAMMA * W2

      W2 = W2 + gain - loss
      gain = loss
```

```
        loss = GAMMA * W3

        W3 = W3 + gain - loss
        gain = loss
        loss = GAMMA * W4
        W4 = W4 + gain - loss

        gain = loss
        W5 = W5 + gain

        ELSE
        ' Harvest
          W1 = 0: W2 = 0: W3 = 0: W4 = 0: W5 = 0: Wprev = 0
          DMGWeight = 0: WWeight = 0

        END IF

END SUB

SUB Calendar

  Daypm(0) = 0
  Daypm(1) = 31
  Daypm(2) = 28
  Daypm(3) = 31
  Daypm(4) = 30
  Daypm(5) = 31
  Daypm(6) = 30
  Daypm(7) = 31
  Daypm(8) = 31
  Daypm(9) = 30
  Daypm(10) = 31
  Daypm(11) = 30
  Daypm(12) = 31
  LENGTHyear = 365
  IF ((Yrcrnt MOD 4) = 0) THEN
    Daypm(2) = 29
    LENGTHyear = 366
  END IF
  Doymnd(1) = Daypm(1)
  Doymnd(2) = Daypm(1) + Daypm(2)
  IF (LENGTHyear = 366) THEN
    Doymnd(2) = 60
  END IF
  mendg = Doymnd(2)
  FOR i = 3 TO 12
    Doymnd(i) = mendg + Daypm(i)
    mendg = Doymnd(i)
  NEXT i

 END SUB


 FUNCTION CHANTER (CHANTERa, CHANTERb, CHANTERc, CHANTERd, TTmat, TIMEthml)
    CHANTER = 1 / CHANTERd * CHANTERa * CHANTERb * CHANTERc * EXP(-CHANTERc * TIMEthml /
 TTmat) / (1 + CHANTERb * EXP(-CHANTERc * TIMEthml / TTmat)) ^ ((CHANTERd + 1) / CHANTERd)
 'INSERTED 20/8/92
 END FUNCTION

 SUB CloseEnd
        PRINT "Your run has been completed successfully"
        CLOSE #2
        STOP
 END SUB
```

```
SUB CropHeight
10849 '************************************************************************
10850 '           CROP HEIGHT
10851 '************************************************************************
10855  IF Stge > 6 THEN 10880
10860  DELHT = FuNTION23(TIMEthml, TTanthesis, HTO) - HTPREV
10862  HT = HT + DELHT * (1 - FW)
10870  IF HT > 1 THEN HT = 1
10875  HTPREV = HT
10880  'RETURN

END SUB

SUB CultivarCharacter


     '********************READING THE CULTIVAR CHARACTERISTICS ****

9575   OPEN NmCulF FOR INPUT AS #1
9651   FOR K = 1 TO 9
       INPUT #1, JC(K), FI(K), CRITthmlperd(K), Ky(K), green(K), trsh(K), YearDum, MonthDum, DayDum,
Store(K), Stem(K), Leaf(K), GrainFruit(K), ST$(K)

       senesced(K) = 100 - green(K)

9652   NEXT K

       INPUT #1, NAMEcrop$
       INPUT #1, NAMEcult$
       INPUT #1, Kvo
       INPUT #1, Kso
       INPUT #1, BO
       INPUT #1, c1: TTmx = c1
       INPUT #1, c2: TTanthesis = c2:
       INPUT #1, c3: TTmat = c3
       INPUT #1, c4: fcanopy = c4
       INPUT #1, c5: fwet = c5
       INPUT #1, c6: froot = c6
       INPUT #1, c7: ExtCoef = c7
       INPUT #1, c8: LAR = c8
       INPUT #1, c9: GROWTHRATEmax = c9
       INPUT #1, c10: TIMElost = c10
       INPUT #1, c11: DENSITYplant = c11
       INPUT #1, c12: LAinitial = c12
       INPUT #1, c13: GAMMA20 = c13:
       INPUT #1, c14: POTENTIALyield = c14
       INPUT #1, c15: BRC = c15
       INPUT #1, c16: BWC = c16
       INPUT #1, c17: BWC = c17
       INPUT #1, c18: BWC = c19
       INPUT #1, c19:
       INPUT #1, c20:
       INPUT #1, PSIC1
       INPUT #1, PSIC2

       CLOSE #1

       T0 = 20  'the optimal temperature for crop growth
 3294  CUC = 7.4          'MINIMUM COLD UNITS<8 REQUIRED TO END TILLERING
 3296  CON1 = 21.8        'ADDITIONAL DD PER UNIT CUDEFICIT DD/CU
 3320  COO = .012
     Tpgrowtho = TTanthesis
     Flg = .05
     DOGPrev = 1
     Lamda = 2
```

```
END SUB

SUB DayLength
PI = 22 / 7
Dist = 10 + .033 * COS(.0172 * DOY)
SolarDeclination = .409 * SIN(.0172 * DOY - 1.39)
SunsetAngle = PI / 2 + ATN((-TAN(Latitude) * TAN(SolarDeclination)) / ((1 - (TAN(Latitude)) ^ 2 *
(TAN(SolarDeclination)) ^ 2)) ^ .5)
'SunsetAngle = PI / 2 - ARCOS(-TAN(Latitude) * TAN(SolarDeclination))
SolarConstant = 1 * Dist * (SunsetAngle * SIN(Latitude) * SIN(SolarDeclination) + COS(Latitude) *
COS(SolarDeclination) * SIN(SunsetAngle))
PossibleHours = 7.64 * SunsetAngle

END SUB

FUNCTION DLENGTH (DOY)
 'DayLength = 12.15 + 1.93 * COS((DOY + 9) / 365 * 2 * 3.14285)      'DAYLENGTH
 DLENGTH = 12.15 + 1.93 * COS((DOY + 9) / 365 * 2 * 3.14285)      'DAYLENGTH
END FUNCTION

FUNCTION DLYR (SO, KT, NMX)
 DLYR = SO * (.25 + .75 * KT / NMX)                    'MJ m^-2 d^-1
END FUNCTION

SUB EffectiveTemp
5545  t = (X(DOY, 1) + X(DOY, 2)) / 2                  ' TEMPERATURE, HEAT
5547  UPRT = X(DOY, 1)
5548  IF X(DOY, 1) > TTmx THEN UPRT = TTmx
5549  EFFGT = (UPRT + X(DOY, 2)) / 2
5550  IF EFFGT < BO THEN EFFGT = BO
5553  HUPREV = TIMEthml
5565  DELHU = EFFGT - BO

END SUB

SUB EnvironmentalVar

5470  ' ******************************************************************
5500  '         ENVIRONMENTAL VARIABLES AND LIMITING FACTORS
5510  '******************************************************************

    CALL EffectiveTemp
    CALL DayLength
    FTP = FuNTION6(t, T0)
    Ffac = (FTP * Fv) * 100
    HU = HU + DELHU
    GAMMA = GAMMA20 * (t - BO) / (20 - BO)

    IF GAMMA < 0 THEN GAMMA = 0

    IF DOG <> 0 THEN
     TIMEthml = TIMEthml + DELHU                  ' HEAT UNITS
     IF TIMEthml < TTmat THEN
      TIMEphysio = TIMEphysio + (DELHU * PossibleHours / ((20 - BO) * 12))
     END IF
    END IF
    CALL WaterStressPhenology

5567  TNITE = X(DOY, 1) / 3 + X(DOY, 2) / 2
5572  ' Calculate potential and actual crop evaporation
    V1DEF = V01(1) - V(1)
    IF V1DEF < 0 THEN V1DEF = 0
    IF DOG = 3 THEN
     PRINT
    END IF
```

```
      Fg = FuNTION21(V1DEF)
      IF Flg >= 1 THEN Flg = .999999
      Le = -LOG(1 - Flg) / .9
      CONSTfig = .9 - .5 * Fg
      Flg = FuNTION9(Le, CONSTfig) + .001
      Eo = X(DOY, 7)
      Mu = 1
      IF Flg <> 0 THEN
       IF FW < .6 THEN
         CONSTfig = .9
         Flg = FuNTION9(LAlg, CONSTfig) + .001
       END IF
       IF fwet = 1 THEN Fl = Fl
       IF fwet > fcanopy AND fwet < 1 THEN Fl = Fl / fwet
       IF fwet <= fcanopy THEN Fl = Fl / fcanopy

       'IF fwet < 1 AND fwet >= fcanopy THEN Fl = 0
       'IF fwet < 1 AND fwet <= fcanopy THEN Fl = (fcanopy - fwet) / (1 - fwet)

       'Kd = (1- fwet) * Fg * Kso
       kvg = Kvo * Flg
      PTRANS = kvg * Eo
      END IF

      Ks = Kso * Fg * (1 - Fl)
      IF DOY = 180 THEN
       PRINT
      END IF
5605   SOILVAP = Ks * Eo
     ' SoilVap = (Ks + Kd) * Eo
'      PRINT USING "#####.##"; FG; V1DEF; SOILVAP
5610   kc = Ks + kvg
5615   PAR = .5 * X(DOY, 4)                    'RFDM
      kv = kvg
END SUB

SUB FUNCTIONS

END SUB

FUNCTION FuNEXPOLIN (GROWTHRATEmax, K, TIMEphysio, TIMElost, LAR)
  FuNEXPOLIN = 1 / (K * LAR) * LOG(1 + EXP(K * LAR * GROWTHRATEmax * (TIMEphysio - TIMElost)))
END FUNCTION

FUNCTION FuNINITINTCP (K, Lo)
 FuNINITINTCP = 1 - EXP(-K * Lo)
END FUNCTION

FUNCTION FuNLostTIME (RM1, Fo)
 FuNLostTIME = -LOG(Fo / (1 - Fo)) / RM1
END FUNCTION

FUNCTION FuNTION16 (V15L, PL, P0L, ML)
      FuNTION16 = V15L * (PL / P0L) ^ (1 / ML)
END FUNCTION

FUNCTION FuNTION18 (V, V16, V01)
   FuNTION18 = (LOG(V / V16)) / LOG(V01 / V16)
END FUNCTION

FUNCTION FuNTION19 (TIMEthml, TTanthesis, ROOTZO)
     FuNTION19 = ROOTZO * (1 / (1 + 44.2 * EXP(-8.5 * TIMEthml / TTanthesis)))  'HT
END FUNCTION

FUNCTION FuNTION2 (PSI, PSICrit)
```

```
 FuNTION2 = 1 - EXP(-8.000001E-03 * (PSI - (PSICrit - 400)))  'Fv
END FUNCTION

FUNCTION FuNTION21 (V1DEF)
   FuNTION21 = EXP(-.03 * V1DEF)                         'Fg
END FUNCTION

FUNCTION FuNTION22 (DOG)
   FuNTION22 = -1600 - 11.7 * (DOG - 50)
END FUNCTION

FUNCTION FuNTION23 (TIMEthml, TTanthesis, HTO)
   FuNTION23 = HTO * (1 / (1 + 44.2 * EXP(-8.5 * TIMEthml / TTanthesis)))
END FUNCTION

FUNCTION FuNTION6 (t, T0)
     FuNTION6 = EXP(-.00277777# * (t - T0) ^ 2)                'Ft
END FUNCTION

FUNCTION FuNTION9 (LAI, CONSTfig)
  FuNTION9 = (1 - EXP(-CONSTfig * LAI))                'Fv
END FUNCTION

SUB HailS

10799  '*****************************************************************
10800  '                      HAIL
10801  '*****************************************************************
10805  HAILPC = 0
10810  FOR i = 1 TO DOYSHAIL
10820       IF DOY <> DOYHAIL(i) THEN 10840
10830       HAILPC = HAILP(i)
10840  NEXT i
10845  'RETURN

END SUB

SUB hdatum

     datum$ = DATE$
     dags = VAL(MID$(datum$, 4, 2))
     Yrcrnt = VAL(MID$(datum$, 7, 4))
     maand = VAL(MID$(datum$, 1, 2))

END SUB

SUB Heading

     '*******************************************************************
17000  'SUB TO CREATE HEADING ON SCREEN
     '*******************************************************************
     CLS
     PRINT
     PRINT "                =========PUTU-IRRIGATION========="
     PRINT
     'PRINT "                   Version A (December 1991)"
     PRINT "        A crop growth and soil waterbalance model developed by "
     PRINT "         the Department of Agrometeorology, U.O.F.S."
     PRINT : PRINT : PRINT : PRINT : PRINT
END SUB

SUB InitialConditions
DIM Nweadf AS STRING * 25
DIM Irigfil AS STRING * 24
DIM NVinitF AS STRING * 24
```

```
DIM MidSeaF AS STRING * 26
DIM OU2 AS STRING * 2

9490   '**********************************************************************
9500   '                    INITIAL CONDITIONS
9505   '**********************************************************************
       NCntF = COMMAND$
       ' NCntF = "c:\putu\control\muk9601.ctl "
       OPEN "I", #1, NCntF
       '******************READING THE CONTROL-FILE ************
       ' EXPERIMENT MANAGER
       ' ******************

1      INPUT #1, NmSite       'EXPERIMENTAL SITE ID FOUR CHARACTERS
2      INPUT #1, YrStrt      'Year in which experiment starts
3      INPUT #1, ExpNum        'Experiment number
41      INPUT #1, HEMISP       'N OR S HEMISPHERE

511     INPUT #1, Nweadf       'WEATHER DATA FILE NAME (IBSNAT)
6      INPUT #1, NAMEramsite  'Site rainfall DATA FILE NAME
7      INPUT #1, NmCulF       'CULTIVAR FILENAME
8      INPUT #1, Irigfil     'NAME OF IRRIGATION FILE
9      INPUT #1, NmSolF       'SOIL FILE NAME
1011     INPUT #1, NVinitF      'Initial soil water contents each layer
11      INPUT #1, Nclimate     'NAME OF LONGTERM CLIMATE FILE
12      INPUT #1, MidSeaF      'File for changing midseason values
13      INPUT #1, Level        ' Modelling Level (0,1,2)

14      INPUT #1, YrStrt      'STARTING YEAR OF SIMULATION
15      INPUT #1, Junk'stmnth         'STARTING MONTH OF SIMULATION
16      INPUT #1, Junk'stday         'STARTING DAY OF SIMULATION
171      INPUT #1, Junk'YrStrt      'Year in which crop is harvested


18      INPUT #1, MnthSow       'Sowing MONTH
19      INPUT #1, Dsow          'Sowing DAY
20      INPUT #1, Stge         'Simulation stage
211      INPUT #1, Niriplot     'IRRIGATION TREATMENT NUMBER
221      INPUT #1, Nseasons

231      INPUT #1, DnSplt       'PLANT POPULATION PER HA
24      INPUT #1, RwWidth       'ROW WIDTH/m
251      INPUT #1, RNDMV          'RANDOM SEED NUMBER
26      INPUT #1, FweadT        'W USE WEATHER DATA - G USE GENERATOR
27      INPUT #1, FLAGraingauge 'Flag to indicate use of raingauge at irrigation plot
281      INPUT #1, VinFlg       'SELECT 1 of 3 POSSIBLE WAYS of specificly vinit and weather for each layer
or not
291      INPUT #1, DffDat       'FLAG FOR DIFFERENT PLANTING DATES

301      INPUT #1, YO           'POTENTIAL YIELD     8/4/93
311      INPUT #1, PrntR        'Y TO PRINT RESULTS ON PRINTER
321      INPUT #1, InVlPrn       'PRINTING INTERVAL IN DAYS
331      INPUT #1, FiriSh       'Y TO USE IRRIGATION FILE - N NO
341      INPUT #1, OU2          'STANDARD OUTPUT
351      INPUT #1, OU2          'OUTPUT PLANT AND SOIL WATER STATUS
361      INPUT #1, OU2          'OUTPUT LEAF DEVELOPMENT AND PHENOLOGY
381      INPUT #1, Direct      'Directory in which PUTU will operate
391      INPUT #1, DPLaw        'Directory in which PUTU will operate

CLOSE #1

        'Direct = "c:"
        'Define all the paths and file names
        Firi = Direct + Irigfil
        Fweadat = Direct + Nweadf
        Flvin$ = Direct + NVinitF
```

```
     Flmds$ = Direct + MidSeaF
     NmCulF = Direct + NmCulF
     Yrcrnt = YrStrt
     'Nseasons = 2'YrH       'NUMBER OF SEASONS TO BE SIMULATED

     IF (UCASE$(PrntR) = "Y") THEN
          OPEN "lpt1:" FOR OUTPUT AS #6
     ELSE
     OPEN "scrn:" FOR OUTPUT AS #6
     END IF

'Determine the DOY on which sowing took place
     DOYsow = INT(((MnthSow - 1) * 30.4)) + Dsow

9566  LAPO = 8
     LAIC = 2700
9568  HTO = 1
     ROOTZO = 2

9654  '****************** READING THE SOIL FILE ********
     OPEN Direct + NmSolF FOR INPUT AS #1
     INPUT #1, Junk
     INPUT #1, W$: W$ = UCASE$(W$)
     INPUT #1, CN2
     INPUT #1, ZEFFO
     FOR L = 1 TO 9
          INPUT #1, DZRT(L)
     NEXT L
     FOR L = 1-TO 9
          INPUT #1, PORO(L)
     NEXT L
     FOR L = 1 TO 9
          INPUT #1, SWULpress(L)
     NEXT L
     FOR L = 1 TO 9
          INPUT #1, SWULcont(L)
     NEXT L
     FOR L = 1 TO 9
          INPUT #1, V01(L)
     NEXT L
     FOR L = 1 TO 9
          INPUT #1, DUL(L)
     NEXT L
     FOR L = 1 TO 9
          INPUT #1, V1500(L)
     NEXT L
     PRINT
     INPUT #1, WaterTableDepth        ' Flag for vertical upward
                              ' movement of water to top soil layer
                              ' for soil evaporation (0,1)
     CLOSE #1

3099 '*************************************************************************
3100 '                  SOIL WATER CHARACTERISTIC
3101 '*************************************************************************
3120 TPAW = 0: ITAW = 0: TAW = 0
    TDZRT = 0: NOLAYMAX0 = 1
3130 FOR L = 1 TO 9
3140  PERC(L) = 0

     PSIS1500(L) = -1500

     B(L) = LOG(-10 / PSIS1500(L)) / (LOG(V01(L) / V1500(L)))

     VCON(L) = (PORO(L) - DUL(L)) / PORO(L)
```

```
    V1600(L) = V1500(L) * (-1600 / -1500) ^ (1 / B(L))

3144  W01(L) = V01(L) * DZRT(L)
3145  W15(L) = V1500(L) * DZRT(L)
3146  W16(L) = V1600(L) * DZRT(L)

3147  PAW(L) = SWULcont(L) * DZRT(L) - W15(L)
    TDZRT = TDZRT + DZRT(L)
    IF TDZRT <= ZEFFO THEN
     NOLAYMAX0 = (L + 1)
    END IF

    'IF TDZRT <= 1 THEN TPAW1 = TPAW1 + PAW(L)
3149  'PRINT W15(L),W01(L),W(L),W16(L),TPAW
    AWLIM = (1 - .1 / DZRT(1)) * (W01(1) - W15(1))
    IF AWLIM < .2 * (W01(1) - W15(1)) THEN AWLIM = .2 * (W01(1) - W15(1))
3150  NEXT L
3412  AP = 2.1          '% OF TOTAL ROOTS FOUND BELOW 0.97
3413  AP = AP / 100
3414  RMO = 100          'NORMALIZED ROOT MASS
3416  KSPOO = -.05       'MAX CONDUCTANCE OF ROOT ZONE  mm/(d kPa m3)
    FOR L = 1 TO 9
     KSPO(L) = KSPOO * DZRT(L)
    NEXT L

3430  '


'INPUT "Press - y   if you wish to view the control file   "; rhhnytj$
CLS
IF rhhnytj$ = "y" OR rhhnytj$ = "Y" THEN
PRINT "******************THE CONTROL-FILE************"
PRINT PrntR; "         Y/N -  RESULTS ON PRINTER"
PRINT NmSite; "          ID - SITE NAME FOUR CHARACTERS"
PRINT FweadT; "              W USE WEATHER DATA - G USE GENERATOR"
PRINT Nweadf; "           WEATHER DATA FILE NAME without year suffix"
PRINT FiriSh; "                Y TO USE IRRIGATION FILE - N NO"
PRINT Irigfil; "                 NAME OF IRRIGATION FILE"
PRINT ; "JUNK$"
PRINT ; "JUNK$"
PRINT Niriplot; "                  IRRIGATION TREATMENT NUMBER"
PRINT Nseasons; "                 NUMBER OF SEASONS TO BE SIMULATED"
PRINT DnSplt, RwWidth; "          PLANT POPULATION PER HA & ROW WIDTH/m"
PRINT MnthSow, Dsow, Stge; "     Sowing month and day and simulation stage"
PRINT InVlPrn, RNDMV; "        PRINTING INTERVAL and RANDOM SEED NUMBER"
PRINT YrStrt; "                      First year of simulation"
PRINT Finisw; "    Y/N INITIAL SOIL WATER SPECIFIED FOR EACH LAYER AT PLANTING"
PRINT NmSolF; "                  SOIL FILE NAME"
PRINT NmCulF; "                  CULTIVAR FILENAME"
PRINT Nclimate; "                NAME OF LONGTERM CLIMATE FILE"
PRINT stmnth, stday; "             STARTING MONTH AND DAY OF SIMULATION"
PRINT
INPUT "Press Enter for next screen"; FLAGscrn$
PRINT OUT2; "                    STANDARD OUTPUT"
PRINT OUT3; "                    OUTPUT PLANT AND SOIL WATER STATUS"
PRINT OUT4; "                    OUTPUT LEAF DEVELOPMENT AND PHENOLOGY"
PRINT OUT5; "                    OUTPUT WEATHER AND EVAPORATION"
PRINT HEMISP; "                    N or S HEMISPHERE"
PRINT VinFlg; "    Select one of 3 possible methods of establishing VINIT"
PRINT DffDat; "                   FLAG FOR DIFFERENT PLANTING DATES"
PRINT PdatF; "                    FILE FOR PLANTING DATE, ROWS & CULTIVAR"
PRINT Junk, Junk; "                 NOT USED"
PRINT YO; "                       POTENTIAL YIELD       8/4/93"
PRINT
```

```
INPUT "Press Enter for next screen"; FLAGscrn$

END IF
END SUB

SUB InitialWater

9660  '***********READING THE INITIAL SOIL WATER *************
PRINT Flvin$

OPEN Flvin$ FOR INPUT AS #1

    FOR L = 1 TO 9
     INPUT #1, VINIT(L)          'INITIAL SOIL water (Volumetric mm/m)
     V(L) = VINIT(L)
     W(L) = V(L) * DZRT(L)
    NEXT L
    CLOSE #1

    TAW = 0
    FOR L = 1 TO 9
     AW(L) = W(L) - W16(L)
     IAW(L) = W(L) - W16(L)
     ITAW = ITAW + IAW(L)
     TAW = TAW + AW(L)  'Total available soilwater and maximum available water in the root zone
    NEXT L

    WatDpth = ZEFFO

END SUB

SUB LeafAreaDevelopment

      dLAI = 0
      IF TIMEthml < TTanthesis THEN
         LAI = 1 / ExtCoef * LOG(1 + (EXP(ExtCoef * LAIinitial) - 1) * EXP(ExtCoef * LAR * GROWTHRATEmax
* TIMEphysio))
        dLAI = (LAI - LPREV) * Fv
      END IF

      LPREV = LAI
Lamda = 2
'GAMMA20 = .75
'GAMMA=GAMMA20*
'GAMMA = .075
      gain = dLAI: loss = Lamda * GAMMA * LAI1

      LAI1 = LAI1 + gain - loss
      gain = loss
      loss = GAMMA * LAI2

      LAI2 = LAI2 + gain - loss
      gain = loss
      loss = GAMMA * LAI3

      LAI3 = LAI3 + gain - loss
      gain = loss
      loss = GAMMA * LAI4
      LAI4 = LAI4 + gain - loss

      gain = loss
      loss = GAMMA * LAI5
      LAI5 = LAI5 + gain

      IF LAI4 < 0 THEN LAI4 = 0
```

```
      LAIg = (LAI1 + LAI2 + LAI3)
      Laist = (LAI1 + LAI2 + LAI3 + LAI4)
10
END SUB

SUB MeanD

2499 '*********************************************************************************************************
2500 '                 MEAN  DATA
2510 '****************************************************************************************************
'2530  DATA 31,28,31,30,31,30,31,31,30,31,30,31
     Daypm(1) = 31: Daypm(2) = 28: Daypm(3) = 31: Daypm(4) = 30: Daypm(5) = 31: Daypm(6) = 30
     Daypm(7) = 31: Daypm(8) = 31: Daypm(9) = 30: Daypm(10) = 31: Daypm(11) = 30: Daypm(12) = 31

'2570  DATA 22.9,21.9,19.8,15.6,11.4,8.1,8.5,10.6,14.6,18,20.1,22.1
     GMT(1) = 22.9: GMT(2) = 21.9: GMT(3) = 19.8: GMT(4) = 15.6: GMT(5) = 11.4: GMT(6) = 8.1
     GMT(7) = 8.5: GMT(8) = 10.6: GMT(9) = 14.6: GMT(10) = 18: GMT(11) = 20.1: GMT(12) = 22.1

'2610  DATA 9.3,8.4,7.9,7.9,8.1,7.8,8.3,9.1,9,9.2,9.8,9.9
     GMS(1) = 9.3: GMS(2) = 8.4: GMS(3) = 7.9: GMS(4) = 7.9: GMS(5) = 8.1: GMS(6) = 7.8
     GMS(7) = 8.3: GMS(8) = 9.1: GMS(9) = 9: GMS(10) = 9.2: GMS(11) = 9.8: GMS(12) = 9.9

' 2650 DATA 84.6,81.9,76.7,53.7,23.5,7.0,90.0,90.0,90.0,90.0,90.0,68.1
     GMR(1) = 84.6: GMR(2) = 81.9: GMR(3) = 76.7: GMR(4) = 53.7: GMR(5) = 23.5: GMR(6) = 7
     GMR(7) = 90: GMR(8) = 90: GMR(9) = 90: GMR(10) = 90: GMR(11) = 90: GMR(12) = 68.1

'2675  DATA 12,11,10,9,8,5,5,8,9,10,11,12
     GME(1) = 12: GME(2) = 11: GME(3) = 10: GME(4) = 9: GME(5) = 8: GME(6) = 5
     GME(7) = 5: GME(8) = 8: GME(9) = 9: GME(10) = 10: GME(11) = 11: GME(12) = 12

END SUB

SUB Means

12499 '*********************************************************************************************************
12500 '                        MEANS
12501 '*********************************************************************************************************
12510  TTOT = TTOT / JX
12520  SRFD = SRFD / JX
12530  PSI2 = PSI2 / JX
12535  PSILM = TPSIL / JX
12540  TFS = TFS / JX
12550  TFW = TFW / JX
12555  TFH = TFH / JX
12560  TFC = TFC / JX
12570  TF = TF / JX
12580  TFTL = TFTL / JX
12590  TFTR = TFTR / JX
12600  TFv = TFv / JX
12610  TFFMAX = TFFMAX / JX
12620  TEFF = TEFF / JX
12630  TRFD = TRFD / JX
12640  TDMG = TDMG / JX
12650  MASSIM = ASSIM / JX
12670  TPV = TPV / JX
12690  Treen = Treen / JX
12700  SRFD = SRFD / 10 ^ 6
12761  IF c < 1 THEN 12770       '2/9/92    STAGE < 3 THEN 12780
12762  FRACG = GL / c
12763  FRACL = BL / c
12765  FRACS = SL / c
12766  FRACR = RL / c
12770  TBWP = TBWP / JX
12777  TBWP = TBWP / JX
```

```
12780  TGWP = TGWP / JX
12790  'RETURN
12791  '

END SUB

FUNCTION MJD (DOY)
34      MJD = (30.84 + 12.65 * COS((DOY + 9) / 365 * 2 * 3.14285))       'MJ m^-2 d^-1
END FUNCTION

SUB OPENoutputfiles
'**********************************************************************
'          SUB TO OPEN    OUTPUT   FILES
'**********************************************************************


  FILresult$ = RTRIM$(NCntF$)
  FILresult$ = MID$(FILresult$, LEN(FILresult$) - 11, LEN(FILresult$))
  FILresult$ = LEFT$(FILresult$, LEN(FILresult$) - 4) 'REMOVE THE FILE EXTENTION

  OPEN Direct + "\Putu\Results\" + FILresult$ + ".prn" FOR OUTPUT AS #4
  OPEN Direct + "\Putu\Results\" + FILresult$ + ".var" FOR OUTPUT AS #3


  PRINT #4, "DOG  DOY  V1  V2  V3  V4  V5  V6  V7  V8  V9  rain"

  PRINT #3, "DOG  Laist TRANS SVP PTRANS   BL     RL     RES     GL     SL    WWeight  V1  V2  V3  V4
V5  V6  V7  V8  V9"


'PRINT #3, "CNT DOG DOY  V1  V2  V3  V4  V5  V6  V7  V8  V9 PPAW FW LAI  PERC TDEF PSIS PSIL FID
Kc  Ks  Kv  TRANS SVAP PTRANS   BL    RL     RES     GL      SL     WWeight     DMG   TREE TIMEthml
DPLcrit YRED AEDplot Eo  Watin WatCap WATloss AED"
END SUB

SUB Partitioning

10899  '**********************************************************************
10900  '                  LEAF GROWTH
10901  '**********************************************************************
       ' DLAP = CHANTER(CHANTERa, CHANTERb, CHANTERc, CHANTERd, TTmat, TIMEthml) * DELHU /
TTmat

IF Stge >= 1 AND Stge <= 9 THEN

      SLOPEFI = (FI(Stge) - FI(Stge - 1)) / (CRITthmlperd(Stge) - CRITthmlperd(Stge - 1))
      PERCFI = (FI(Stge) + SLOPEFI * (TIMEthml - CRITthmlperd(Stge)))

      SLOPEgreen = (green(Stge) - green(Stge - 1)) / (CRITthmlperd(Stge) - CRITthmlperd(Stge - 1))
      PERCgreen = (green(Stge) + SLOPEgreen * (TIMEthml - CRITthmlperd(Stge)))

      SLOPEsenesced = (senesced(Stge) - senesced(Stge - 1)) / (CRITthmlperd(Stge) - CRITthmlperd(Stge - 1))
      PERCsenesced = (senesced(Stge) + SLOPEsenesced * (TIMEthml - CRITthmlperd(Stge)))

      SLOPEtrsh = (trsh(Stge) - trsh(Stge - 1)) / (CRITthmlperd(Stge) - CRITthmlperd(Stge - 1))
      PERCtrsh = (trsh(Stge) + SLOPEtrsh * (TIMEthml - CRITthmlperd(Stge)))

      SLOPEStore = (Store(Stge) - Store(Stge - 1)) / (CRITthmlperd(Stge) - CRITthmlperd(Stge - 1))
      PERCStore = (Store(Stge) + SLOPEStore * (TIMEthml - CRITthmlperd(Stge)))

      SLOPEStem = (Stem(Stge) - Stem(Stge - 1)) / (CRITthmlperd(Stge) - CRITthmlperd(Stge - 1))
      PERCStem = (Stem(Stge) + SLOPEStem * (TIMEthml - CRITthmlperd(Stge)))

      SLOPELeaf = (Leaf(Stge) - Leaf(Stge - 1)) / (CRITthmlperd(Stge) - CRITthmlperd(Stge - 1))
      PERCleaf = (Leaf(Stge) + SLOPELeaf * (TIMEthml - CRITthmlperd(Stge)))
```

```
    SLOPEGrainFruit = (GrainFruit(Stge) - GrainFruit(Stge - 1)) / (CRITthmlperd(Stge) - CRITthmlperd(Stge -
1))
    PERCGrainFruit = (GrainFruit(Stge) + SLOPEGrainFruit * (TIMEthml - CRITthmlperd(Stge)))

    FI = PERCFI

    PROD = 100 + PERCtrsh
    Flg = FI * PERCgreen / PROD
    Fsenesced = (100 - PERCgreen) / PROD * 100
    Ftrash = PERCtrsh / PROD * 100

    IF DOG = 3 THEN
    PRINT
    END IF
    'LAI = LAI + DLAP * Fv
    LAIg = LAI * (green(Stge) - (green(Stge) - green(Stge + 1)) / (CRITthmlperd(Stge + 1) -
CRITthmlperd(Stge)) * (TIMEthml - CRITthmlperd(Stge))) / 100
    'LAIst = LAI * (trsh(Stge) - (trsh(Stge) - trsh(Stge + 1)) / (CRITthmlperd(Stge + 1) - CRITthmlperd(Stge)) *
(TIMEthml - CRITthmlperd(Stge))) / 100


    IF LAIg < 0 THEN LAIg = 0
    IF Laist < 0 THEN Laist = 0

    RES = PERCStore / 100 * WWeight         ' Partition Reserves
    BL = PERCleaf / 100 * WWeight          ' Partition Leaf
    SL = PERCStem / 100 * WWeight           ' Partition Stem
    GL = PERCGrainFruit / 100 * WWeight      ' Partition Grain

    END IF
END SUB

SUB PsicLeaf
5690 '*****************************************************************
5700 '           CRITICAL LEAF WATER POTENTIAL
5702 '*****************************************************************
5710 PSICrit = FuNTION22(DOG)
5720 IF PSICrit > -1600 THEN PSICrit = -1600
5730 IF PSICrit < -2300 THEN PSICrit = -2300
   PSICrit = (PSIC1 + PSIC2) / 2

   'PSICrit = -2100


END SUB

SUB ReadInseasonData

9720 '******READING FILE WITH MEASURED VALUES DURING SEASON*****

    OPEN Flmds$ FOR INPUT AS #2
725  IF ERR = 53 THEN
      OPEN "O", #2, Flmds$
      PRINT Flmds$
      'OPEN Flmds$ FOR OUTPUT AS #2
      PRINT #2, ""
      A$ = "DOY": B1$ = "V1": B2$ = "V2": B3$ = "V3": B4$ = "V4": B5$ = "V5"
      B6$ = "V6": B7$ = "V7": B8$ = "V8": B9$ = "V9": LAI$ = "LAI"
      PRINT #2, USING "\     \"; A$; B1$; B2$; B3$; B4$; B5$; B6$; B7$; B8$; B9$; LAI$
      'RESUME 9728
    ELSE
       K = 0
       INPUT #2, Junk, Junk
       WHILE NOT EOF(2)
         INPUT #2, DOYMEAS
```

```
        IF DOYMEAS = 0 THEN GOTO 9728
        MeasValue(DOYMEAS, 1) = DOYMEAS
        FOR K = 2 TO 11
          INPUT #2, MeasValue(DOYMEAS, K)
            IF K < 11 THEN MeasValue(DOYMEAS, K) = MeasValue(DOYMEAS, K) * 10
          'INPUT #2, K
        NEXT K
      WEND
    END IF
9728 '
730
CLOSE #2
'9790   RETURN

END SUB

SUB RECORDseason

    PRINT #6, "Ù"
    IF gedruk = 0 THEN
      PRINT #6, "Maturity Reached"
    END IF
    VIEW PRINT 10 TO 25
    'CLS

     IF y < 0 THEN y = 0
     Yperc = y
     y = y / 100 * YO

    PRINT #5, USING " #### #####"; YrStrt; y

        PRINT #6,

   PRINT #6, "   Environmental potential for "; YrStrt; " "; : PRINT #6, USING "#####"; Yperc; : PRINT #6, " % of
maximum yield"
    'PRINT #6, " "
    PRINT #6, "   Environmental potential for "; YrStrt; " "; : PRINT #6, USING "#####"; y; : PRINT #6, " kg/ha"

    INPUT "Do you wish to repeat the calculation for a further season(Y/N)", ANSWER$
  IF ANSWER$ <> "N" THEN
    'CALL CloseEnd
  END IF
2205  Ky = Ky(9)

END SUB

SUB ResetSub

2400  '**********************************************************************
2401  'RESET ALL STATUS VAR. TO ZERO AND COEFFICIENTS, RE-ESTABLISH INITIAL
2402  '   CONDITIONS AND REST PHASE
2403  '**********************************************************************
2420  HUPREV = 0
    TIMEphysio = 0
2430  TIMEthml = 0
2460  DOG = 0
2470  Tree = 0
2480  Stge = 1
2485  BL = 0: GL = 0: RES = 0: SL = 0: RL = 0: c = 0: CB = 0: CA = 0
2490  x1 = 0: x2 = 0: X3 = 0: X4 = 0: X5 = 0: X6 = 0: X7 = 0: X8 = 0: X9 = 0
    LAI1 = 0: LAI2 = 0: LAI3 = 0: LAI4 = 0: LAI5 = 0: LPREV = 0
    W1 = 0: W2 = 0: W3 = 0: W4 = 0: W5 = 0: Wprev = 0

    'CALL Summary
```

```
END SUB

SUB ReWetSoil STATIC

2691 '*********************************************************************
2700 '    DISTRIBUTION OF INFILTRATION WATER THROUGH SOIL PROFILE
2710 '*********************************************************************
2715 'IF DOG = 0 THEN 3090
      INFIL = 0
2830  IF X(DOY, 3) = 0 AND X(DOY, 6) = 0 THEN 3060
     IF X(DOY, 3) < 3 THEN X(DOY, 3) = 0
     IF X(DOY, 6) < 3 THEN X(DOY, 6) = 0
2840  RUNOF = .2
2850
     INFIL = X(DOY, 3) + X(DOY, 6)
2860  IF INFIL < 50 THEN RUNOF = .1
2870  IF INFIL < 25 THEN RUNOF = .05
2880  IF INFIL < 15 THEN RUNOF = 0
     RUNDUM = RUNOF


'   INFIL = (X(DOY, 3) + X(DOY, 6) / fwet) * (1 - RUNOF)
'   INFIL = INFIL + CONDlateral * (V(1) - Vnoroot(1)) * DZRT(1) / froot
'   No-root Compartment
'   INFIL = X(DOY, 3) + CONDlateral * (V(1) - Vnoroot(1)) * DZRT(1) / (1 - froot)

    INFIL = (X(DOY, 3) + X(DOY, 6)) * (1 - RUNOF)
    RUNOF = (X(DOY, 3) + X(DOY, 6)) * RUNOF

     PINF = INFIL
3060
     PERC(1) = INFIL

      FTAW = 0
      FOR L = 1 TO 9
        FTAW = FTAW + (W(L) - W16(L))
      NEXT L


       FOR L = 1 TO 9
       W(L) = W(L) + PERC(L)
       V(L) = W(L) / DZRT(L)
       IF W(L) > (SWULcont(L) * DZRT(L)) THEN
          PERC(L + 1) = W(L) - (SWULcont(L) * DZRT(L))
          W(L) = SWULcont(L) * DZRT(L)
          V(L) = SWULcont(L)
          PERC(L) = 0
        ELSE
          IF W(L) >= DUL(L) * DZRT(L) THEN
            PERC(L + 1) = (VCON(L) * (V(L) - DUL(L))) * DZRT(L)
            W(L) = W(L) - PERC(L + 1)
            V(L) = W(L) / DZRT(L)
           ELSE
           V(L) = W(L) / DZRT(L)
           PERC(L + 1) = 0
          END IF
       END IF
    NEXT L
    IF Stge > 1 THEN
       DEEPERC = DEEPERC + PERC(10)
    END IF

      FTAW = 0
      FOR L = 1 TO 9
        FTAW = FTAW + (W(L) - W16(L))
```

```
    NEXT L
   GOTO 3086


     FOR L = 1 TO 9
    HOLD = (SWULcont(L) - V(L)) * DZRT(L)
    IF PINF <= HOLD THEN
     V(L) = V(L) + PINF / DZRT(L)          'RECALC
3070   IF V(L) >= DUL(L) THEN DRAIN = (V(L) - DUL(L)) * VCON(L) * DZRT(L) ELSE DRAIN = 0
     PINF = DRAIN
     V(L) = V(L) - DRAIN / DZRT(L)          'RECALC
    ELSEIF PINF > HOLD THEN
     V(L) = SWULcont(L)                     'RECALC
3075   PINF = PINF - HOLD
     DRAIN = VCON(L) * (SWULcont(L) - DUL(L)) * DZRT(L)
     PINF = PINF + DRAIN
     V(L) = V(L) - DRAIN / DZRT(L)          'RECALC
    END IF

3080  IF L = 9 AND PINF > 0 THEN DEEPERC = DEEPERC + PINF
    W(L) = V(L) * DZRT(L)
    ' SoilwaterPot

    PSIS(L) = PSIS1500(L) * (V(L) / V1500(L)) ^ B(L)
   NEXT L

   PERCOL = PERC(NOLAYMAX)


3086  FOR L = 1 TO 9
3087   PERC(L) = 0
   'PRINT USING "####.###"; V(L); SWULcont(L); DUL(L); W(L)

3088  NEXT L

3090
END SUB

SUB RootDevelopment

12986 '********************************************************************
13000 '                    ROOT DEVELOPMENT
13001 '*********************************************************************
13010  IF DOG = 0 THEN 13175
13015  IF Stge > 7 THEN 13175
13020  RDEVF = FuNTION19(TIMEthml, TTanthesis, ROOTZO)
13030  IF RDEVF < .3 THEN RDEVF = .3
    ZEFF = RDEVF
13040  IF RDEVF > ZEFFO THEN ZEFF = ZEFFO
13050  A = -LOG(AP) / (.97 * RDEVF)
13060  ZBOT = 0
13070  RMASS = 0

    TDZRT = 0: NOLAYMAX = 0: TPAW = 0

    FOR L = 1 TO 9
     RPROP(L) = 0
     IF L = 1 THEN
       ZTOP = 0
       ZBOT = DZRT(1)
       ZBOTT(1) = ZBOT
       RPROP(L) = (EXP(-A * ZTOP) - EXP(-A * ZBOT)) / .979
       RMASS = RMASS + RPROP(L)
       IF ZEFFO >= ZTOP AND ZEFFO <= ZBOT THEN NOLAYMAX = 1
```

```
       ELSE
        ZTOP = ZTOP + DZRT(L - 1)
        ZBOT = ZTOP + DZRT(L)
        ZBOTT(L) = ZBOT
        RPROP(L) = (EXP(-A * ZTOP) - EXP(-A * ZBOT)) / .979
        RMASS = RMASS + RPROP(L)
        IF ZEFFO >= ZTOP AND ZEFFO <= ZBOT THEN NOLAYMAX = L
       END IF
      NEXT L
13165 IF RM < 15 THEN RM = 15
      IF ZEFF <= ZBOTT(1) THEN
       NOLAY = 1
      ELSE
       FOR L = 2 TO 9
        IF ZEFF > ZBOTT(L - 1) AND ZEFF <= ZBOTT(L) THEN NOLAY = L
       NEXT L
      END IF
13168 FOR L = 1 TO 9
13169  RPROP(L) = RPROP(L) / RMASS
13170  IF L > NOLAY THEN RPROP(L) = 0
13172 NEXT L
      FOR L = 1 TO 9                     'SOIL WATER POTENTIAL
       IF V(L) > DUL(L) THEN
        PSIS(L) = -10
       ELSE
        IF V(L) < V1500(L) THEN
         Vdummy(L) = V1500(L)
        ELSE
         Vdummy(L) = V(L)
        END IF                  'if v(L) < V1500(L) etc
       'PSIS(L) = FuNTION15(P0(L), M(L), Vdummy(L), V1500(L))
       ' PROF JIMMY WILL INTRODUCE CLAP & HORNBERGER SOMETIME
       END IF                   'if v(L) > dul(L)
      NEXT L
13175
' RETURN

END SUB

SUB ScheduleIrrig

6000 '*******************************************************************
6010 '            SCHEDULING IRRIGATION
6020 '*******************************************************************
6030 ' IF X(DOY,7) <> 22 THEN 7690
6040 IF PSIL > -800 THEN FUDGE = -700 ELSE FUDGE = 0
6050 IF X(DOY, 5) >= 2 THEN
       FEVAP = X(DOY, 7)
     ELSE
       FEVAP = 2
     END IF
     FID = (TAW - .4 * TPAW / 2) / FEVAP
6060 '
6070 'RETURN
6080 '


END SUB

SUB SoilRootCond

13290 '*************************************************************************
13300 '    SOIL ROOT CONDUCTANCE AND LEAF WATER POTENTIAL
13301 '*************************************************************************
13302 IF DOG = 0 THEN 13890
```

```
13309 KSPEFF = 0: PSIST = 0:  WMPSIS = 0
13310 FOR L = 1 TO NOLAY
13330 KSP(L) = KSPO(L) * (RPROP(L) * RM) ^ .5 * FuNTION18(V(L) + 1, V1600(L), V01(L)) / 10
13340 KSPEFF = KSPEFF + KSP(L)
13350 WMPSIS = WMPSIS + KSP(L) * PSIS(L)
13370 NEXT L
13380 PSIST = WMPSIS / KSPEFF     ' WEIGHTED MEAN PSIS
13395 CALL PsicLeaf
    PSIL = PSIST + PTRANS / KSPEFF

      PSIHI = 0: PSILO = -3500
      PSIT = (PSIHI + PSILO) / 2
      Fv = 1 - EXP(-8.000001E-03 * (PSIT - (PSICrit - 400)))
      IF (Fv > 1) THEN Fv = 1
      IF (Fv < 0) THEN Fv = 0
      TRANS = Fv * PTRANS
      PSIL = PSIST + TRANS / KSPEFF
      TEST = PSIL - PSIT

      WHILE (TEST > 5 OR TEST <= -5)
          PSIT = (PSIHI + PSILO) / 2
          IF (PSIT <= -3500) THEN
            PRINT " ULTRA-STRESS, PSIL = -3000, ON DOY %d\n", DOY
           ' END
          END IF

          Fv = 1 - EXP(-8.000001E-03 * (PSIT - (PSICrit - 400)))
          IF (Fv > 1) THEN Fv = 1
          IF (Fv < 0) THEN Fv = 0

          TRANS = Fv * PTRANS
          PSIL = PSIST + TRANS / KSPEFF
          TEST = PSIL - PSIT

          IF (TEST > 5) THEN PSILO = PSIT
          IF (TEST <= -5) THEN PSIHI = PSIT

      WEND

          '***********************************************************************
          '             EXTRACT WATER FROM EACH SOIL LAYER
          '***********************************************************************


     FTAW = 0
13730  FOR L = 1 TO 9

13740  TS(L) = -(PSIS(L) - PSIL) * KSP(L)
      IF TS(L) < 0 THEN TS(L) = 0
13810  NEXT L


13821  TDEFICIT = 0
13823  TRANS = 0
13824  t = 0: PAWC = 0: TPAW = 0: TAW = 0
13825  wtest = W(1) - TS(1) - SOILVAP
     ' wtest = W(1) - TS(1) / froot - SoilVap
     ' noroot compartment
     ' wtest = W(1) - TS(1) - Ed

     ' FIRST SOIL LAYER
     LL(1) = V1500(1)
13826  IF wtest < W16(1) THEN
        TS(1) = W(1) - W16(1): W(1) = W16(1)
```

```
       SOILVAP = 0
       GOTO 13828
     END IF
13827  W(1) = wtest
13828  V(1) = W(1) / DZRT(1)
13829  TRANS = TS(1)
     AW(1) = W(1) - W16(1):   TAW = TAW + AW(1): PAWL(1) = AW(1) / PAW(1) * 100
13830  TPAW = TPAW + PAW(1): PAWC = ((DUL(1) - LL(1)) / 2) * DZRT(1)
     TDZRT = DZRT(1)
13831  IF V(1) > V01(1) THEN DEFICIT(1) = 0 ELSE DEFICIT(1) = V01(1) * DZRT(1) - W(1)
13832  TDEFICIT = TDEFICIT + DEFICIT(1)
     ' NEXT 8 SOIL LAYERS
13838  FOR L = 2 TO 9
     LL(L) = V1500(L)
      TDZRT = TDZRT + DZRT(L)
13840   wtest = W(L) - TS(L)
'     wtest = W(L) - TS(L) / froot + CONDlateral * (V(L) - Vnoroot(L)) * DZRT(L) / froot
'     noroot Compartments
'     wtest = W(L) + CONDlateral * (V(L) - Vnoroot(L)) * DZRT(L) / (1 - froot)
13845   IF wtest < W16(L) THEN
         TS(L) = W(L) - W16(L)
         W(L) = W16(L)
         GOTO 13850
      END IF
13847   W(L) = wtest
      V(L) = W(L) / DZRT(L)                   'RECALC
13850   TRANS = TRANS + TS(L)
13853   IF L > NOLAY THEN 13880
'      Practice deficit irrigation by calculating deficit relative to V01
'      and not SWULcont
13855   IF V(L) > V01(L) THEN DEFICIT(L) = 0 ELSE DEFICIT(L) = V01(L) * DZRT(L) - W(L)
13857   TDEFICIT = TDEFICIT + DEFICIT(L)
13860
13862   AW(L) = W(L) - W16(L)
13863   PAWC = ((DUL(L) - LL(L)) / 2) * DZRT(L) + PAWC
13865   PAWL(L) = AW(L) / PAW(L) * 100
13866   FAW(L) = W(L) - W16(L)
13864   TAW = TAW + AW(L): TPAW = TPAW + PAW(L)   'Total available soilwater and maximum available
water in the root zone

13880  NEXT L

     IF DOG = 2 THEN
       WATstrt = TAW
     END IF

13882  PPAW = TAW / TPAW * 100
     IF PTRANS <> 0 THEN


13885  Fv = TRANS / PTRANS
     IF Fv > 1 THEN Fv = 1
     IF Fv < 0 THEN Fv = 0
13886  FW = (1 - TRANS / PTRANS)         'FW = (1 - FNTION3(PSIL, PSICrit))
     END IF
13887  IF FW > 1 THEN FW = 1
13888  IF FW < 0 THEN FW = 0

'WaterTableDepth = 0
IF WaterTableDepth > 0 THEN
      QVMAX = (4.2 * 10 ^ 5 / ((TDZRT * 100 - 17.4 * ZEFF) ^ 3)) * 10
      QSMAX = (4.2 * 10 ^ 5 / ((TDZRT * 100 - DZRT(1) * 5) ^ 3)) * 10


      QSMAX = QSMAX * (1 - EXP(-.007 * (-PSIS(1) * 10 - 100)))
```

```
    QVMAX = QVMAX * (1 - EXP(-.007 * (-PSIST * 10 - 100)))

    IF QSMAX < 0 THEN QSMAX = 0
    IF QVMAX < 0 THEN QVMAX = 0
    IF QVMAX > .8 * TRANS THEN QV = .8 * TRANS ELSE QV = QVMAX
    IF QSMAX > .8 * SOILVAP THEN QS = .8 * SOILVAP ELSE QS = QSMAX


    QWAT = QV + QS
    QINI = QWAT

    FOR L = NOLAY TO 1 STEP -1
        wtest = W(L) + QWAT
        IF wtest > DUL(L) * DZRT(L) THEN
            IF W(L) < DUL(L) * DZRT(L) THEN
                QWAT = QWAT - (DUL(L) * DZRT(L) - W(L))
                W(L) = DUL(L) * DZRT(L)
            ELSE QWAT = QWAT
            END IF
        ELSE W(L) = W(L) + QWAT
            QWAT = 0
        END IF

        V(L) = W(L) / DZRT(L)          'RECALC
    NEXT L

IF QWAT > 0 THEN QTOT = QTOT + (QINI - QWAT) ELSE QTOT = QTOT + QINI


    IF NOLAY > 1 THEN
        FOR L = 1 TO NOLAY ~~- 1~~
            IF V(L) > DUL(L) THEN Vdummy(L) = DUL(L) ELSE Vdummy(L) = V(L)
                THET1 = (Vdummy(L) - LL(L)) / 1000
                THET2 = (Vdummy(L + 1) - LL(L + 1)) / 1000
                DIF = .88 * EXP(35.4 * (THET1 + THET2) / 2)
                FLOWUNSAT = (DIF * (THET2 - THET1) / ((DZRT(L) * 100 + DZRT(L + 1) * 100) / 2)) * 10
                W(L) = W(L) + FLOWUNSAT
                W(L + 1) = W(L + 1) - FLOWUNSAT
            NEXT L
    END IF
END IF

13890


END SUB

SUB SoilWaterContent

2250 '**********************************************************************
2251 'SUB TO ADJUST THE SOIL WATER CONTENT OF ALL 9 LAYERS AT TIME OF PLANTING
'    SHOULD IT BE DESIRED
2252 '**********************************************************************

2260 PRINT "SOIL WATER (mm/m) AT PLANTING IS: "
2265 FOR L = 1 TO 9
2270   PRINT USING "#####"; V(L)
2275 NEXT L
2280 INPUT "SHOULD YOU WISH TO ALTER THIS ENTER 9 "; qtest
2285 IF qtest <> 9 THEN 2350
2290 FOR L = 1 TO 9
2295 PRINT "LAYER No. "; L
2300 INPUT "INITIAL SOIL WATER    "; VINIT(L)
2310 W(L) = VINIT(L) * DZRT(L)
2315 V(L) = VINIT(L)
```

```
2320  PRINT #6, USING "######"; V(L)
2325  NEXT L
2350  'RETURN

END SUB

SUB Summary

    VIEW PRINT 1 TO 24
    CLS
    PRINT #6, "Kindly note that the component totals will only balance when"
    PRINT #6, "in season adjustments to soil water content have not been applied"
    PRINT #6, " "
2190  PRINT #6, : PRINT #6, "SEASONAL TOTALS FOR COMPONENTS OF THE WATER BALANCE (mm) : "
': PRINT #6,
    PRINT #6, "LOST FROM ROOT ZONE"
    PRINT #6, " DEEP PERCOLATION            ", INT(DEEPERC); " mm"

    PRINT #6, " RUN OFF                     ", INT(TRUNOF); " mm"
    PRINT #6, " EVAPORATION FROM SOIL SURFACE ", INT(TSEVAP); " mm"
    PRINT #6, " EVAPORATION FROM CROP SURFACE ", INT(STTRANS); " mm"

    PRINT #6, "GAINED BY ROOT ZONE"
    PRINT #6, " RAIN                        ", INT(Tree); " mm"
    PRINT #6, " IRRIGATION                  ", INT(Tirrig); " mm"
    PRINT #6, " CAPILLARY RISE FROM WATERTABLE", INT(QTOT); " mm"
    PRINT #6,
    PRINT #6, "DIFFERENCE BETWEEN INITIAL AND FINAL PROFILE WATER CONTENT";
    PRINT #6, USING "####"; (ITAW - FTAW)

    PRINT #6, USING "                              #####"; ITAW;
    PRINT #6, " - ";
    PRINT #6, USING "#####"; FTAW;
    PRINT #6, " = ";
    PRINT #6, USING "######"; ITAW - FTAW
    y = YO * (Yred(2) * Yred(3) * Yred(4) * Yred(5) * Yred(6) * Yred(7) * Yred(8))
    PRINT #6, "SIMULATED YIELD ";
    PRINT #6, USING "######"; y;
    PRINT #6, "  kg/ha"
    'SLEEP 5
    CLOSE
 2195  END


 END SUB

 SUB TableHeading

 5250  '
 5300  '********************************************************************
 5350  '                    TABLE HEADING
 5400  '********************************************************************
 PRINT #6, " "
 PRINT #6, "DOY  FW   LAI  IR  RAIN PERC  PPAW  DEF   PSI  TIMEthml  kc  AED   Eo  FID "
 PRINT #6, "                                ST    L"
 PRINT #6, "    (%)      (mm)         (%)  (mm) (MPa*100) (DD)       (mm)   (mm) (d)"


 END SUB

 SUB TitlePage
 5000  '********************************************************************
 5010  '                    TITLE PAGE
 5020  '********************************************************************
     CLS
```

```
5030  PRINT #6, TAB(7); "PUTU-Anycrop SIMULATION  OF  "; NAMEcrop$
5035  PRINT #6, "                                    Run date : "; DATE$; "  Time : "; TIME$
5130  PRINT #6, TAB(7); NmSite
5150  PRINT #6, TAB(10); , "PLANT POPULATION "; TAB(40); , "CULTIVAR"; TAB(55); , "PLANTING DATE"
5160  PRINT #6, TAB(20); DnSplt; " (/ha)"; TAB(40); NAMEcult$; TAB(55); Dsow; "/"; MnthSow; "/"; YrStrt
5170  PRINT #6,
5180  PRINT #6, TAB(10); , "SOIL DESCRIPTION:"; W$
5210  PRINT #6, TAB(10); , "SOIL MOISTURE (mm/m)"
5230  PRINT #6, TAB(15); "MAXIMUM"; TAB(30); "MINIMUM"; TAB(40); "INITIAL"; TAB(50); "EFFECTIVE
ROOTING DEPTH"
5240  PRINT #6, USING "          ###          ###       ###          ##.# m"; V01(2); V1500(2); VINIT(2); ZEFFO

   IF (UCASE$(PrntR) = "Y") THEN
     PRINT TAB(7); "PUTU-Anycrop SIMULATION OF  "; NAMEcrop$
     PRINT "                                    Run date : "; DATE$; "  Time : "; TIME$
     PRINT TAB(7); NmSite
     PRINT TAB(10); , "PLANT POPULATION "; TAB(40); , "CULTIVAR"; TAB(55); , "PLANTING DATE"
     PRINT TAB(20); DnSplt; " (/ha)"; TAB(40); NAMEcult$; TAB(55); Dsow; "/"; MnthSow; "/"; YrStrt
     PRINT
     PRINT TAB(10); , "SOIL DESCRIPTION:"; W$
     PRINT TAB(10); , "SOIL MOISTURE (mm/m)"
     PRINT TAB(15); "MAXIMUM"; TAB(30); "MINIMUM"; TAB(40); "INITIAL"; TAB(50); "EFFECTIVE ROOTING
DEPTH"
     PRINT USING "          ###          ###       ###          ##.# m"; V01(2); V15(2); VINIT(2); ZEFFO
     'PRINT #6, "m"
   END IF

END SUB

SUB Totals

11999 '*********************************************************************
12000 '                    SUB TOTALS
12001 '*********************************************************************
12010  JX = JX + 1
12020  IF DOY >= (DOYsow) OR DOG <> 0 AND TIMEthml < TTmat THEN
         DOG = DOG + 1
       END IF
       IF DOY = (DOYsow - 1) THEN
         CALL ResetSub
         DOG = 0
       END IF
       IF Stge > 1 AND Stge < 9 THEN
12050    TSEVAP = TSEVAP + SOILVAP
12080    Treen = Treen + X(DOY, 3)
12090    Tree = Tree + X(DOY, 3)
         Tirrig = Tirrig + X(DOY, 6)
         TRUNOF = TRUNOF + RUNOF
       END IF
       'RUNOF = 0
       IF DOG = 2 THEN
         WATin = 0
         WATcap = TPAW
         AEDplot = 0
         DPLcrit = -(1 - DPLaw / 100) * TAW    '.5 * TAW
         WATloss = 0
       END IF
       IF DOG <> 0 THEN
         DPLcrit = AEDplot - DPLaw / 100 * TAW
         WATin = WATin + INFIL       ' alternative'X(DOY, 3) + X(DOY, 6)
         AEDplot = AEDplot + SOILVAP + PTRANS
         WATcap = TPAW + AEDplot
         IF WATin >= WATcap THEN
              WATloss = WATin - WATcap
              WATin = WATcap
```

```
    END IF
     IF WATin <= DPLcrit THEN
         WATin = DPLcrit
    END IF
    IF DOG <= 1 THEN
         WATin = 0
         WATcap = 0
         AEDplot = 0
         DPLcrit = 0
         WATloss = 0
    END IF
   END IF

12100 'TREEN=average rainfall for print interval
12110 'TREE=total rainfall up to present date
12120 'TTOT=total temp for appropriate print interval
12130 TDMG = TDMG + DMG
12140 TTOT = TTOT + t
    IF Stge > 1 AND Stge < 9 THEN
12160 TTRANS = TTRANS + TRANS  '*****************************
12164 STTRANS = STTRANS + TRANS
12166 STPTRANS = STPTRANS + PTRANS
12170 TPTRANS = TPTRANS + PTRANS'*****************************
12172 'TLYS = TLYS + X(DOY, 8)
12175
    END IF

END SUB

SUB Translocation ' (GL, ALPHA, BL, BETA, RES, PHI, RL, RHO, SL, THETA, TLAI, SPL, GD, X8, CD, X9, BD,
x1, SD, x2, RD, X3, CA, CB, c, TR, X4, X5, X6, X7, DA, DB)

11499 '*********************************************************************
11500 '                    TRANSLOCATION
11501 '*********************************************************************
11530 GL = GL + ALPHA
11540 BL = BL + BETA
11550 RES = RES + PHI
11560 RL = RL + RHO
11580 SL = SL + THETA
11600 GD = GD + X8 * GL
11610 CD = CD + X9 * RES
11620 BD = BD + x1 * BL
11630 SD = SD + x2 * SL
11640 RD = RD + X3 * RL
11650 CA = GL + RES + BL + SL + GD + CD + BD + SD     'PROBLEM!!!

11660 CB = RL + RD
11670 c = CA + CB
11680 TR = X4 * GD + X5 * CD + X6 * BD + X7 * SD
11690 DA = TR + GD + CD + BD + SD
11700 DB = RD
11710 'NB C INCL STAND DEAD
11770 'RETURN
11998 '

END SUB

SUB TriggerS1
'
660  '*********************************************************************
1500 '              TRIGGER 1  for the end ofthe rest period
1505 '*********************************************************************

    IF TIMEthml >= CRITthmlperd(9) THEN 1585
```

```
   IF DOY < (DOYsow) THEN 1585
1515  Stge = Stge + 1
1517  FLAGprint = 1
1520  'PRINT #6, "  Total rainfall in rest period="; TREE
1530  Tree = 0
1535  TTRANS = 0
1540  TPTRANS = 0
      Ky(1) = 0
      Yred(1) = 1
1558  Ky = Ky(2)
1561  'CRITthmlperd = HUCO
1580  PRINT #6, : PRINT #6, "  GROWTH STAGE 2 -  '"; ST$(Stge)
1585  'RETURN
1590  '

END SUB

SUB TriggerS2

1595  '*****************************************************************
1600  '            TRIGGER 2    for SOWING
1605  '*****************************************************************

   IF TIMEthml < CRITthmlperd(2) THEN 1650
1607  FLAGprint = 1
1619  Stge = Stge + 1
1627  RT = TTRANS / TPTRANS
   IF RT >= 1 THEN RT = 1
   Yred(Stge - 1) = 1 - Ky * (1 - RT)
1635  Ky = Ky(3)
1640  TTRANS = 0: TPTRANS = 0
1645  PRINT #6, : PRINT #6, "   GROWTH STAGE 3 -    "; ST$(Stge)

1650

END SUB

SUB TriggerS3
1690  '*****************************************************************
1700  '                    TRIGGER 3
1705  '*****************************************************************

   IF TIMEthml < CRITthmlperd(3) THEN 1746
1715  Stge = Stge + 1
1717  FLAGprint = 1

1727    RT = TTRANS / TPTRANS
      IF RT >= 1 THEN RT = 1
      Yred(Stge - 1) = 1 - Ky * (1 - RT)
      TTRANS = 0: TPTRANS = 0
      Ky = Ky(4)
1745  PRINT #6, : PRINT #6, "   GROWTH STAGE 4 -       "; ST$(Stge)

1746  '

END SUB

SUB TriggerS4

      '*****************************************************************
1800  '                    TRIGGER 4
      '*****************************************************************

    IF TIMEthml < CRITthmlperd(4) THEN 1845
1815  Stge = Stge + 1
```

```
1817  FLAGprint = 1
1821  RT = TTRANS / TPTRANS
    IF RT >= 1 THEN RT = 1
    Yred(Stge - 1) = 1 - Ky * (1 - RT)
1826  TTRANS = 0: TPTRANS = 0
1830  Ky = Ky(5)
1840  PRINT #6, : PRINT #6, "GROWTH STAGE 5 -       "; ST$(Stge)
1845
END SUB

SUB TriggerS5
1895  '***********************************************************************
1900  '                    TRIGGER 5
1910  '***********************************************************************

    IF TIMEthml < CRITthmlperd(5) THEN 1958
1922  Stge = Stge + 1
    LAImx = LAI
1924  LAPX = LAP
1925
1927  FLAGprint = 1
1942  RT = TTRANS / TPTRANS
    IF RT >= 1 THEN RT = 1
    Yred(Stge - 1) = 1 - Ky * (1 - RT)
1947  TTRANS = 0: TPTRANS = 0
1950  Ky = Ky(6)
1957  PRINT #6, : PRINT #6, "GROWTH STAGE 6 -           "; ST$(Stge)
1958  'RETURN



END SUB

SUB TriggerS6

1995  '***********************************************************************
2000  '                    TRIGGER  6
2010  '***********************************************************************

    IF TIMEthml < CRITthmlperd(6) THEN 2046
      Stge = Stge + 1
2027  FLAGprint = 1
2032  RT = TTRANS / TPTRANS
    IF RT >= 1 THEN RT = 1
    Yred(Stge - 1) = 1 - Ky * (1 - RT)
2039  TTRANS = 0: TPTRANS = 0
2040  Ky = Ky(7)
2045  PRINT #6, : PRINT #6, "GROWTH STAGE 7 -       "; ST$(Stge)
2046
END SUB

SUB TriggerS7
2090  '***********************************************************************
2100  '                       TRIGGER  7
2110  '***********************************************************************

    IF TIMEthml < CRITthmlperd(7) THEN 2146
2125  Stge = Stge + 1
2127  FLAGprint = 1
2132  RT = TTRANS / TPTRANS
      IF RT >= 1 THEN RT = 1
      Yred(Stge - 1) = 1 - Ky * (1 - RT)
      TTRANS = 0: TPTRANS = 0
2140    Ky = Ky(8)
  PRINT #6, : PRINT #6, "GROWTH STAGE 8 -       "; ST$(Stge)
```

```
2146


END SUB

SUB TriggerS8

2152 '**********************************************************************
2155 '                 TRIGGER  8
2165 '**********************************************************************

    IF TIMEthml < CRITthmlperd(8) THEN 2220
     Stge = Stge + 1
     FLAGprint = 1
     RT = TTRANS / TPTRANS
     IF RT >= 1 THEN RT = 1
     Yred(Stge - 1) = 1 - Ky * (1 - RT)
     Yred(9) = 1
     TTRANS = 0: TPTRANS = 0
     Ky = Ky(9)

     FOR L = 1 TO 9
      FTAW = FTAW + (W(L) - W16(L))
     NEXT L

   CALL Summary

     FLAGstg8 = 1
     FLAGrest = 1

    PRINT #6, : PRINT #6, "GROWTH STAGE 9 -       "; ST$(Stge)

2220 '
END SUB

SUB TriggerS9

   'Trigger 9 ends at maturity of the crop
   IF TIMEthml >= CRITthmlperd(9) THEN
      Stge = Stge + 1
      PRINT , "GROWTH STAGE  10  - Rest  after the growing season"
   END IF

END SUB

SUB Update

  FILvinit1$ = LEFT$(Flvin$, 18) + RIGHT$(STR$(YrStrt + 1 - 1900), 2) + "01.vin"
  OPEN Flvin$ FOR INPUT AS #1
  OPEN FILvinit1$ FOR OUTPUT AS #2

  LINE INPUT #1, Var$
  PRINT #2, USING "####"; V(1); V(2); V(3); V(4); V(5); V(6); V(7); V(8); V(9)
  WHILE NOT EOF(1)
   LINE INPUT #1, Var$
   PRINT #2, Var$
  WEND
  CLOSE #1, #2


END SUB

SUB WaterStressPhenology
   DayDev = DayDev + 1
```

```
  SeasTFv = SeasTFv + Fv
  SeasMFv = SeasTFv / DayDev
  Tpgrowth = Tpgrowtho * (1 - (1 - SeasMFv) * .3)
END SUB

SUB WeatherDataInput STATIC
'************************************************************************
'                TO READ DATA
'************************************************************************
        PRINT
        IF (UCASE$(FweadT) = "G") THEN
                'CALL WeatherGen        ' DATA GENERATOR
                GOTO 10780
        ELSE

                'OPEN "I", #1, Fweadat
                OPEN Fweadat FOR INPUT AS #1
                VIEW PRINT 1 TO 24

                LOCATE 12, 2
        END IF
        VIEW PRINT 15 TO 24

'**************Input IBSNAT data************

        LINE INPUT #1, X$
        INSTW$ = MID$(X$, 1, 2)
        STATW$ = MID$(X$, 2, 2)
        Latitude = VAL(MID$(X$, 14, 7))
        Longitude = VAL(MID$(X$, 29, 7))

        WHILE NOT EOF(1)
                LINE INPUT #1, X$
                Yr = VAL(MID$(X$, 6, 2))
                DOY = VAL(MID$(X$, 9, 3))
                X(DOY, 4) = VAL(MID$(X$, 13, 5))  'Radiation (MJ/m^2)
                X(DOY, 1) = VAL(MID$(X$, 19, 5))  'Max temp (oC)
                X(DOY, 2) = VAL(MID$(X$, 25, 5))  'Min temp (oC)
                X(DOY, 3) = VAL(MID$(X$, 31, 5))  'Rain (mm/d)
                X(DOY, 5) = VAL(MID$(X$, 37, 5))  'PAR
                X(DOY, 7) = VAL(MID$(X$, 43, 5))  'Eo (mm/d)
                X(DOY, 8) = VAL(MID$(X$, 49, 5))  'SVDD sat vapour pressure deficit (kPa)

                'X(DOY, 1) = VAL(MID$(X$, 13, 5))  'Radiation (MJ/m^2)
                'X(DOY, 2) = VAL(MID$(X$, 19, 5))  'Max temp (oC)
                'X(DOY, 3) = VAL(MID$(X$, 25, 5))  'Min temp (oC)
                'X(DOY, 4) = VAL(MID$(X$, 31, 5))  'Rain (mm/d)
                'X(DOY, 5) = VAL(MID$(X$, 43, 5))  'PAR
                'X(DOY, 6) = VAL(MID$(X$, 49, 5))  'Eo (mm/d)
                'X(DOY, 7) = VAL(MID$(X$, 55, 5))  'SVPD sat vapour pressure deficit (kPa)
                'Eo = X(DOY, 6)
         qtest = 10
         IF qtest = 1 THEN
                IF INT(DOY / 5) = DOY / 5 THEN
                        INPUT kjgfhjo
                END IF
                '       PRINT X$
                '       PRINT USING "####.#"; DOY; X(DOY, 1); X(DOY, 2); X(DOY, 3); X(DOY, 4); X(DOY, 5)
                  PRINT DOY, Eo

         END IF
        WEND
 CLOSE #1

         IF (UCASE$(FiriSh) = "Y") THEN
```

```
'*********************READING THE IRRIGATION-FILE******

    'OPEN "I", #7, Firi
    OPEN Firi FOR INPUT AS #7
    INPUT #7, Junk
    WHILE NOT EOF(7)
     INPUT #7, DOYIRR
     FOR i = 1 TO 10
      INPUT #7, IRRIGAT
      IF i = Niriplot AND DOYIRR <> 0 THEN
       X(DOYIRR, 6) = IRRIGAT
       IF X(DOYIRR, 6) <> 0 THEN
         'PRINT DOYIRR, x(DOYIRR, 6)
       END IF
      END IF
      NEXT i
    WEND
   END IF
CLOSE #7

   Yrcrnt = Yrcrnt + 1
  ' Fweadat = LEFT$(Fweadat, 25) + RIGHT$(STR$(Yrcrnt), 2)

10780
END SUB

SUB WriteResultP


END SUB

SUB WriteResults STATIC


  IF DOG > 0 THEN
    count = count + 1
    PRINT #3, USING "#### "; DOG - 1;
    PRINT #3, USING "##.### ##.# ##.# ##.# ####.## #####.# #####.# #####.# #####.# #####.# "; Laist;
TRANS; SOILVAP; PTRANS; BL; RL; RES; GL; SL; WWeight;
    PRINT #3, USING "### "; V(1); V(2); V(3); V(4); V(5); V(6); V(7); V(8); V(9)
  END IF


  'IF DOG > 0 THEN
   '  count = count + 1
   '  PRINT #3, USING "### "; count; DOG - 1; DOY; V(1); V(2); V(3); V(4); V(5);
   '  PRINT #3, USING "### "; V(6); V(7); V(8); V(9);
   '  PRINT #3, USING "### ### ####.## ### ###"; PPAW; FW * 100; LAIst; DEEPERC; TDEFICIT;


    'PRINT #3, USING "##### ##### #### #.#  #.#  #.#  "; PSIST / 10; (PSIL + FUDGE) / 10; FID; kc; Ks; kv;
    'PRINT #3, USING "##.# ##.# ##.# #####.# #####.# #####.# #####.# #####.# #####.# "; TRANS;
SOILVAP; PTRANS; BL; RL; RES; GL; SL; WWeight;


   ' PRINT #3, USING "##### #####  ##### #####    ###.## ####  ####.## ####  ####   ####  ###.##"; DMG;
Tree; TIMEthml; DPLcrit; Yred(STAGE); AEDplot; Eo; WATin; WATcap; WATloss; TRANS + SOILVAP


  'END IF

 END SUB

 SUB Zero
```

```
9999  '*********************************************************************
10000  ' set all variables to zero
10001 '*********************************************************************


     SeasMFv = 0: SeasTFv = 0: Tpgrowth = Tpgrowtho
     SeasTFv = 0
     DayDev = 0

10010
10020  JX = 0
10030  Treen = 0
10040  TTOT = 0
10060  SRFD = 0
10070  SP = 0
10080  PSI2 = 0
10085  TPSIL = 0
10090  AL = 0
10100  VMIN = W01(9) / DZRT(9)
10110  TFG = 0
10114  STTRANS = 0
10116  STPTRANS = 0
10120  'TTRANS=0
10130  'TPTRANS=0
10140  TVER = 0
10150  TPV = 0
10160  TBWP = 0
10170  TGWP = 0
10180  TF = 0
10190
10200  TFW = 0
10205  TFH = 0
10210  TFTP = 0
10220  TDMG = 0
10230  TFC = 0
10240  TFv = 0
10250  TFTR = 0
10260  TFTL = 0
10270  TEFF = 0
10280  TFFMAX = 0
10290  TRESP = 0
10300  TMAIN = 0
10310  ASSIM = 0
10330  TDMG = 0
10340  DMG = 0
'10350  RETURN

END SUB
```