EFFECT OF SOIL WATER, NITROGEN AND PHOSPHORUS ON MAIZE GROWTH AND YIELD IN A SEMI ARID ENVIRONMENT

By

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DECLARATION

I hereby declare that the work contained in this thesis is my original work and has not been submitted for a similar degree in any other university.

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10/01/2005 Date

This thesis has been approved for submission.

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ABSTRACT

A field study was carried out for three seasons from November 1999 to February 2001 to investigate the influence of irrigation on growth, light and nitrogen use in maize under semi-arid conditions in Machakos, Kenya. The study also assessed the potential and applicability of the World Food Studies (WOFOST) model in predicting maize growth and yield in the same area. The work spanned three seasons namely short rains 1999 (SR1999, Nov. 1999 – March 2000); long rains 2000 (LR2000, April to August 2000) and SR2000 (November 2000 to March 2001). The rainfall received in the three seasons was 350, 143 and 534 mm respectively. The experimental design was randomized complete block design laid out as split plot with water regime as main plots (irrigated, rainfed), nitrogen (N) (0, 50, 100 kg N ha^{-1}) and phosphorus (P) (0, 25 kg P_2O_5) factorially combined as subplots. Data collected included leaf area index (LAI), photosynthetically active radiation (PAR) interception, maize grain yield, total dry matter (TDM) accumulation, nitrogen uptake and soil moisture.

Irrigation significantly increased TDM (at physiological maturity) by about 2 to 10 fold during the study period. Grain yields were lowest in driest season (LR2000) (151 kg ha^{-1}) and highest (6,027 kg ha^{-1}) in wettest season (SR2000). Irrigation significantly increased leaf area index (LAI) by about 2 fold (maximum LAI, 1.3, 2.8 for rainfed and irrigated respectively) in the dry season but had no effect in the wetter seasons. PAR interception increased by the same factor as LAI (maximum PAR interception 33 %, 64 % for rainfed and irrigated respectively in the dry season). Maize light extinction coefficient was lower (0.30) under moderate and low water supply (rainfed SR1999 and LR2000) and higher (0.37) under high water supply (irrigated LR2000 and SR2000). The total plant N uptake was highest (175 kg ha^{-1}) in wettest season (SR2000) and lowest (14 kg ha^{-1}) in the driest season. Irrigation increased N uptake by a factor of 2 and 10 in the moderately wet season and dry season respectively. Cumulative evapotranspiration was higher with irrigation in the season with moderate rainfall (SR1999) by about 2 fold and 5 fold in the dry season (LR2000).

Soil water extraction was higher in the fertilized maize (at 30 and 45 cm) compared to the unfertilized maize in the three seasons. Nitrogen application improved TDM, grain yield, LAI, PAR interception and N uptake in the seasons when water was not limiting (wet season or under irrigation) in the three seasons. Light use efficiency ranged from 2.2 to 2.5 g/MJ with N application and high water supply and 1.04 g/MJ under low water supply (rainfed).

The WOFOST model overestimated grain yield by 10 to 20 % because of overestimation of partitioning coefficients. The prediction of the various variables (LAI, soil profile moisture, leaves and stems dry matter, TDM and grain yield) were closer to measured values under wet (278 to 534 mm rainfall) or irrigated conditions but were highly overestimated (30 – 765 %) under dry conditions (LR2000). This could be due to the differences in dry matter partitioning under adequate water supply (used in model calibration) and those under very dry conditions. The validation showed that reasonable estimation (80 - 90%) of grain yield, leaves, stems and total dry matter can be made under adequate water supply. The optimal N application was 50 kg ha^{-1} above which there was no improvement in maize growth and yield. Supplementary irrigation can increase maize yield even at low fertilizer input level in semi-arid Kenya.

CHAPTER 1

INTRODUCTION

1.1 General introduction

Agriculture is the mainstay of Kenya's economy and plays a critical role in the National economic growth, development, employment and foreign exchange creation. Its overall contribution to the Gross Domestic Product (GPD) was 37 % in the early 1970,s to about 25 % at the end of 2000. Of Kenya's 44.6 million hectares of land, only about 8.6 million hectares are medium to high potential agricultural land (Government of Kenya, 1997). The rest (about 80 %) is arid and semi-arid (ASAL) and supports 25 % of the human population and 50 per cent of the total livestock population. Population pressure in the high potential areas has resulted in high influx of people from the high potential areas to the semi-arid lands for agriculture and settlement (Mungai, 1991; Otengi, 1996; Kinama, 1997). Crop productivity output level in the ASAL areas is estimated to be rising at 1.5 % (Daines *et al*, 1978). Thus the ASAL are likely to play a major role in Kenyan agriculture in future in terms of increased food production and poverty reduction.

Maize is a major staple food for people in the semi arid areas and in Kenya as a whole (Government of Kenya, 1994; Mugunieri *et al*, 1996). In 1992 it was estimated that to attain self sufficiency in maize, an annual growth rate in production of 2.5 % was required (Government of Kenya, 1994) but currently this target has not been achieved due to insufficient rainfall in some years, poor soil fertility and poor marketing policies (Government of Kenya, 1997). The area under maize has stabilized at around 1.5 million hectares with limited potential for further expansion given competition on land use

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(Government of Kenya, 2002). In 1975, 29 per cent of the total hectarage under maize in Kenya was in ASAL areas (Central Bureau of Statistics, 1975).

It has been noted however that in recent years, there has been a general decline in not only maize production but other food crops as well (Government of Kenya, 2002). There is therefore an urgent need to find alternative ways and means of increasing productivity to match the increase in food demand due to population growth. On average, maize yields is 2 tonnes per hectare in Kenya but there exists the potential to increase the average yield to over 6 tonnes per hectare. Adoption and strengthening of water management technologies for sustainable food production and rural development has been suggested as one way of solving the declining yield trends (Government of Kenya, 1997). Irrigation has been identified as one of the technological support farmers need to make the country self sufficient in production of various agricultural crops including maize. At present smallholder irrigation in semi-arid Kenya is concentrated along Yatta furrow, in Makindu, Kibwezi, Kaiti, Kilome and Mbooni Divisions of Machakos and Makueni Districts (Daines *et al.,* 1978; Kamami, 1996).

The bulk of the ASAL area fall under two land utilization types,

1. Smallholder, rainfed arable farming, traditional technology. Here modern inputs for farming are not applied because of other overriding factors that restrict the application. The major constraint is unreliable rainfall in both short and long rains.
2. Smallholder, rainfed arable farming intermediate technology. Here certain inputs (fertilizers, farm yard manure (FYM), insecticides, mechanizations are used on a

modest scale at lower levels than recommended in research trials (Daines *et al.*, 1978). Drought risks are the main reason for low inputs in both systems.

1.2 Water and N Limitation on maize yields

It has been suggested that, irrigation emphasis in semi-arid Kenya should focus on high value crops, mostly horticultural or industrial crops and cereals for subsistence (Mann and Kariuki, 1978). Mostly the small scale farmers in semi-arid areas are peasants with no other sources of income (Kinama, 1997). The idea of irrigating both a cash crop and maize for subsistence would be more appealing to the farmers than having to buy the maize with the hard earned money from the cash crop. The Government has committed itself to assess irrigation technology, especially in the semi-arid areas, with a view to finding suitable low cost methods, reducing infrastructural costs of irrigation schemes, and building local capacity in planning, operating and managing irrigation projects (Government of Kenya, 2002). With improved and efficient irrigation methods like the drip irrigation the farmer can increase inputs and even realize the potential maize yield estimate of 6 t ha^{-1}. Animal drawn carts which are widely used in the semi-arid areas, combined with readily available cheap labor can assist greatly in making effective irrigation methods (drip irrigation) cheaper and acceptable to farmers.

Nutrient inputs are low in the ASAL areas in Kenya (Mathuva *et al.*, 1998) resulting in net depletion of nutrients. Nitrogen deficiency is widespread because continuous cultivation is practiced combined with low external N inputs (Probert *et al.*, 1992). Nitrogen uptake by the crop may be improved through external inputs of nutrients and/or by increasing the soil water supply (Novoa and Loomis, 1981). Increased water supply increases uptake of available soil N or increases mineralization of organic N (Pilbeam *et al.*, 1995a and b; Jarvis *et al.*, 1996). Matching crop phenology with rainfall distribution supplemented with irrigation (Kamami, 1996) are possible strategies of increasing maize yield. Variations in N availability affect growth and development of maize (Sergio *et al.*, 1995). Maize yield response to soil available N is a function of both N uptake from the soil and utilization of N within the plant to produce grain (Ma *et al.*, 1999).

Most nitrogen fertilizer experiments in semi-arid Kenya have been undertaken in rainfed conditions (Reimund, 1993) and therefore maximum potential maize production is hardly attained. The mean sole Katumani B maize yield under rainfed conditions at Machakos, Kenya between 1989 and 1995 with 40 kg N ha^{-1} and 18 kg P ha^{-1} ranged from 1.44 to 3.95 t ha^{-1} and 1.40 to 2.67 t ha^{-1} without fertilizer (Muthuva *et al.*, 1996). The insufficient and unreliable nature of rainfall limited utilization of the applied nitrogen and so the benefit of irrigation has not been thoroughly explored. Due to the prominent role maize plays in Kenya agriculture, there is a need to evaluate the effect of supplemental irrigation and nitrogen on maize growth and yield.

1.3 Modeling as a planning tool

A modern approach of addressing food uncertainty and shortages is to use crop simulation modeling as a forecasting tool. Simulation modeling can be applied in prediction of short-term yield and in extrapolation and interpolation of crop performance over large regions.

Prediction of crop yields based on soil and climatic data is therefore useful for purposes of food security, planning and land suitability assessment. Availability of reliable yield estimates can help the land use planners in making sound decisions based on scientifically researched information.

1.4 OBJECTIVES

1.4.1 Overall objective

To assess the effects of soil water, nitrogen and phosphorus on growth and yield of maize in a semi arid environment in Kenya.

1.4.2 Specific Objectives:

1. To determine the effect of soil moisture, nitrogen and phosphorus on maize growth, yield, solar radiation, N and water use.
2. To assess the potential and applicability of the WOFOST model in predicting maize growth and yield in a semi arid environment.
3. To determine the relationship between grain yield and total dry matter accumulation by maize to N uptake, evapotranspiration and cumulative Photosynthetically Active Radiation (PAR) interception.

1.4.3 HYPOTHESES:

1. Increased soil water will increase N uptake resulting in increased radiation interception, growth and yield of maize.
2. WOFOST model is capable of predicting maize growth and yields in semi-arid environments of Kenya.

CHAPTER 2

LITERATURE REVIEW

2.1 Importance of soil water in crop production

Water is a reactant in many plant biochemical processes, a medium of transport, thermal regulation, maintenance of turgor of organs and a constituent of biochemical molecules. Most of these processes are physical except photosynthesis. Of the total quantity of water used by the plant, only about 0.01 % is required for photosynthesis while the rest of the water is used for translocation and distribution of nutrients and metabolites throughout the entire plant and for maintaining turgor in plant cells (Mengel and Kirkby, 1982). For most crop species, optimum soil moisture levels are in a range of -200 kPa to 50 kPa. Soil water contents directly affect evaporation from the soil and indirectly regulate crop transpiration through their influence on crop water status (Bennett, 1990). Transpiration is the process through which water is moved through out the plant system from the root surface to the leaf cells and into the atmosphere through the stomata (Russell, 1988). The rate of transpiration is directly proportional to rate of photosynthesis because water and carbon dioxide are transported through the stomata although in opposite directions. Under limited water supply photosynthesis is reduced primarily through reduced CO_2 uptake due to stomatal closure.

Soil water (the major source of the transpired water) is influenced by a number of factors which include: rainfall amount, irrigation, underground seepage to the root zone, soil evaporation and plant transpiration (evapotranspiration), deep percolation and runoff. Soil water affects crop development either positively or negatively. Severe water deficits in certain critical development periods lengthen the vegetative growth period of a crop and reduce the economic yield (Howell, 1981). In maize soil water stress during vegetative development reduces expansive growth of stems and leaves and resulting in reduced height and lower LAI while more severe stresses are generally required before the number of leaves produced is affected (Bennett, 1990). A steady supply of soil water results in high dry matter production (Boyer, 1996).

Maize is particularly sensitive to water stress at tasselling stage and water stress in maize at tasselling causes abortion of newly formed seeds during pollination. Hence reduced grain yield (Mengel and Kirkby, 1982). Soil water for crop production may be increased by supplementary irrigation or by decreasing run-off to (or increasing run-on from) surrounding uncropped area (Pilbeam, 1995c) and reducing losses through soil surface evaporation and deep drainage. Improvement in crop management through weed control and fertilizer application have frequently been reported to increase the volume of water transpired by a crop (Gregory, 1989; Pilbeam, 1995c). Matching crop phenology with rainfall distribution and irrigation are possible strategies of increasing crop yield. When water is not limiting, nitrogen is the nutrient that mostly limits crop production (Novoa and Loomis, 1981).

2.2 Importance of Nitrogen in crop production

Nitrogen is essential for plant growth because it is a constituent of all proteins and nucleic acids and hence of all protoplasm (Russell, 1988). N for crop production is derived from either organic or inorganic (fertilizers) sources and also from biologically fixed N. Nitrogen is taken up either as ammonium or nitrate ions (Russell, 1988). Nitrogen supply affects both leaf area development and leaf senescence and consequently crop radiation interception (Eik and Hanway, 1965; Lemcoff and Loomis, 1986; Muchow, 1994). Leaf area index, leaf area duration, crop photosynthetic rate, and therefore percent of radiation interception and radiation use efficiency are increased by nitrogen supply (Novoa and Loomis, 1981; Lemcoff and Loomis, 1986; Sergio and Andrade, 1995).

Photosynthesis rates of maize at the leaf level increased with increasing fertilizer N application level resulting in increased radiation use efficiency (RUE) (Muchow and Davis, 1988). Low soil N significantly reduced maize leaf area as a result of reduced leaf size, but had little effect on the final number of leaves produced however both water and N stress lengthened the time from emergence to tasselling and silking (Bennet *et a*l., 1989). The leaf area in many crops is roughly proportional to the amount of nitrogen supplied (Russell, 1973). The higher the nitrogen supply the more rapidly the synthesized carbohydrates are converted to proteins and to protoplasm. The magnitude of response in maize grain yield to N application can vary across experiments due to confounding influences of soil N supply from non-fertilizer sources, weather variation, variety and cropping practices (Muchow, 1994). Thus N trials should be location and variety specific to allow easier interpretation.

2.2.1 Fertilizer N mineralization and recovery

The transformation from organic N (N derived from organic matter sources) into ammonium N is termed mineralization while the opposite is termed immobilization (Silgram and Sherpherd, 1999). The balance between mineralization and immobilization (net mineralization) determines the effect on the magnitude of the soil mineral nitrogen (SMN) pool (Silgram and Sherpherd, 1999). Changes in the availability of soil water have a number of effects on N mineralization (Jarvis *et al.*, 1996), (i) deficiency/stress limits biological activities and hence mineralization; (ii) excess reduces aerobicity and therefore alters the activities of different microsites i.e. reduces mineralization; (iii) soil water content controls solute diffusion and mass distribution of the products of microbial activity; and (iv) cycles of wetting/drying increase the availability of substrates.

Some of the factors affecting fertilizer N uptake by crops are genotype, soil characteristics, N source and rate, climatic conditions and N application method and time (Sigunga, 1997). These factors may, in turn be influenced by such processes as leaching, denitrification, NH_3 volatilization and soil N mineralization rate. Irrigation increases nitrogen mineralization in the soil thus increasing available N for crop uptake (Pilbeam, 1995c). Thus adoption of some management practices in semi-arid Kenya (like supplementary irrigation) combined with good husbandry would increase fertilizer N recovery.

The recovery of fertilizer N in arable crops is generally in the range 40 – 60 % (Kumar and Goh, 2000). Higher N application in excess of crop assimilate capacity decreases nitrogen recovery (Kumar and Goh, 2000). Recovery of applied fertilizer N in corn on Arenosols, of North Carolina ranged from 43 to 57 % while that recovered in grain ranged from 17 – 20 % (Reddy and Reddy, 1993). In various other experiments total fertilizer recovery ranged from 15 to 60 % and as low as 1.7 in one dry season (Hernandez *et al.*, 2000; Abdelrahman *et al.*, 2001; Simard, 2001; Vanlauwe, *et al.*, 2001a and Vanlauwe *et al.*, 2001b).

2.3 Water - nitrogen interactions

Management practices that ensure a non-limiting nitrogen supply throughout a plant's life cycle, enhance the efficiency of water use per unit of applied water and also transpiration efficiency (van Keulen, 1981; Mengel and Kirkby, 1982). The management practices may include among others: provision of adequate water supply and application of N in either organic or inorganic forms. In situations where the soil moisture supply is limited, application of nitrogenous fertilizers to crops grown for their reproductive organs, may lead to excessive vegetative growth, early use of available moisture, leading to water shortage in the most economically important part of the life cycle (van Keulen, 1981). This problem can be solved by using supplemental irrigation. High fertilizer application in conditions of limited water supply reduces soil water potential close to the roots causing a lower net flow of water into the roots of the high fertilized crop (van Keulen, 1981).

In an experiment with irrigation and various fertilizer N rates, irrigation increased number of ears/area, 100-grain wt, number of grains/ear, plant height and ear length of corn (Boquet *et al.*, 1987). Partitioning of dry matter in Makueni composite maize under rainfed conditions varied with season, with the reproductive tissues (cob) constituting 39-67 % of the above - ground dry matter (Pilbeam *et al.*, 1995b and c) while nitrogen uptake varied from 23.7 kg ha^{-1} to 87.4 kg ha^{-1} under dry (135 mm) and wet (424 mm) rainfall seasons respectively.

Nitrogen application during tasselling in maize increased grain yield if the crop was irrigated (Mengel and Kirkby, 1982). In field grown maize at Gainesville, Florida, water stress at tasselling reduced grain yield by 50 % (with high application - 413 kg N ha^{-1}) and by 30 % (with low N – 168 kg N ha^{-1}) (Saka, 1985). Late season water shortage accelerates senescence of vegetative parts, rapidly reduces photosynthesis, impairs grain filling and hampers N translocation to grain (van Keulen, 1981). This results in grain with low N content and low weight while the straw has higher nitrogen content at harvest compared to the grain. This phenomenon is frequently observed in semi-arid regions; in extreme cases resulting in shriveled grains (Van Keulen, 1981). In long term trials with N rates of 0, 80, 160 and 240 kg N ha^{-1}, grain, biomass yields and harvest index increased with increase in N rate up to 160 kg N ha^{-1} (Berzsenyl, 1988). Water stress during flowering reduced grain yield and harvest index even at optimum plant density.

Table 2.1 shows a summary of grain yield, biomass and N uptake for maize at various N application levels and rainfall conditions. Without N application and rainfall of between 135 to 2000 mm, N uptake ranged from 24 to 149 kg ha^{-1} while with N application of between 100 to 134 kg ha-1 and rainfall of 385 to 1264 mm, N uptake ranged from 78 to 180 kg ha^{-1}. Grain yield ranged from 1.4 to 6 t ha^{-1} without N application and with rainfall of between 102 to 2000 mm while with N application of between 40 to 134 kg ha^{-1} grain yield ranged from 1.4 to 9.4 t ha^{-1}.

Table 2.1. Maize grain, biomass yield and N uptake for maize at various N application levels and rainfall conditions.

Country	Rainfall (mm)	N level (kg ha^{-1})	Grain yield (t ha^{-1})	Biomass (t ha^{-1})	N uptake (kg N ha^{-1})	Author
Kenya	135				24	Pilbeam *et al.*,
	424				87	(1995b and c)
Kenya	102-703	0	1.4 – 2.7			Mathuva *et al.*,
		40	1.4 – 4.0			(1996)
Brazil	1264	0	1.8 – 4.2	4.4 – 10.7	39 – 74	Glovc *et al.*,
		100	4.1 – 7.4	9.3 – 15.1	78 - 146	(1983)
Puerto	2000	0	1.7 – 5.9		43 – 149	Fox *et al.*,
Rico		134	3.0 – 6.0		97 - 180	(1974)
Ottawa	385 - 494	0	4.6 – 6.0		49 – 95	Ma *et al.*,
		100	7.0 – 9.4		105 - 150	(1999)
Canada	Irrigated	250 - 268	Over 10		225 - 264	Karlen *et al.*,
						(1987)

2.3.1 Effect of water availability on N uptake and N use efficiency

Maize grown on sandy soils supplied with 116 and 401 kg N ha^{-1} under water stress conditions, observed no significant effect on total biomass, N accumulation and grain yield of corn (Bennet *et al.*, 1990). As generally expected for many crops, when high N levels were applied, water stress reduced the efficiency of N utilization. With high N, crop N uptake in rainfed and irrigated treatments amounted to 26 % and 67 % of that applied (104 and 267 kg N ha^{-1}). With low N and irrigation accumulated N amounts were near that applied but only 60 % of applied N (70 kg N ha^{-1}) was taken by the crop under severe water stress in combination with low N. The effect of water on the efficiency of N utilization was also observed by Panchanathan *et al.*, (1987). Maize irrigated with a total of 351 mm per season and 60 kg N ha^{-1} gave highest yields when compared with other rates of 0, 120, and 180 kg N ha^{-1}. When higher rate (449 mm) of irrigation was used the 120 kg N ha^{-1} gave the highest yield. Thus high N application rates should be followed by sufficient irrigation levels to allow full utilization of the N fertilizer. Work with corn has shown that maximum fertilizer use efficiency can be obtained with low N rates applied in-season and with light, frequent irrigation (Raun and Johnson, 1999).

Maize (hybrid 511) N uptakes of between 115-130 kg ha^{-1} have been observed in Vertisols of western Kenya under rainfed conditions and N application of 100 kg ha^{-1} and improved soil drainage (Sigunga, 1997). Seasonal variations in rainfall or improvement of water supply to the crop through supplementary irrigation can result in variations in crop N-uptake (Sigunga, 1997). Recovered nitrogen in the grain decreases when soil moisture supply decreases due to decreased growth rate as well as availability of soil nitrogen (Novoa and Loomis, 1981).

2.3.2 Seasonal effects

Monocropped and intercropped maize positively responded to nitrogen and phosphate fertilizer application under rainfed conditions at Katumani (FURP, 1994). The response functions to application of N and P for maize calculated over a period of 10 years were influenced by season:

Season 1 (March – August): $Y = 1{,}225 + 3.63N + 11.2P - 0.16P^2$ $r^2 = 0.38$

Season 2 (Nov. – March): $Y = 2{,}718 + 11.0N$ $r^2 = 0.73$

where; Y = grain yield, N = nitrogen application (kg ha^{-1})

P = phosphorus application (kg P_2O_5 ha^{-1}).

The constant in each function shows the yield that was obtained without application of fertilizers. Season 1 was March to August (long rains) and season 2 was November to February (short rains). Average yields were higher in season 2 because rains were less erratic. The highest economic return for Katumani composite B maize was obtained at 52 kg N ha^{-1} and 20 kg P_2O_5 ha^{-1} (Nadar and Faught, 1984). The mean sole Katumani B maize yield under rainfed conditions at Machakos, Kenya between 1989 and 1995 with 40 kg N ha^{-1} and 18 kg P ha^{-1} ranged from 1.44 to 3.95 t ha^{-1} and 1.40 to 2.67 t ha^{-1} without fertilizer (Muthuva *et al.*, 1996).

2.3.3 Light use

Light use is the proportion of the incident radiation that is intercepted by plants during their life cycle and which is available for photosynthesis (photosynthetically active radiation – PAR) (Squire, 1990). Light levels have a profound influence on plant growth (Sinclair *et al.*, 1999). Leaves absorb strongly in the visible region of the spectrum (photosynthetically active radiation) but weakly in the near infrared (Monteith, 1965; Njihia, 1980).

2.3.3.1 Influence of plant canopies

Leaf surfaces intercept light and absorb carbon dioxide in the process of photosynthesis

(Brown, 1988). Photosynthesis and dry matter production of a plant are proportional to the amount of leaf area on the plant as long as some leaves are not heavily shaded by others (Brown, 1988). The light intensity penetrating plant canopies decreases as LAI increases. The intercepted radiation (IPAR) and LAI are related by Beer's law equation (Monteith, 1965):

$$IPAR = PAR\ (1-e^{-kL})$$

Where;

PAR = In coming photosynthetically active radiation

k = extinction coefficient

L = leaf area index

If the ratio of intercepted Photosynthetically Active Radiation (IPAR) to PAR is denoted by f (fraction of intercepted PAR) the slope of the linear relationship between L and ln(1-f) is the extinction coefficient (k) which indicates the probability of a beam being intercepted thin a short distance.

ht interception for maize was closely associated with LAI until the tasselling *et al.*, 1968). At tasselling all the maize canopies were essentially closed more than 90 percent of the sunlight. By the end of grain filling a AR is intercepted by partially senesced upper leaves with reduced (Otegui *et al.*, 1995). For short season maize hybrids, maximum attained when the critical LAI (defined as LAI needed to produce 95 percent ion of the light) was between 2.9 and 4.0 at plant population of between 48,000 and 0,000 plants/ha (Hunter *et al.*, 1970; Gallo, 1985; Tetio-Kagho and Gardener, 1988).

Intercepted PAR in maize canopies is reported to have increased as a function of green LAI up to silking and then decreased due to absorption by stalks and non-green leaves, (Gallo, 1985). Fractional light interception was 97 %, by 35 days after sowing (DAS) (Tetio-Kagho and Gardener, 1988). PAR interception ranged from 90 to 98 % with LAI range of 2.0 to 4.8 for maize cv. Pioneer 3851 and Pioneer 3925 respectively in irrigated fields near Elora, Ontario (Tollenaar and Bruulsema, 1988). Measurements of PAR interception were done between 2 weeks before to 6 weeks after silking. Reported extinction coefficients for corn range from 0.34 to 0.40 at row spacings of between 66 and 100 cm (Muchow *et al.*, 1990; Flenet *et al.*, 1996).

2.3.3.2 Light use efficiency

Light use efficiency is the energy required to produce a unit of dry matter (Kiniry *et al.*, 1989; Gallo *et al.*, 1993). Light use efficiency can be influenced by temperature, plant genotype, location, population densities and management (Kiniry *et al.*, 1989). Crop canopies exhibit linearity in the response of photosynthetic rate to increasing solar radiation (Kiniry *et al.*, 1989). This factor results in shoot dry weight production of any crop being strongly correlated to the amount of photosynthetically active radiation intercepted (IPAR) by its canopy (Kiniry *et al.*, 1989; Otegui *et al.*, 1995). Under non stress environments, the slope of this relationship, called radiation use efficiency (RUE) (DM produced per unit intercepted photosynthetically active radiation (IPAR), is often assumed to be constant for each cultivated species (Kiniry *et al.*, 1989). The mean radiation use efficiency for maize under non-stress environments ranged from 2.1 to 4.5 g/MJ IPAR (Kiniry *et al.*, 1989). The variability of the shoot : root ratio among maize genotypes could be a major factor contributing to the variability of RUE estimates for maize under non-stressed environments. Under stressed environments RUE is not constant and varies with plant growth stage (Kiniry *et al.*, 1990).

2.3.4 Crop water use and water use efficiency

Crop water use is the mass of water used by the crop in its whole growth cycle and usually includes direct evaporation from the soil surface (Boyer, 1996). Agronomic water use efficiency (WUE) is defined as the amount of above ground dry matter produced per unit of water lost in both transpiration (T) and evaporation from the soil surface (Pilbeam *et al.*, 1995; Boyer, 1996).

$$\mathrm{WUE} = \frac{\mathrm{TDM}}{\mathrm{ET}}$$

Where;

TDM = total dry matter (kg ha^{-1})

ET = Amount of water used (evapotranspiration) (mm)

Crop water use can be worked out from a simple water budget of water fluxes into and out of a soil profile as follows:-

$\mathrm{ET} = \mathrm{P} - \mathrm{R} - \mathrm{D} - \mathrm{S}$

where ET is evapotranspiration (sum of transpiration and evaporation from the soil surface), P is precipitation, R is run-off/run-on, D is drainage and S is change in storage in the soil profile. In situations where R and D are negligible the equation reduces to:-

$\mathrm{ET} = \mathrm{P} - \mathrm{S}$

A lot of work has been done on water use and water use efficiency for maize under both rainfed and irrigated conditions but this information is scanty for the local Kenyan maize cultivars.

2.3.4.1 Factors that influence water use and water use efficiency

Total water use may be increased by supplementary irrigation or by reducing losses through evaporation from the soil surface. Increasing soil water supply or improvement of the nutrient status of the soil are alternative strategies of enhancing water use by the crop (Pilbeam *et al.*, 1995). When the plant canopy is large, and its duration is long, evaporation losses from the soil surface are often small, and transpiration losses are commensurately greater (Pilbeam *et al.*, 1995). Crop type also influences effective water use because of species differences in both the pattern and extent of both root and shoot growth. Water use and water use efficiency of maize were increased by application of nitrogen to an Alfisol soil at Palampur, India (Masand *et al.*, 1993). Water stress during vegetative phase reduces growth of stems, leaves, lowers LAI and reduces water use efficiency (Bennett, 1990, Boyer, 1996). Water deficits during silking, tasselling and pollination are detrimental to yield and may result in delayed silking, reduced silk elongation and inhibition of pollination (Bennett, 1990).

2.3.4.2 Effects of various managements and environments on water use and water use efficiency.

Research carried out in the USA under both rainfed (Allessi and Power, 1975; Bennett, 1990) and irrigated conditions (Stone *et al.*, 1996; Tolk *et al.*, 1998) indicate corn grain water use efficiencies ranging from 4 to 17 kg ha^{-1} mm^{-1} (Table 2.2) and total biomass water use efficiencies ranging from 15.4 to 32.2 kg ha^{-1} mm^{-1}. Under fully irrigated treatments in two other experiments grain water use efficiency ranged from 12.7 to 13.5 kg ha^{-1} mm^{-1} with different maize cultivars. Stone *et al.* (1996) further reported that corn had significant increases in water use and grain yield as irrigation amount increased from 0 to 111 mm, 111 to 213 mm, 213 to 314 mm and 314 to 421 mm. However irrigation amounts higher than 213 mm showed no significant increase in water use efficiency. Irrigation production efficiency (IPE) (the ratios of grain and total dry matter (TDM) yield to water supplied (irrigation + rainfall)) for sorghum in the semi-arid Gezira, (Sudan), decreased with addition of supplementary irrigation (Farah *et al.*, 1997). A linear relationship of forage yields verses supplied water (rainfall + irrigation) for grain sorghum was found but grain yields attained a maximum level with water supply of 5885 m^{3} ha^{-1} (588.5 mm), beyond which more water resulted in lower yield. Maximum grain sorghum yield occurs when 80 % of the soil water deficit is replaced, rather than 100 % (Farah *et al.*, 1997). Higher water contents above 80 % of the soil water deficit probably interferes with root respiration resulting in lower yield.

Table 2.2. Maize water use efficiency response to N and P applications.

Nutrient amount (kg ha^{-1})	Maize variety/ Characteristics	ET (mm)	Grain WUE (kg ha^{-1} mm^{-1})	Total biomass WUE (kg ha^{-1} mm^{-1})	Area	Author/s and year
N 40	Katumani Composite B.	450	13.2	--	Machakos, Kenya	Stewart (1983)
N 0 and 134	68 days	--	4 – 10.2	15.4 – 28.8	Northern Mandan N.D, USA	Allessi and Power, 1975; Bennett, (1990)
N 178	Not specified	540	15.7	--	Kansas, USA	Stone *et al.*, (1996)
P 21	Not specified	644	15.2	--	Kansas, USA	Stone *et al.*, (1996)
Not fertilized	100 days maturity	328 - 617	13.2 - 17.0	23.4 – 32.2	Bushland, USA	Tolk *et al.*, (1998)

-- data not available

The data in Table 2.2 indicate that with N above 100 kg N ha^{-1} maize grain and total biomass WUE varies between 10.2 to 15.2 kg ha^{-1} mm^{-1} and 15 – 32 kg ha^{-1} mm^{-1} respectively. The effect of location, expected due to soil evaporation component in ET is not apparent with this data. The high WUE values reported by Tolk *et al.*, (1998) under unfertilized conditions may suggest that the plots they used were quite fertile and may have supplied over 100 kg N ha^{-1} through soil N mineralization.

Seasonal ET requirements for maize are between 500-800 mm (Doorenbos and Kassam, 1979). Maize crop evapotranspiration under furrow irrigation in South Western Spain averaged 625 mm (Fernandez *et al.*, 1997). The estimated maximum evapotranspiration (ET_m) requirement for Katumani Composite B maize under sub-humid conditions is 465 mm (Mugah and Stewart, 1982). However ET_m requirements at Katumani can be expected to be higher because of higher evaporation demand. Results from Katumani National Dryland Station indicate that, Katumani Composite B maize estimated water requirements is 589 mm (Stewart, 1983). With 450 mm yields were 5.92 t ha^{-1} for pure stands of maize. Application of nitrogen beyond 40 kg N ha^{-1} did not result in higher yields. At 40 kg N ha^{-1} grain production occurred when water use was 218 mm, but without N fertilizer 298 mm of water was required (Stewart, 1983). Water use beyond 450 mm will be investigated with a view to finding out whether the increased water would improve both N nitrogen use and maize growth and production. There is a strong linear relationship between both maize dry above ground biomass and grain yield to evapotranspiration (ET) (Zhudeju and Lujingwen, 1993; Bennett, 1990).

2.4 Role of Simulation modeling in crop production

Crop growth models draw on knowledge from such fields as crop physiology, soil science, agro climatology and phytopathology. They calculate the yield response to growth-controlling environmental factors on basis of knowledge of the fundamental relationships between crop performance and soil, weather, and water as manipulated by the farmer (van Diepen *et al.*, 1991). The relationships used are based on the results of research on basic processes, such as transport processes in the soil, crop transpiration, CO_2 assimilation, respiration, phenological development and nutrient uptake.

Models increase the usefulness of experimental results and improve the extrapolability and interpolability of conclusions from ongoing trials, extrapolating and interpolating crop performance over large regions, predicting short term yield and data analysis to create links h other sciences (Penning de Vries *et al.*, 1989). They have also been used to determine w far crop growth in different situations can be explained from documented theory and ta. Crop performance can be predicted for climates where the crop has not been grown fore, or not grown under optimal conditions. Modeling requires the availability of fficient basic data and knowledge of the model functions. Literature on basic data is mited and an inventory for a range of crops is usually quite difficult to make. The relations etween all principal variables of the system and the values of key constants must be nown, but this is not always the case.

2.4.1 The WOFOST Model

WOFOST is the acronym for World Food Studies. The model simulates growth and production of field crops under a wide range of weather and soil conditions (Van Diepen *et al.*, 1989). The analysis assesses to what extent crop production is limited by factors of light, moisture and macro-nutrients. It was developed by the centre for World Food Studies in Wageningen and the centre for Agrobiological Research (CABO), the Netherlands. In principle, the model is applicable anywhere where crops are produced although it was developed primarily for agriculture in the tropics. The calculated theoretical yields allow one to evaluate the relative importance of the principal constraints of crop production, such as light, temperature, water, and macro-nutrients nitrogen, phosphorus and potassium. This information is used to assess reasonable combinations of inputs needed for attaining certain target yields.

WOFOST model simulates crop growth for one growing season from emergence to maturity. Crop growth and soil water balance are described with a time resolution of one day. WOFOST calculates crop yields under three principal growth constraints, resulting in three production levels (Van Diepen *et al.*, 1989). These are:

(i) Potential production where crop growth is limited by light and temperature regime only. Water and nutrient supply are assumed to be optimum.

(ii) Water-limited production where moisture supply may limit crop growth but nutrient supply is optimum.

(iii) Nutrient-limited production where the soil nutrient supply is introduced as a growth-limiting factor. Nitrogen, phosphorus and potassium are considered as the most constraining macro-nutrients for crop growth.

Other factors, such as the influence of weeds, pests and diseases, and the effectiveness of farm operations are not taken care of in the model. With respect to practical farming, (i) indicates the production ceiling for irrigated farming, (ii) for rainfed farming and indicates whether irrigation or drainage is needed to realize a potential yield. Running (ii) for different water management scenarios allow evaluation of their effects on crop yields. (iii) represent farming without fertilizer application and indicates how much fertilizer should be applied to realize (i) and (ii).

The model follows the following principles:

- Daily plant development is a function of the difference between average daily air temperature and a base temperature (threshold temperature).
- Dry matter accumulation depends on the amount of intercepted solar energy during the time interval observed and also on the weight of carbohydrates

lost through maintenance respiration.

- The amount of solar energy intercepted determines the net quantity of CO_2 fixed during the day light hours and will change as water or temperature become limiting. Above or below the optimum soil moisture potential the plant senses stress and react by actively curbing its water consumption through partial or complete closure of its stomata. The consequence of this is interference with CO_2 intake resulting in reduction of assimilation and hence lowering of dry matter production.
- Net photosynthesis is converted from CO_2 to carbohydrates (CH_2O) by using the ratios of the molecular weights of carbohydrates and CO_2 (30/44).
- Dry weight is then distributed to the various plant organs depending on the plant development stage.
- The distribution is done using set variety specific partitioning factors for the various plant organs (i.e. roots, leaves, stems and storage organs)

The summarized input and output data are listed in Appendix 1.

Before the model can be used it requires calibration. Calibration is an essential step in model development, aimed at adjusting or deriving parameter values on basis of experimental data. According to Van Keulen (1976), the main purpose of calibration is to "adapt, within reasonable limits, weak or unknown parameters or relations" on the basis of experimental data, in order to reach the best overall agreement between simulated and observed results". A calibration effort is justified when information from experiments clearly shows that some of the parameters introduced in the model were not determined sufficiently accurately, especially, if these are known to be crucial for model behavior (Rotter, 1993).

2.4.2 Application and approaches of maize prediction in Kenya

The number of models available worldwide is quite extensive and vary widely in areas of applicability and complexity. Due to the immense seasonal variability of rains, prediction of yield ratios (actual/maximum yield) based on water balance models and derived indices as promoted by FAO (Doorenbos & Kassam, 1979) has received special attention worldwide resulting in various adaptations of the approaches towards simulation modeling (Reimund, 1993). Besides World Food Studies (WOFOST) various other models have been developed that specifically deal with maize production (Simaiz, CORNF and CERES-maize) but of these only CERES-maize seems flexible enough to be adapted to tropical conditions (Rotter, 1993). Keating *et al.*, (1990), reported on validation experimentation done on nitrogen version of CERES - maize model at Katumani and Kiboko research stations and in a farmer's farm at Wamunyu between 1985 and 1989. The aim was to develop a capability to model maize growth and yield in relation to the major soil, management and climatic constraints. The model was originally developed in Northern Australia. A number of revisions were done to the original model to deal with problems encountered in Kenya. The authors concluded that the modified CERES-maize referred to as CM-KEN is capable of simulating maize growth and yield in relation to water, nitrogen and management controls in this environment (Keating *et al.*, 1990). However the changes made were based on limited data and may not have wider validity, but their objective was to develop the best possible simulation within a defined region.

Keating (1990) further reported that the model dealt inadequately with longer-term changes in soil organic matter content, and did not simulate soil property change as a result of tillage and soil erosion. Neither does it attempt to deal with limitations imposed by weeds, pests, diseases or nutritional limitations other than nitrogen. These limitations mean that the model is not suitable for the regional estimation of farm production, as many of these constraints will be operational, and suitable input data are unavailable on a regional scale.

Rotter (1993) evaluated the applicability of the WOFOST model in predicting maize growth and yields under rainfed conditions in arid and humid Kenya and reported that on average, predictions of relative yields using the WOFOST model deviate by 15 % from reality. He used maize varieties, Katumani composite B, H512, H613c, H614 and H625. For yields of 2, 4 and 6 t ha^{-1}, yield predictions, on average, would deviate by 0.3, 0.6 and 0.9 t ha^{-1}, respectively. However for Katumani composite B at Katumani Dryland Farming Research Station actual grain yield was overestimated by 1,850 kg ha^{-1} (42 % error) by the model.

Experimental maize yields for maize variety, Katumani composite B with 75 kg ha^{-1} of N and P and 362 mm rainfall, at Gachoka, Kenya were lower than the WOFOST simulated yield (4.4 t ha^{-1} verses 8.5 t ha^{-1}) (Wokabi, 1994). The difference has been reported to be probably due to inadequate inputs in the experimental study. However the experimental yields for hybrid 511 (at Embu, Kenya) with the same fertilizer inputs and rainfall of 559 mm and 576 mm (season I and II respectively) were comparable to predicted WOFOST yields (4.5 t ha^{-1} verses 5.1 t ha^{-1} and 8.3 t ha^{-1} verses 9.7 t ha^{-1}) The high yield overestimation for Katumani composite B maize Wokabi (1994), may be explained by the fact that that he did not calibrate the model with his local maize varities but used a model already calibrated using a standard maize cultivar. It is probable that the standard maize cultivar had physiological characteristics more similar to H511 than Katumani composite B and hence the better observed results with the former maize variety compared with the latter.

2.4.3 Criteria for selecting WOFOST model

The model was preferred to other models because of minimum data requirements and its high generality. For instance, CERES-Maize without nitrogen balance requires a considerable amount of data and many assumptions, such as weighing factors for root distribution for various depth intervals and soil albedo. Rotter (1993) reported on comparisons of CERES-Maize version 2.10 and WOFOST version 4.1 done by Ritchie (1989), using data sets from Kenya which revealed that the results of the latter model more closely resembled observed data.

2.5 Identified knowledge gaps

There is a general lack of literature on N recovery in semi-arid environments including Kenya (for both rainfed and irrigated conditions) and hence investigations along this line will contribute greatly to the existing knowledge. Irrigation has been used in other dry parts of the world to enhance nitrogen use and nitrogen use efficiency but not in semi arid Kenya. Combination of supplemental irrigation and fertilizer nitrogen application can improve maize production in semi arid Kenya where irrigation is mainly done on horticultural crops but maize is still the main food crop. There is potential of growing maize in rotation with vegetables under irrigation in these areas. A lot of literature exist on water-nitrogen interactions for maize worldwide however, there is very little information on nitrogen uptake for the local Kenyan maize cultivars. This research will contribute to the availability of this information for Katumani composite B maize. Further there is no information at all on light use and light use efficiency for the local Kenyan maize cultivars. This research will attempt to fill part of this information gap by collecting light use data for Katumani Composite B maize and relating it to soil water availability and nitrogen use.

Rotter (1993) was unable to address the semi-arid areas fully due to lack of reliable data on Katumani composite B maize. The missing data included:

- Dry matter distribution with time.
- Continuous observations on leaf area index .
- Partitioning data, i.e., distribution of dry matter with time to the various maize organs.
- Data on nutrient uptake and soil moisture.

Further more the season he used for model calibration had inadequate moisture levels for calibration purposes (total of 289 mm - rainfall 129 mm and supplementary irrigation 160 mm).

This research undertook to collect all the above relevant data and to investigate in more detail the relevance and suitability of the WOFOST model in predicting maize growth and yields in semi-arid Kenya.

CHAPTER 3

MATERIALS AND METHODS

3.1 Experimental site

The study was conducted at Katumani Dryland Farming Research station, Machakos District, 9 km south of Machakos town ($1^{0}35'$ S, $37^{0}14'$ E and altitude of 1600 m). The mean annual rainfall is 711 mm which is bimodally distributed. The average seasonal rainfall for the long rains (LR)-(March to May) and the short rains (SR)-(November-February) is 301 and 283 mm respectively. The mean, annual, minimum and maximum temperatures are 20, 14 and 26^{o}C respectively. The area falls under agro-climatic zone IV with a low potential for rainfed agriculture (Sombroek *et al.*, 1982). Soils are well drained chromic luvisols with poor inherent soil fertility (Gicheru and Ita, 1987) however they now classify as Haplic Alisols (Appendix II), (FAO, 1989). Soil carbon content and total nitrogen were low ranging from 0.7 to 0.8 % and 0.07 to 0.08% respectively, phosphorus was high (26-46 ppm) and the pH ranged between 6.0 and 6.7 (Appendix II).

3.2 Experimental design

The experimental design was randomized complete block design laid out as a split plot with irrigation as the main plot (irrigated-(Ir) x rainfed-(R) respectively). The subplots consisted of N and P applications at levels of 0, 50, 100 kg N ha^{-1} (N_0, N_{50}, N_{100}) applied as calcium ammonium nitrate (CAN) and 0 and 25 kg P_2O_5 ha^{-1} applied as triple super phosphate (TSP) factorially combined and replicated three times. CAN was applied in two split applications (half at planting and the other half at maize 11th leaf stage at about 25 days after emergence (DAE) while phosphorus was applied at planting. The subplot size was 9 m x 2.4 m. Drip irrigation system (Sijali, 2001) was used to supply water at a rate of 5.4 mm day^{-1} between sowing and physiological maturity. Total applied irrigation water was 405, 561 and 83.7 mm during short rains 1999 (SR1999), long rains 2000 (LR2000) and short rains 2000 (SR2000) respectively. The maximum soil evaporation recorded in the area (Kinama, 1997) under a non-mulched maize crop, was 5.9 mm day^{-1} with seasonal mean of 4.1 mm day^{-1}. Katumani composite B maize (a short maturity variety – 110 days) was sown at a spacing of 75 cm between the rows and 30 cm within the rows (44,444 plants ha^{-1} after thinning to one plant per hole). In SR1999 the maize was planted on 14th November 1999 and harvested on 17th March 2000. In LR2000 the planting and harvesting dates were 5th April and 30th August respectively while in SR2000 the dates were 16th November 2000 and 12th March 2001 respectively. Diprex applied to the whorl, was used to control maize stock borer while cutworms and termites were controlled using furadan applied to the holes at sowing. The site was kept free of weeds by hand weeding twice per season.

3.3 Data collection

3.3.1 Leaf area index and dry matter accumulation

Leaf area index (LAI) was determined every 5 days on 8 plants per subplot using the length width method (Francis *et al.*, 1969; Daughtry and Hollinger., 1984). Dry matter accumulation with time was determined by harvesting four plants per sub-plot every ten days throughout the growing period. Maize biomass was partitioned into leaves, stems and grain depending on crop phenological stage. The maize plants were then chopped into small pieces and oven dried at 70^{o}C to constant weight. The final grain yield was determined by harvesting plants from 5.4 m^2 from each subplot and the final yield adjusted to 12.5 %

moisture content. Nitrogen content was determined from the stover and grains using SKALAR methods (Walinga *et al.*, 1989).

3.3.2 Light interception

Percent fractional interception of photosynthetically active radiation (PAR) was determined by placing a sunfleck ceptometer SF80 (Decagon Pulman Washington) perpendicular to the maize rows. Eight readings were taken per subplot and percentage PAR interception (f) calculated as:

$$f = \frac{(a - b)*100}{a}$$

where a = PAR flux above the canopy and b = PAR flux below the canopy.

Existing daily values of global solar radiation (in langleys) for the study area were converted to MJm^{-2} by multiplying with a factor of 0.04173 (Kiniry, 1989; Rotter, 1993). Daily PAR was obtained from global radiation by multiplying by 0.45 (Monteith, 1965; Kiniry 1989) and the amount of PAR intercepted by the maize calculated by multiplying daily fractional PAR interception (calculated by interpolation between sampling dates) with the daily global PAR.

3.3.3 Soil water content

A neutron probe (model CPN 503DR Hydroprobe–Martinez, Califonia, USA) was used to determine soil moisture at 15, 30, 45, 60, 90 and 120 cm depth in each plot at a 10 to 12 day interval. A PVC access tube (52 mm internal diameter) was installed in each plot to a depth of 140 cm (where soil depth allowed) midway between two plants in the central row. Maize water use was determined by water balance calculations using moisture data from the neutron probe measurements. Neutron counts (counts/second) were converted to soil water content using the equation below:

$$Y = 26.66711x - 9.02471, \qquad R^2 = 0.90$$

Where;

Y = Volumetric soil moisture

X = count ratio (counts/standard count). An average measured standard count of 6444 was used in all seasons.

Sampling of the soils at the site was done at the beginning of the study in order to get a more up to date analysis (Hinga *et al.*, 1980) of physical and chemical properties of the soils and also at the begining of every planting for fertility analysis (Appendix 2). Climatic data (daily maximum and minimum temperatures, daily rainfall, global radiation, humidity and wind speed) from Katumani meteological station which is 300 meters from the site were used in maize yield simulations.

3.4 Model assessment approach

3.4.1 Model calibration and validation

The potential and suitability of the WOFOST (World Food Resources) model was assessed by first calibrating then validating. The partitioning factors for Katumani composite B maize determined under irrigated conditions during LR2000 and SR2000 and also under high rainfall (534 mm) during SR2000 indicated that the values suggested by Rotter (1993) required adjustment. Leaf area index, leaf, stem and total above ground dry mass, soil profile volumetric soil moisture, grain yield and yield components measured in short rains 2000 (rainfed treatments) were used for model calibration because high rainfall (534 mm) was received in that season and maize growth was vigorous.

Calculation of degree days for the three seasons from germination to flowering (TSUM1) and flowering to maturity (TSUM2) using measured mean daily temperatures and a base temperature (threshold temperature (TBASE) of 9°C yielded mean TSUM1 of 518 degree days and TSUM2 of 557 degree days. Threshold temperature is the temperature below which phenological development stops and is crop specific. TSUM1 and TSUM2 of 524 and 573 degree days were used for the calibration. TSUM of 524 degree days gave the best agreement between simulated and observed pre-anthesis (germination to flowering) duration. Specific leaf area (expressed in hectares of green area per kg of dry matter of leaf blades - SLATB) at germination (ha kg^{-1}) and at flowering were determined by calculating the leaf area using the measured leaf length and width (Francis *et al.*, 1969; Daughtry and Hollinger, 1984) and the plant dry matter.

Model validation is the testing of the model with other sets of completely independent data to show whether the model yields proper results under different conditions (Van Keulen, 1976).

3.4.2 Processes used in model calibration and validation

Calibrating a model is the adjustment of some parameters so that the model matches one set of measured data (Penning de Vries *et al.*, 1989). Model calibration in this study involved:-

i) Incorporating the Katumani composite B maize partitioning factors (distribution of the increased dry matter at specified growth stages to roots, leaves, stems and storage organs) (Appendix 4) into crop file. Values for partitioning to roots from Rotter (1993) were used.

ii) Determining TSUM1 and TSUM2 and incorporating them into the crop file. Mean TSUM's were determined from the average daily temperature by subtracting a TBASE of 9 °C and summing up the daily difference over the two growth phases (germination to flowering (pre-anthesis) and flowering to maturity (post-anthesis). Maturity was taken as the time when the maize grain becomes hard while anthesis is the moment when the first flowers open and pollen is shed (FURP, 1990).

iii) The model was run at 10 day interval and the predicted output (leaf area index, leaf and stem dry weight, total dry matter, storage organs – grains and cobs) compared with measured values.

iv) Adjusting the specific leaf area factors (SLATB in ha kg^{-1}) (i.e. leaf area index /leaves dry weight (kg/ha)) at emergence (to adjust values in (iii)). The SLATB at emergence and flowering were determined by using measured leaf area index and leaf dry weight.

v) Re-adjusting of the partitioning factors to allow best match between measured values and simulated values.

Validation was carried out by comparing simulated volumetric profile soil moisture, leaf area index, leaves, stems and above ground dry weight with measured values for SR1999, LR2000, SR2000 and also using 1988 to 1991 seasonal grain yields obtained by Fertilizer Use Recommendation Project (FURP, 1994). The crop, soil and climate files used for the exercise (Appendix 6) were compiled from the experimental data collected by FURP, data gathered through this research and from Rotter (1993). Actual vapor pressure (hPa – hundredth of a pascal) were calculated using the equation:

$$e_a = H*6.11e^{((17.4*Ta)/(Ta+239))}$$

where

e_a = actual vapor pressure

H = mean monthly air humidity

e = 2.7182818

Ta = mean air temperature

Data on long term mean irradiation (1974-1980) (KMD, 1984) were used for May to December 1990 and for January to August 1991 because actual measured data for these periods were not available.

3.5 Statistical analysis

Analysis of variance was used to evaluate the effects of treatments and their interactions on the response variables using Mstat Statistical Package (Michigan State, University, USA) and the least significant different (LSD) was used to separate the means at $P \leq 0.05$, linear regression analysis was also applied to some of the relationships among variables (Steel and Torrie, 1981). Results are presented in chapters 4 to 9.

CHAPTER 4

Maize growth

4.1 Climatic data

Figure 4.1 shows the mean monthly temperatures and radiation for short rains 1999 SR1999), long rains 2000 (LR2000) and short rains 2000 (SR2000). The mean temperatures for SR1999 and SR2000 were similar however there was a sharp decrease in mean temperature during grain filling and ripening phases in LR2000 (June and July). The low mean temperatures in June and July are normal during that time of the year. Figure 4.2 shows the rainfall distribution and days after maize emergence during the three seasons. The total seasonal rainfall was 350 mm, 143 mm and 534 mm in SR1999, LR2000 SR2000 respectively. The values reflect the wide variability of seasonal rainfall in the study area. The rainfall during SR1999, LR2000 and SR2000 was 81, 85 and 52 % of the total respectively during establishment phase, i.e., (first 25 days after crop emergence (DAE)), 17, 6 and 4.0 % during vegetative phase (26 to 42 DAE), 2, 5 and 33 % during flowering phase (43 to 56 DAE) and 0, 4 and 12 % during grain-filling and ripening phase (57 to 106 DAE).

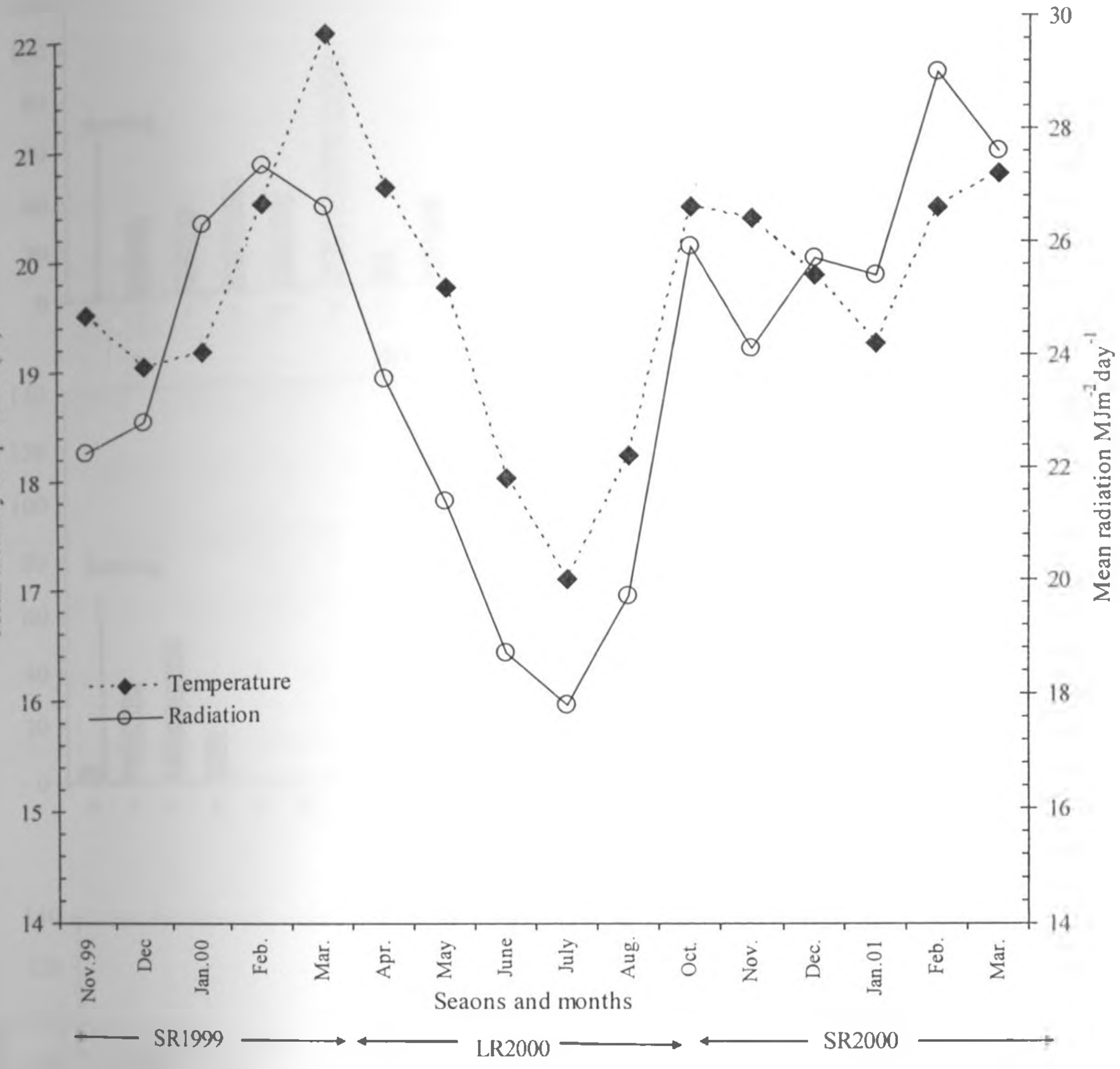


Figure 4.1. Mean monthly temperatures and radiation for the seasons SR1999, LR2000 and SR2000 at Katumani, Kenya .

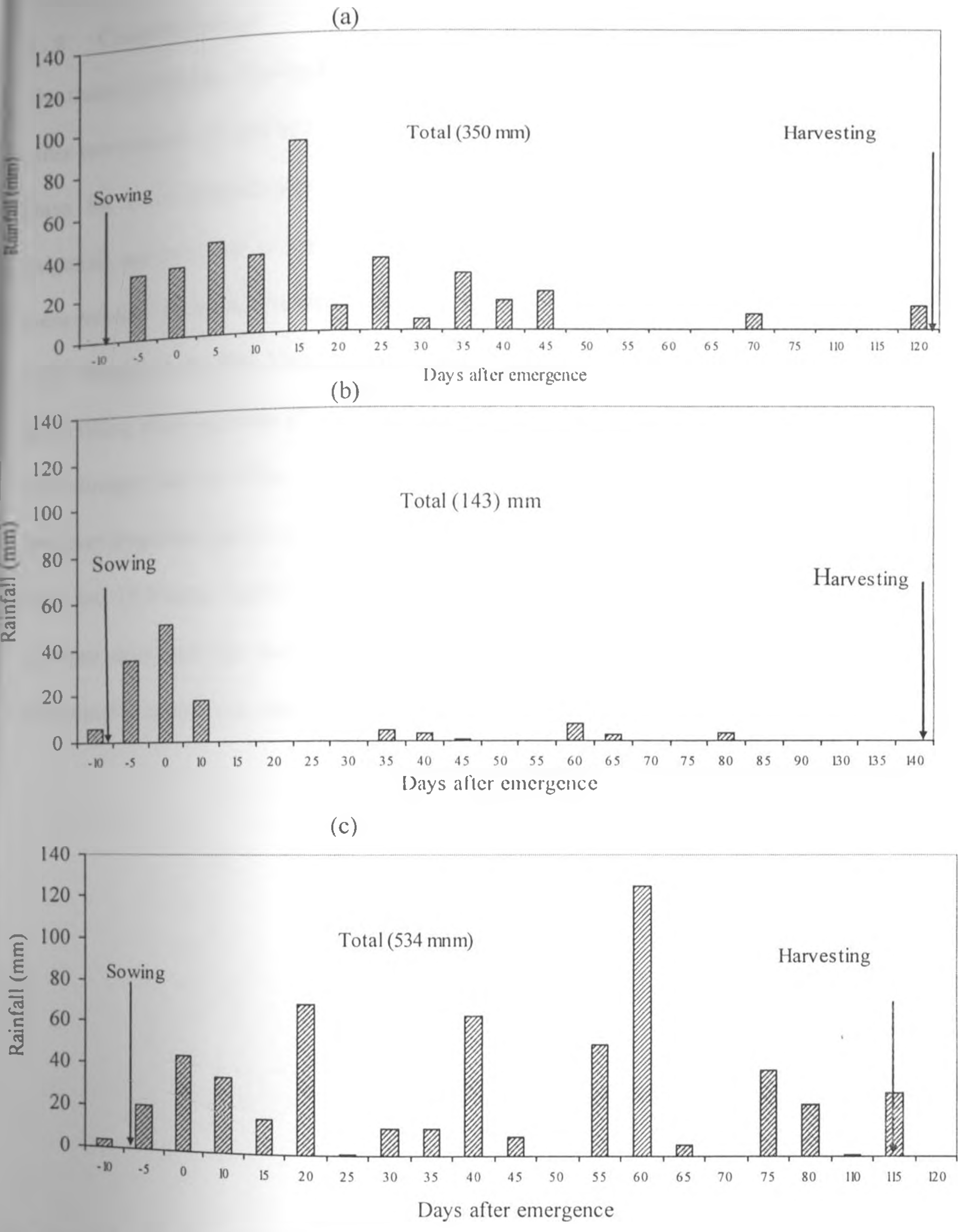


Figure 4.2. Rainfall distribution at Katumani (5 day totals), (a) SR1999, (b) LR2000 and (c) SR2000.

4.2 Crop Phenology

The maize in SR2000 flowered and matured earlier (46 and 100 days respectively) than the other two seasons (54 and 107 days for SR1999; 48 and 107 days for LR2000) (Table 4.1). Days for other phenological stages, degree days and cumulative applied (rainfed or irrigated) are indicated in the Table 4.1. Further information on growth phase durations were referred from experimental files by FURP 1988-1993. Establishment (I) (0 to 25 days after emergence (DAE), Vegetative (II) (26 to 42 DAE), flowering (III) (43 to 56 DAE), grain filling ripening phase (IV) (48 to 107 DAE depending on particular season). Irrigation and nitrogen had no effect on duration to tasseling and flowering in the three seasons, however irrigation significantly decreased the duration to 8th leaf stage in LR2000 (mean of 16.7 and 15.3 days, rainfed and irrigated treatments respectively, $LSD_{(0.05)}$ of 0.75) while nitrogen decreased the duration in SR2000 (Figure 4.3) but had no effect in the other seasons. No interactions were significant.

Table 4.1. Summary of crop phenology data for Katumani composite B maize, SR1999, LR2000 and SR2000 seasons at Katumani, Kenya.

Season	Crop stage	Duration[1]		Cumulative water applied (mm)		
		Days	°C days[2]	Rainfed	Applied water	Total Water applied
SR1999	Emergence	7	60	46	0	46
	8th leaf stage [3]	-	-	-	-	-
	Tasseling	44	439	336	149	485
	Flowering	54	538	346	184	530
	Physiological maturity	107	1127	350	405	755
	Harvest	120	1300	350	405	755
LR2000	Emergence	7	81	86	0	86
	8th leaf stage	16	189	122	81	203
	Tasseling	41	457	130	204	334
	Flowering	48	527	135	239	374
	Physiological maturity	107	1028	143	561	704
	Harvest	141	1329	143	561	704
SR2000	Emergence	7	79	109	0	109
	8th leaf stage	17	192	201	0	201
	Tasseling	39	416	332	14	346
	Flowering	46	490	407	19	426
	Physiological maturity	100	1072	534	84	618
	Harvest	115	1125	534	84	618

[1] *Days after emergence (DAE)*

[2] *Summation of daily mean temperatures less a daily base temperature of 9 °C*

[3] *This stage marks change from establishment phase to vegetative phase*

- data not available.

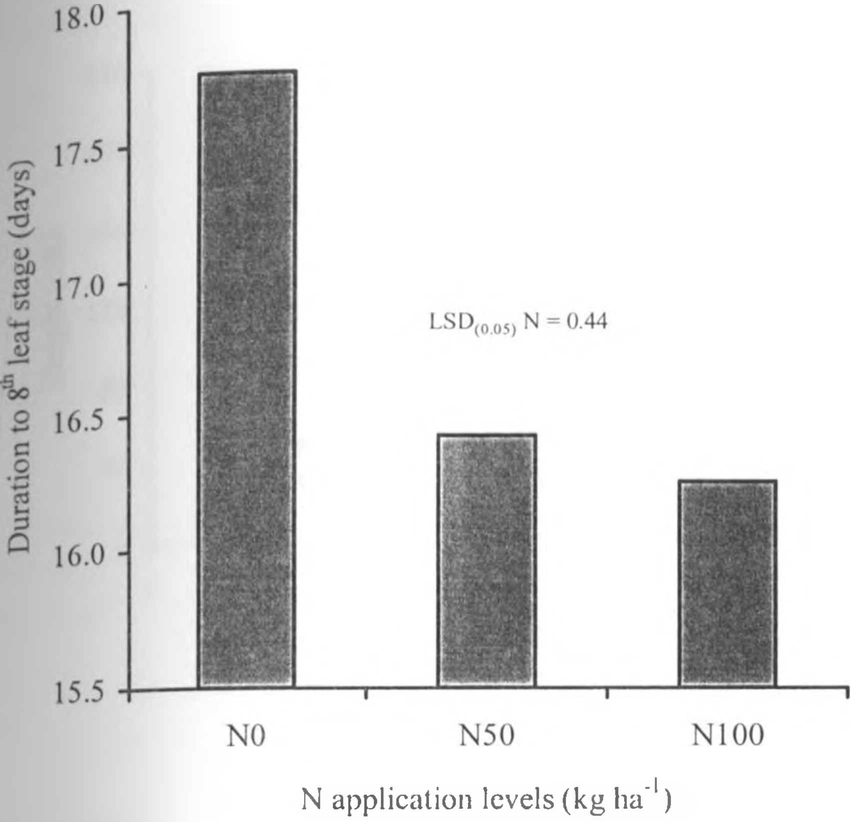


Figure 4.3. Duration to 8th leaf stage (days) for maize, under different N application levels, SR2000 at Katumani, Kenya. N0, N50 and N100 = N application levels of 0, 50 and 100 kg N ha^{-1}.

4.3 Maize growth

4.3.1 Maize height

Irrigation significantly increased maize height throughout the growing period in the dry season (LR200) (Figure 4.4 and Appendix 7) but had no effect on maize height in the wet seasons (SR1999 and SR2000).

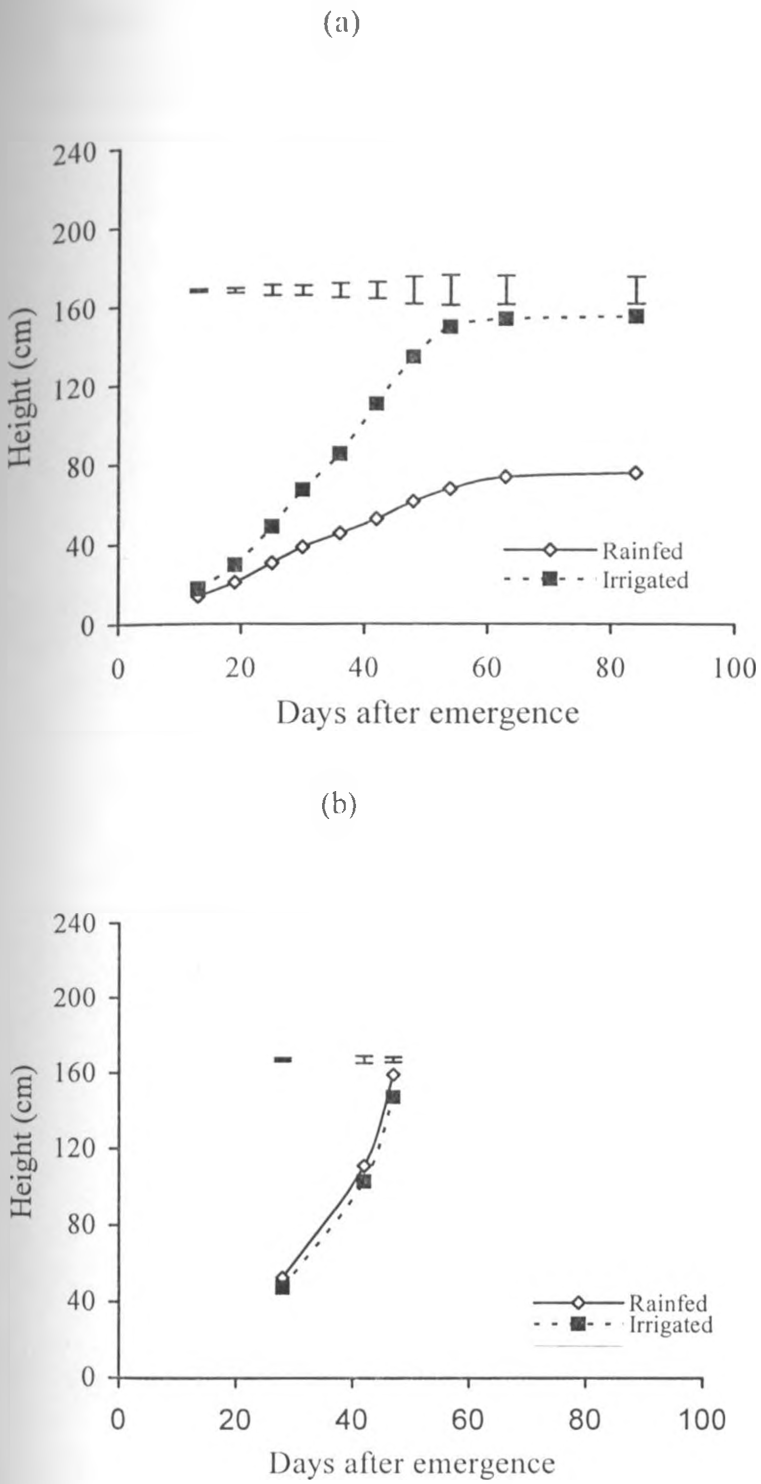


Figure 4.4. Maize height under different moisture regimes, (a) LR2000 and (b) SR2000, at Katumani, Kenya. (R, Ir)= rainfed and irrigated treatments.

However, there were few significant irrigation responses in maize height during mid vegetative (33 DAE) and flowering phase (42 and 47 DAE) in SR2000 (Figure 4.4 and Appendix 7).

The interaction of irrigation and N was significant on height in some periods during vegetative and flowering phases in LR2000 (25, 36 and 50 DAE) and in some periods during flowering and grain filling in SR2000 (DAE 53 and 65) (Table 4.2).

Table 4.2. Maize height under different moisture regimes and N application levels, LR2000 and SR2000, at Katumani, Kenya.

		LR2000			SR2000	
		DAE				
Water regime	N level (kg ha^{-1})	25	36	42	53	65
Rainfed	0	30.15	44.65	54.82	184.43	192.00
	50	31.88	47.32	53.80	187.10	189.22
	100	29.42	43.87	48.57	194.07	199.57
	Mean					
Irrigated	0	42.33	74.52	101.73	169.77	183.47
	50	51.97	89.63	111.25	189.17	196.22
	100	51.00	89.20	116.05	182.87	190.53
	Mean					
LSD$_{0.05}$ Ir		5.14	7.15	9.26	ns	ns
N		3.82	5.33	6.84	6.06	5.76
Ir x N		5.41	7.54	9.68	8.57	8.14

Data pooled for P

Nitrogen significantly increased maize height throughout the growing periods in SR1999 season and during establishment to vegetative phases in irrigated LR2000 season (Figures 4.5 and Appendix 7). In the wet SR2000 season nitrogen significantly increased maize height from establishment to early grain filling phase (16 to 65 DAE) (Figure 4.5 and Appendix 7). Overall the maize plants were tallest in the wettest season (SR2000).

Phosphorus significantly increased maize height from establishment to vegetative phase in the two wet seasons (Table 4.3 and Appendix 7).

Table 4.3. Maize height (cm) under different phosphorus application levels, SR1999 and SR2000 seasons at Katumani, Kenya.

Season	P level (kg ha^{-1})	DAE	
		23	28
SR1999	0	16.53	24.97
	25	19.45	27.66
	LSD$_{(0.005)}$	2.40	2.37
SR2000		16	28
	0	17.17	48.27
	25	18.45	51.74
	LSD$_{(0.005)}$	0.96	2.75

Values pooled for rainfed and irrigated treatments

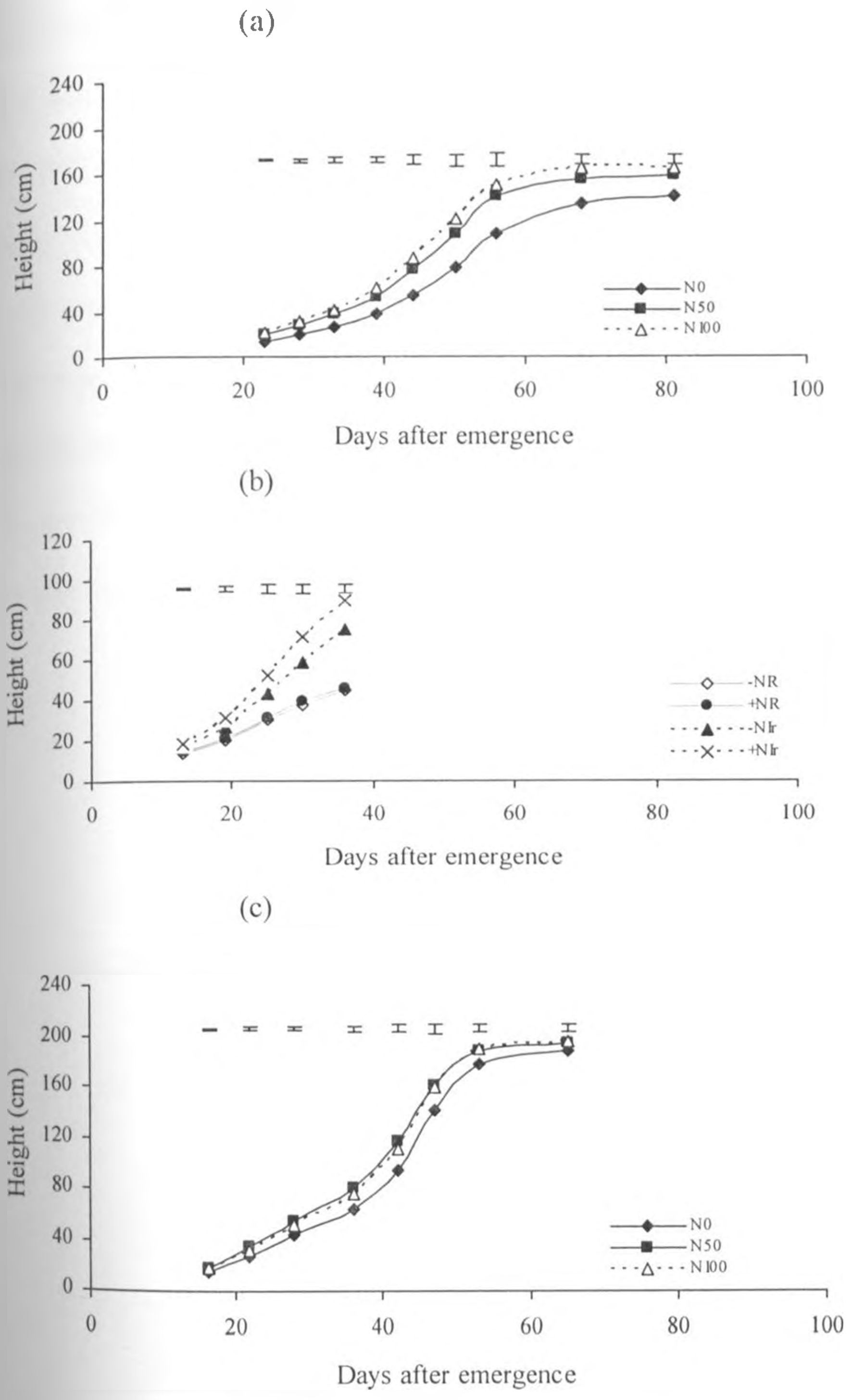


Figure 4.5. Maize height under different N application levels, SR1999, LR2000 and SR2000 at Katumani, Kenya. (N0, N50 and N100) = N application levels of 0, 50 and 100 kg N ha^{-1}. (-, +N) = without and with N application; (R, Ir)= rainfed and irrigated treatments. (NB. scale of b different from a and c).

4.3.2 Leaf area index

Phosphorus did not significantly affect LAI in the three seasons. Irrigation had no significant effect on LAI in the wet SR2000 and SR1999 (except at 75 DAE). Irrigation significantly increased leaf area index during the dry LR2000 season (Figure 4.6 b and Appendix 8) which was a dry season. In wet seasons all treatments were similar when both N and water were not limiting. Nitrogen significantly increased LAI in the wet seasons of SR1999 and SR2000 (Figure 4.6 a and c and Appendix 8) but did not affect LAI in the dry LR2000 season. Nitrogen application beyond 50 kg N ha^{-1} did not result in significant increase in LAI during SR1999 and SR2000 (Figure 4.6 b and c).

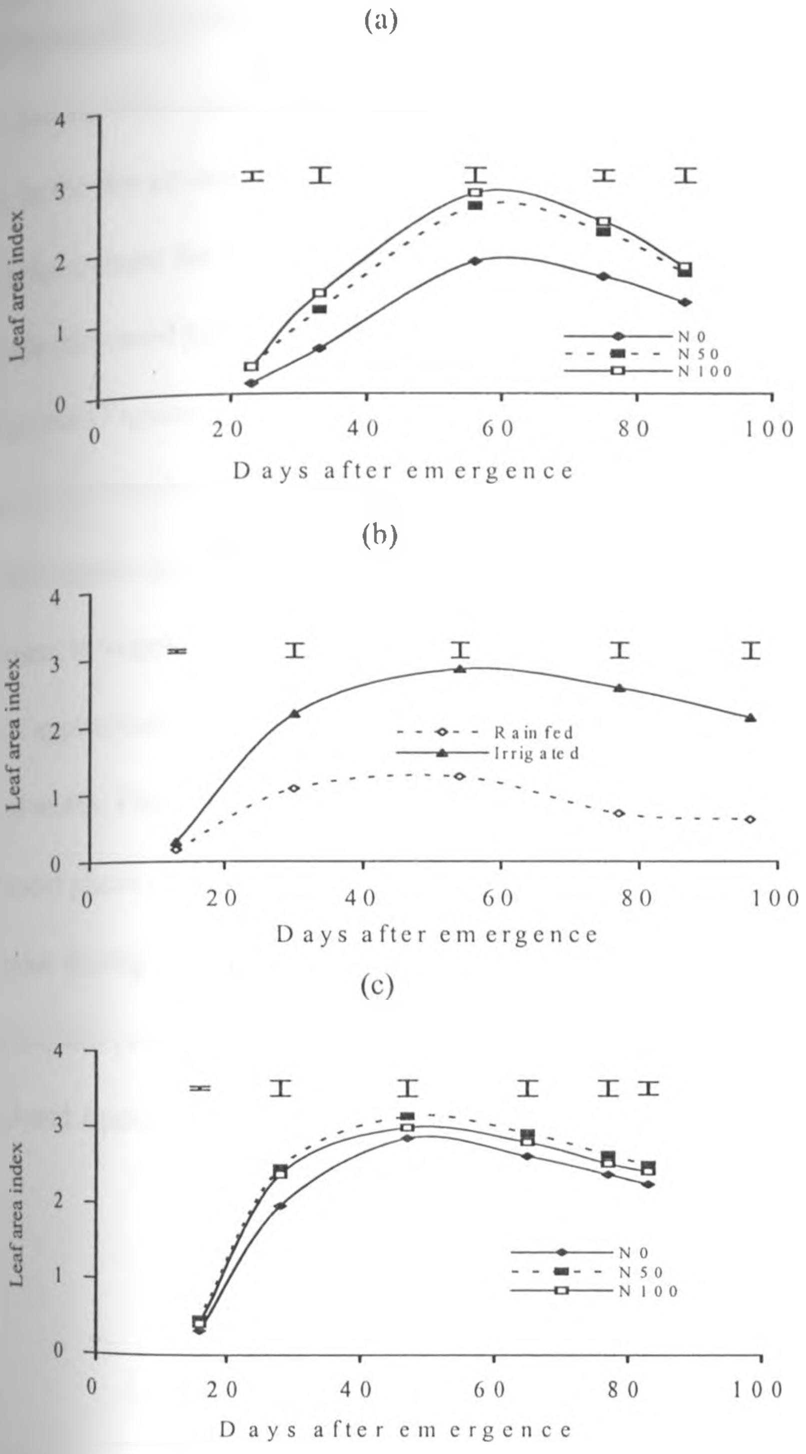


Figure 4.6. Maize leaf area index under different water and N application levels, (a) SR1999 (b) LR2000 and (c) SR2000 at Katumani, Kenya. R = rainfed, Ir = irrigated, (N0, N50, N100) = N application levels. Data pooled in LR2000.

.3 Leaf length and width

igation had no effect on leaf length and width in the wet seasons (SR1999 and R2000). In the dry season (LR200), irrigation significantly increased leaf length d width throughout the season (Figure 4.7 and Appendix 9 and 10). Nitrogen gnificantly increased leaf length and width throughout the growing periods in R1999 season (Figures 4.8, 4.9 and Appendix 9 and 10) and leaf width during tablishment to vegetative phases in irrigated LR2000 season (Figure 4.9). In the et SR2000 season nitrogen significantly increased leaf length and width from tablishment to vegetative phase (16 to 42 DAE) (Figure 4.8, 4.9 and Appendix 9 nd 10). N application above 50 kg ha^{-1} did not result in any further increases of leaf ngth and width. Phosphorus only significantly increased leaf length during stablishment phase (Table 4.4 and Appendix 9). Phosphorus increased leaf width in ome periods during vegetative phase (28 DAE) in SR1999, during establishment in rigated LR2000 (13 DAE) and between flowering and grain filling in SR2000 Table 4.4 and Appendix 10).

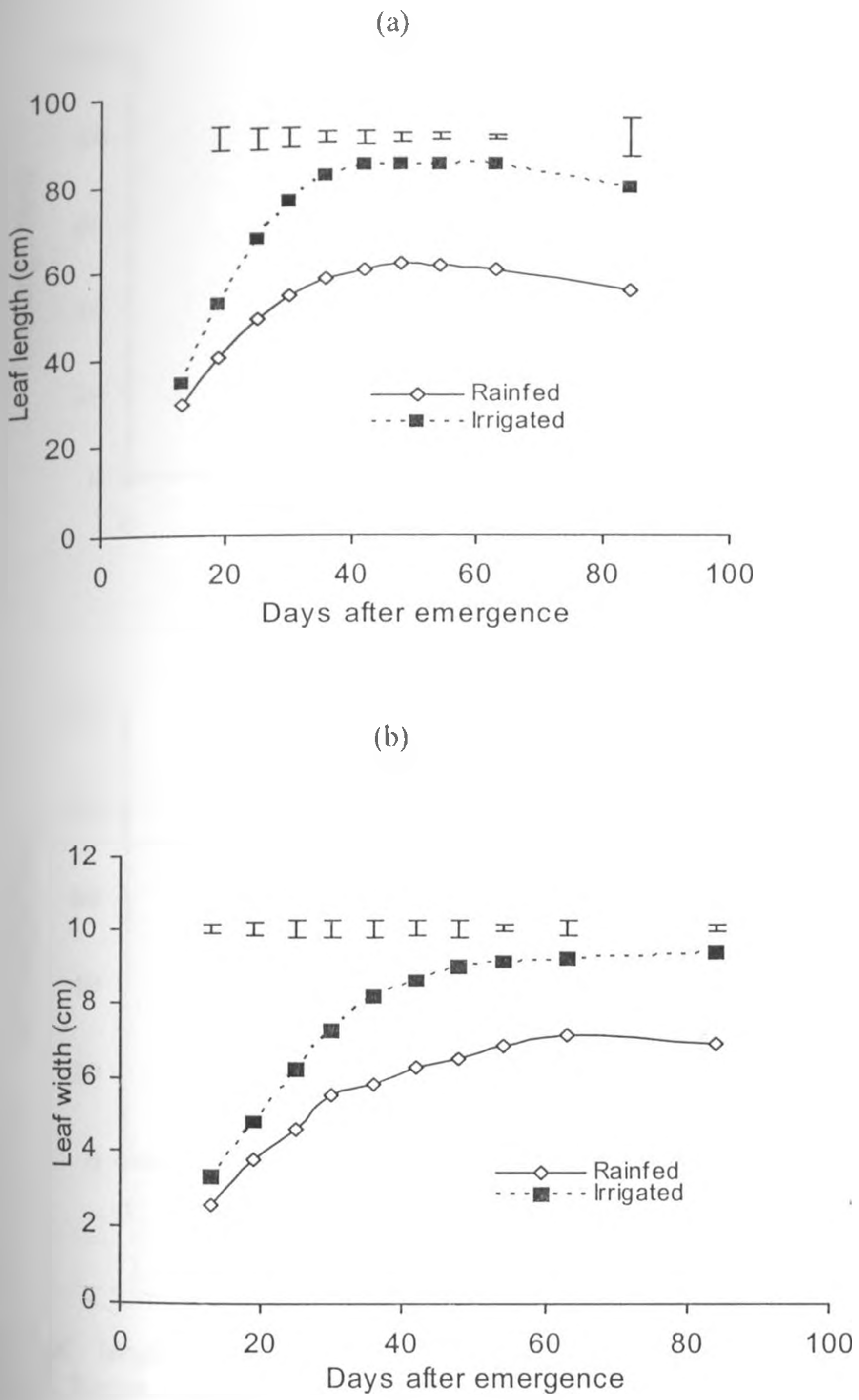
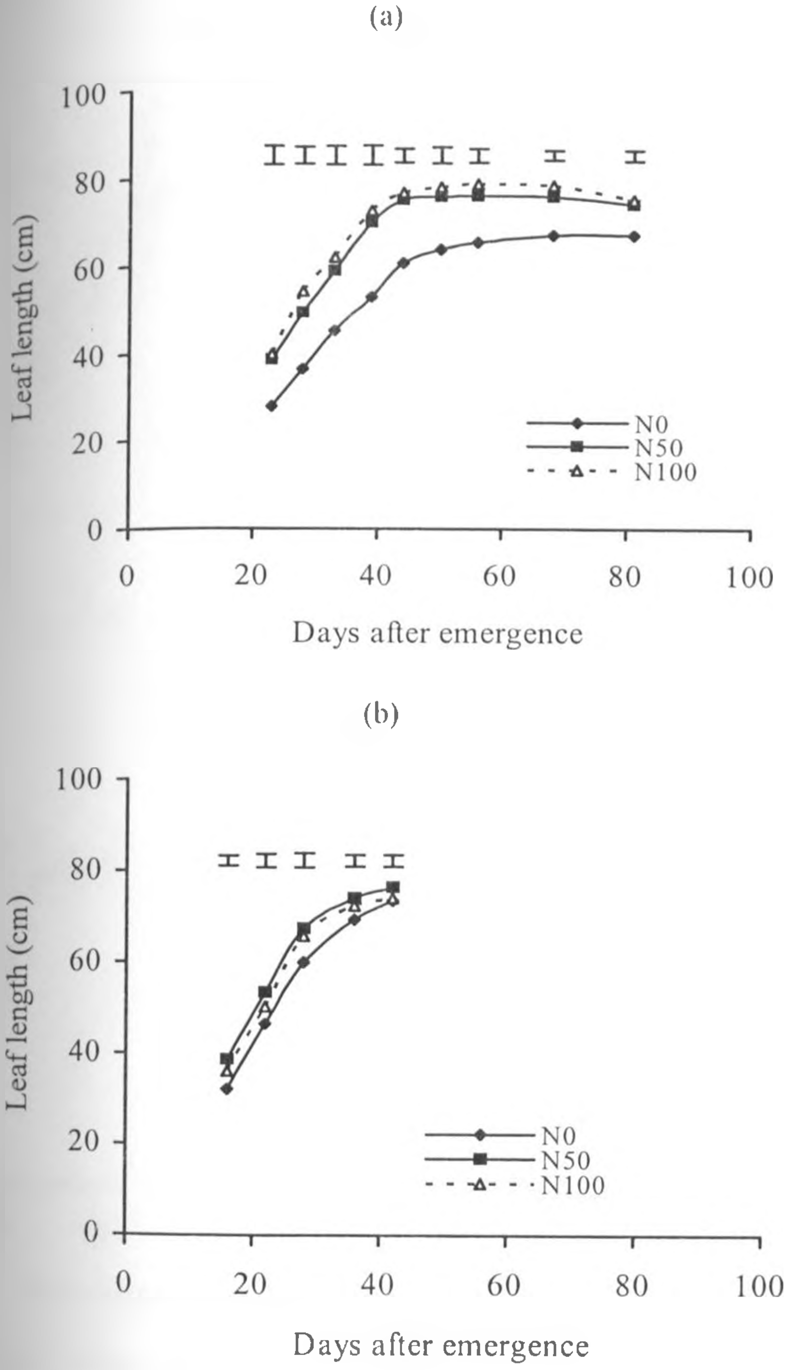
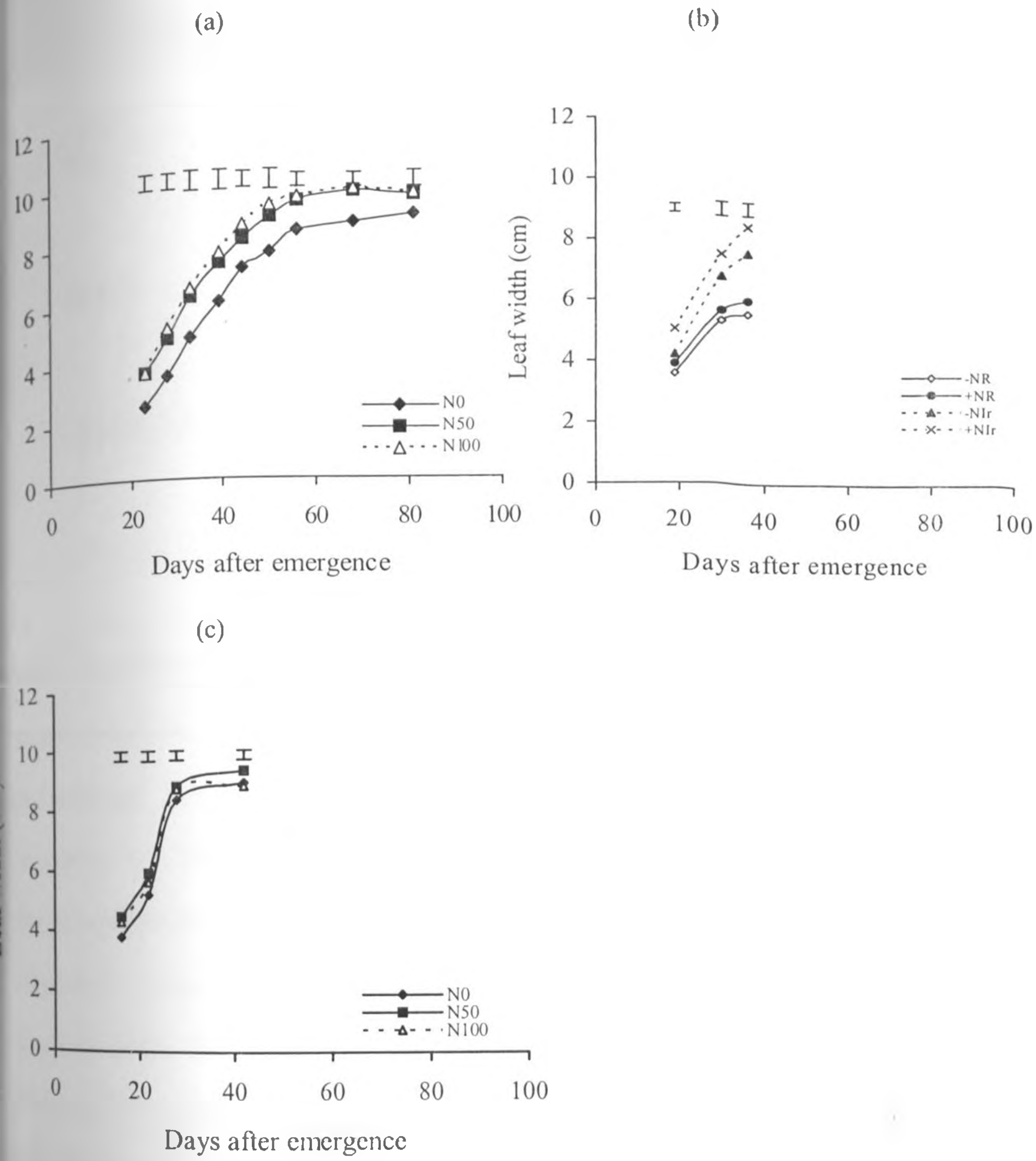


Figure 4.7. Maize leaf length and width under different moisture regimes, LR2000, at Katumani, Kenya.



igure 4.8 Maize leaf length under different N application levels, (a) SR1999 and (b) R2000 at Katumani, Kenya. (N0, N50 and N100) = N application levels at 0, 50 and 100 g N ha^{-1}.



igure 4.9. Maize leaf width under different N application levels, (a) SR1999, (b) LR2000 nd (c) SR2000 at Katumani, Kenya. (N0, N50 and N100) = N application levels of 0, 50 nd 100 kg N ha^{-1}. (-, +N) = without and with N application; (R, Ir)= rainfed and irrigated eatments.

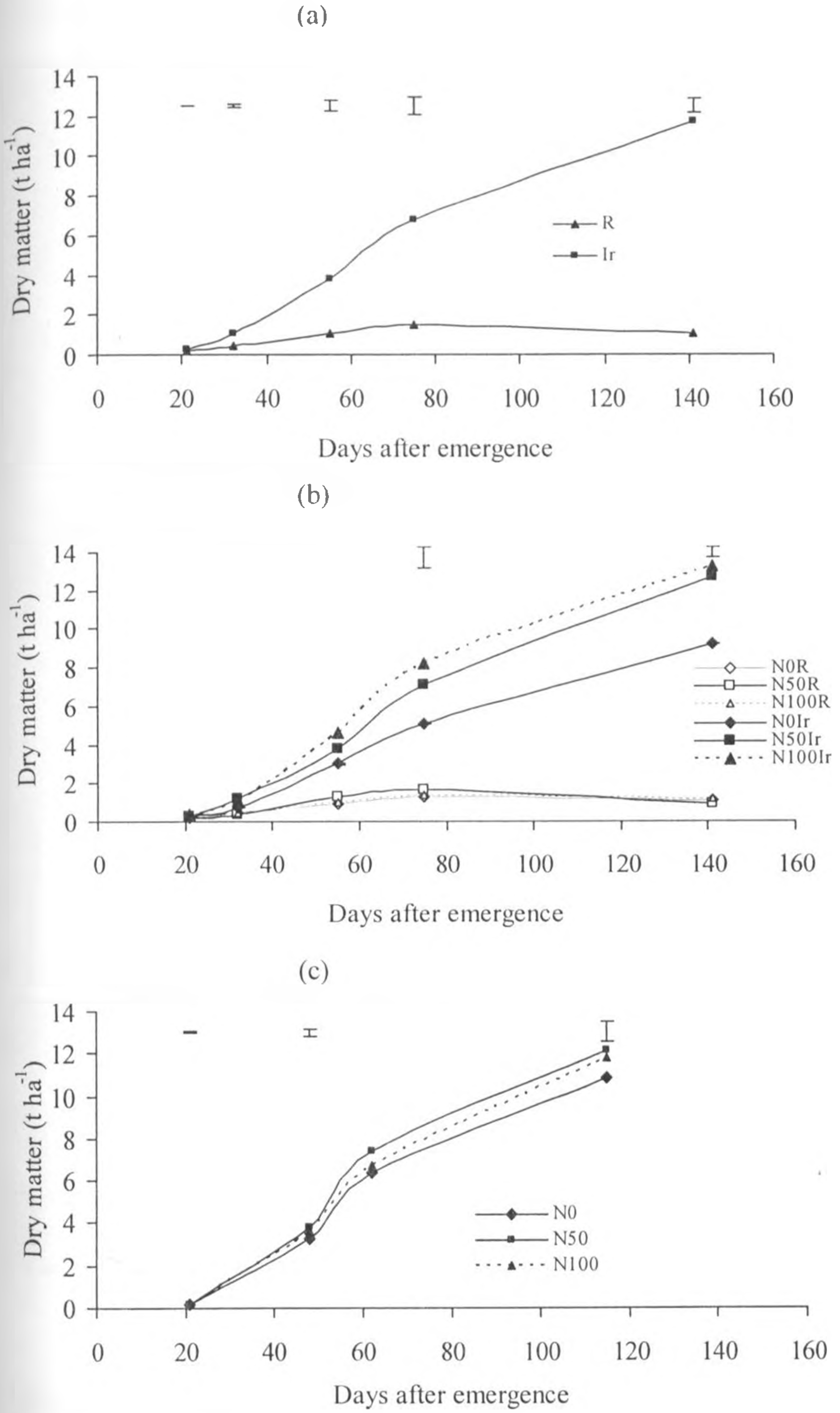
Table 4.4. Maize leaf length and width under different phosphorus application levels, SR1999, LR2000 and SR2000 seasons at Katumani, Kenya.

Season	P level (kg/ha)	DAE	Length (cm)	Width (cm)
SR1999	P0	28	44.19	4.15
	P25		49.06	4.64
	$LSD_{(0.05)}$ (P)		3.00	0.42
SR2000	P0	16	34.6	4.04
	P25		36.49	4.26
	$LSD_{(0.05)}$ (P)		1.88	ns
LR2000 (Ir)*	P0	13	31.62	3.10
	P25		31.93	3.50
	$LSD_{(0.05)}$ (P)		ns	0.199

4.3.4 Dry matter accumulation

Irrigation and nitrogen increased total dry matter (TDM) at harvest (120 DAE) in SR1999 but increased TDM significantly throughout the season in LR2000 (Figure 4.10 and Appendix 10). There was significant interaction between irrigation and N on TDM throughout the LR2000 season. In the rainfed treatments of LR2000 there was no fertilizer response but in the irrigated treatments, nitrogen had a significant effect on TDM at 32,75 and 141 DAEs. The TDM accumulated in the N_{50} and N_{100} were similar. In SR2000 irrigated and rainfed treatments accumulated similar amounts of dry matter. Dry matter initially increased slowly with N application (0 – 40 DAE) and then slightly higher thereafter (Figure 4.10). The maize attained the final total dry matter at a height of around 160 cm in irrigated LR2000 and at 195 cm in the wet SR2000 season (Figure 4.11). The curves suggest curvilinear relationships of TDM with height in both seasons. Equations elating TDM with height were derived using exponential type regressions (Figure 4.11).

rrigation significantly increased crop growth rate in LR2000 (Figure 4.12a). The rrigated treatments had constant linear crop growth rate (63 to 70 kg ha^{-1}day-1 or 6.3 to 7 g m^{-2}day^{-1}) throughout the season while rainfed treatments growth rate was linear (2 g m^{-2} day^{-1}) up to around 70 DAE after which the growth rate decreased rapidly to zero at 100 DAE when the crop dried up completely. Nitrogen significantly increased crop growth rate in SR2000. Figure 4.11c shows that the greatest growth rate occurred during the flowering phase (48 to 56 DAE) (about 25 g m^{-2} day^{-1} (Figure 4.11 b) after which the growth rate steeply decreased.



re 4.10. Dry matter accumulation of maize under different water regime and N application s, LR2000 (a) and (b), and SR2000 (c) at Katumani, Kenya. Bars in b indicate N effect (N0, N100) = fertilizer application levels, Bars only shown where significant diffences are, R = fed, Ir = irrigated.

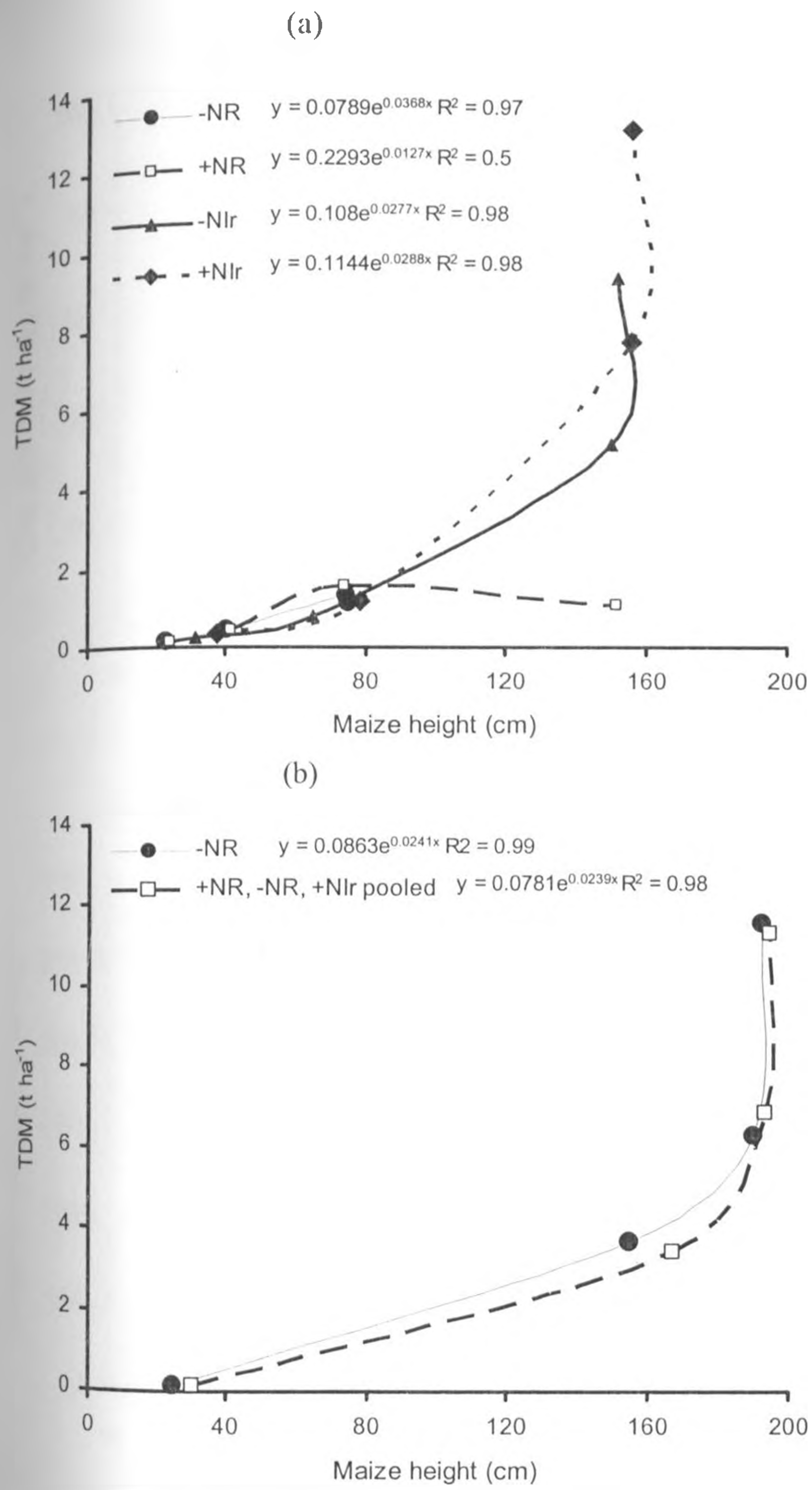


Figure 4.11. Maize total dry matter (TDM) verses maize height under rainfed and irrigated water regimes and with N (+N) or without N (-N) application, LR2000 (a) and SR2000 (b) grown at Katumani, Kenya. (Equations derived using exponential type regressions).

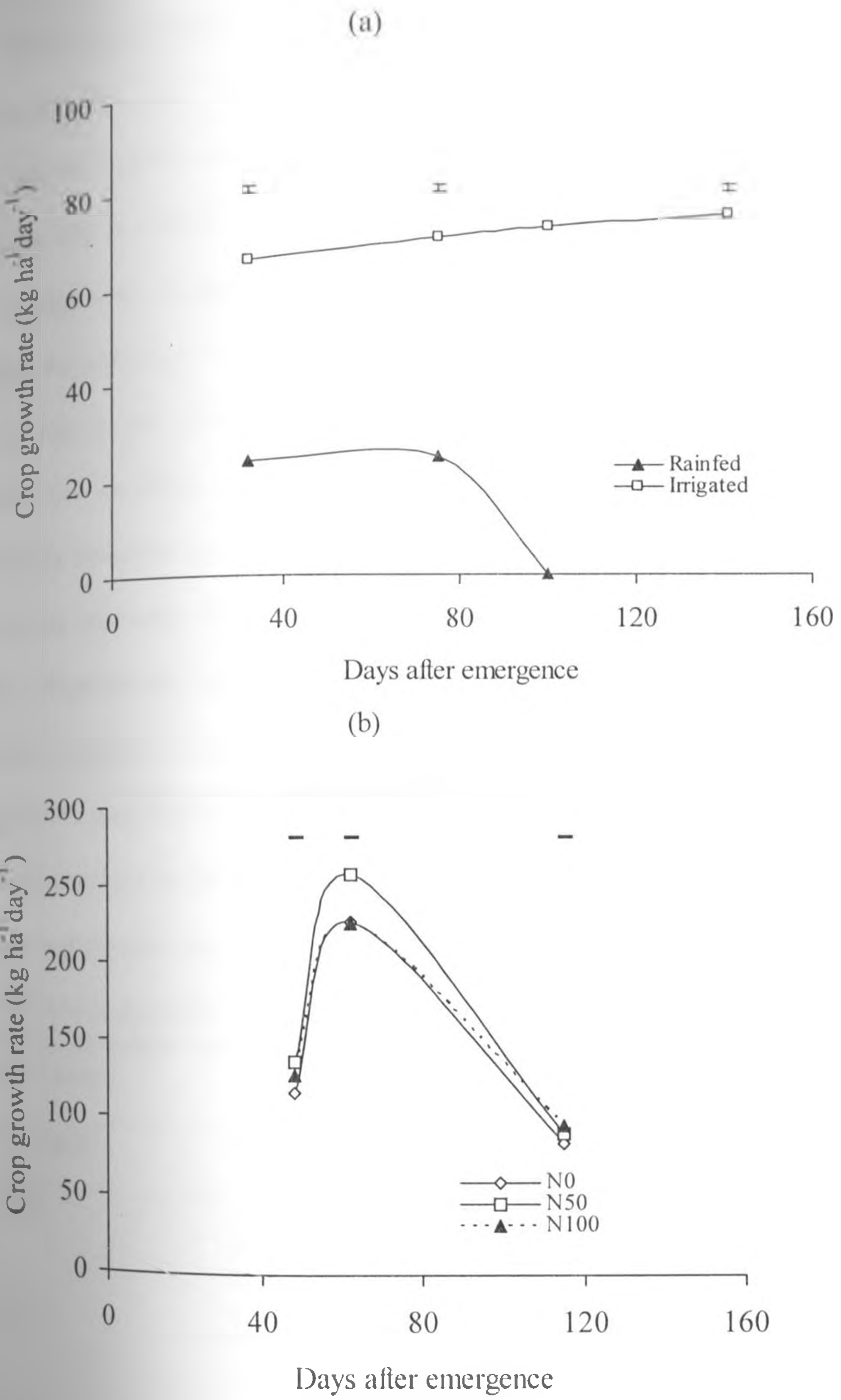


Figure 4.12. Maize crop growth rate (kg ha^{-1} day^{-1}) (a) LR2000 and (b) SR2000 at Katumani, Kenya.

4.3.5 Dry matter partitioning to various maize organs

Phosphorus had no effect on dry matter partitioning in all the seasons (Appendix 12). The interaction of irrigation and N in LR2000 was significant on dry matter partitioning (Appendix 12). In LR2000 irrigated treatment nitrogen application had no effect on dry matter partitioning throughout the season. In rainfed LR2000 nitrogen significantly increased the proportion of dry matter partitioned into leaves and significantly decreased the proportion of dry matter partitioned into storage organs (grain + cobs) (Table 4.5). Irrigation had no effect on dry matter partitioning in the establishment phase but it significantly decreased the proportion of dry matter partitioned into leaves by 7, 30 and 50 % during vegetative, flowering and grain filling-ripening phases respectively (Figure 4.13 a) Irrigation also significantly increased the proportion of dry matter partitioned to the stems during the vegetative and flowering phases (32 DAE to 55 DAE) by on average 36 % and significantly decreased the proportion to 61 % by harvest time (141 DAE) (Figure 4.13 b). Stems in this case refer to all maize dry matter left after removal of leaves and storage organs (grains and cobs).

Table 4.5. Maize dry matter partitioning between leaves and storage organs (grain + cobs) at harvest under rainfed and irrigated conditions and different N levels, LR2000, at Katumani, Kenya.

Water regime	N level (kg ha^{-1})	Dry matter partitioning	
		Leaves	Storage organs
Rainfed	0	0.368	0.248
	50	0.472	0.138
	100	0.425	0.152
Irrigated	0	0.205	0.487
	50	0.187	0.535
	100	0.183	0.523
LSD (Ir x N)		0.05	0.07

The decreases in the proportion of dry matter partitioned into leaves and stems resulted in irrigation significantly increasing the proportion of dry matter partitioned to the reproductive organs (storage organs) during flowering and grain filling-ripening phases (Figure 4.13 c and Appendix 12). In LR2000 irrigated treatment the cobs constituted a mean of 39.8 % and 14 % of the storage organs at 75 DAE and at harvest (141 DAE) respectively compared to 40 % and 24.4 % respectively under rainfed conditions.

All treatments (irrigation, nitrogen and phosphorus) had no effect on dry matter partitioning during SR2000 so the data was pooled for all factors (Figure 4.13 d and Appendix 6). On average about 16 % more dry matter was partitioned to grain (0.524) in SR2000 compared to irrigated treatments in LR2000 (0.442) however the dry matter partitioning were not significantly different between the two seasons (Figure 4.13). For both rainfed and irrigated conditions during SR2000, the cobs constituted a mean of 58.3 % and 13.8 % of the storage organs in 62 DAE and at harvest (115 DAE) respectively.

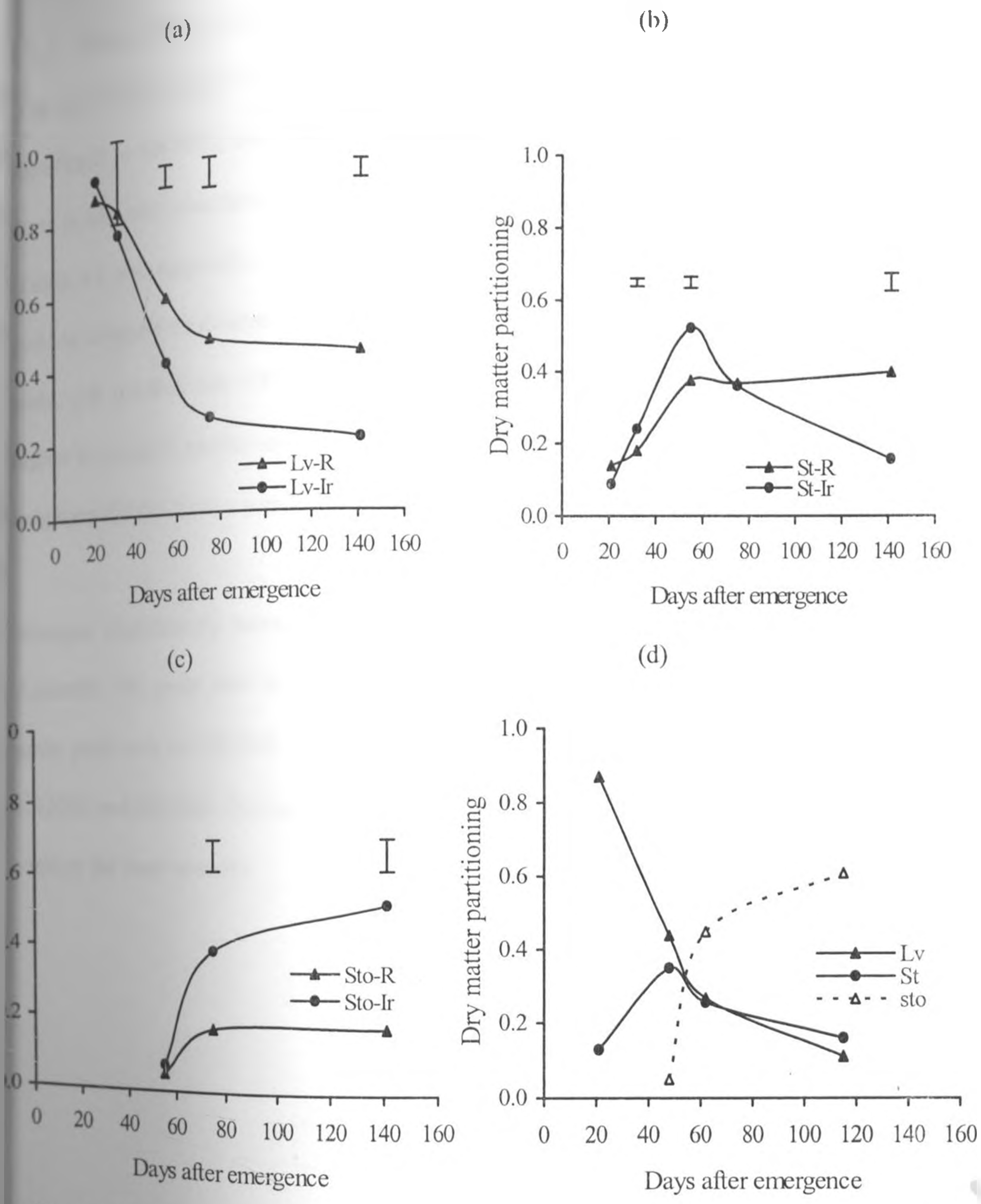


Figure 4.13. Mean dry matter partitioning coefficients of maize under irrigated and rainfed conditions LR2000 (a, b and c) and mean for both irrigated and rainfed conditions SR2000 (d) at Katumani, Kenya. (Lv = leaves, R = rainfed, Ir = irrigated, St = stems, Sto = storage organs (maize grain + cobs).

3.6 Maize grain yield and yield components

The interaction between irrigation and N on maize yield and yield components was not ignificant in SR1999, but it had a positive significant effect on grain yield and 100 seed mass in irrigated treatments of LR2000 and on grain yield in irrigated treatments of SR2000 Table 4.6 and Appendix 13). Irrigation x P also had a positive significant effect on grain yield in irrigated treatments of LR2000 (Appendix 13). In SR1999 and LR2000 maize grain yield, cob number and 100 seed mass and also cob length in LR2000 were significantly higher in irrigated treatments compared to rainfed treatments (Table 4.6 and Appendix 13). Irrigation did not have a significant effect in SR2000.

Nitrogen significantly increased grain yield and cob length in SR1999 (Table 4.6 and Appendix 13), grain yield in SR2000, 100 seed mass in irrigated treatments of LR2000 and grain yield only in SR2000. Nitrogen had no effect on grain yield in rainfed treatments in LR2000 and SR2000. Nitrogen application beyond 50 kg ha^{-1} did not result in higher grain yield in the three seasons.

Table 4.6. Grain yield and yield components of maize under different water regimes and N application rates SR1999, LR2000 and SR2000, at Katumani, Kenya.

Season/ LSD	Water regime	N Level (kg ha^{-1})	Grain yield (kg ha^{-1})	Cob length (cm)	Cob number m^{-2}	100 seed mass (g)
SR1999	Rainfed	0	1,447	9.9	3.4	26.3
		50	2,643	13.2	3.9	27.5
		100	2,450	15.2	3.2	28.7
		Mean	2,180	12.8	3.5	27.5
	Irrigated	0	3,897	12.8	4.9	38.4
		50	5,290	14.8	5.4	39.0
		100	5,501	15.2	5.4	38.0
		Mean	4,896	14.3	5.2	38.5
LSD$_{0.05}$	Ir		490	ns	0.51	3.2
	N		621	1.13	ns	ns
	Ir x N		ns	ns	ns	ns
LR2000	Rainfed	0	228	7.2	2.6	21.7
		50	96	7.1	2.0	17.7
		100	130	6.7	3.2	21.0
		Mean	151	7.0	2.6	20.1
	Irrigated	0	3,734	13.9	5.2	30.4
		50	5,899	14.7	5.4	34.2
		100	5,958	15.4	5.5	32.7
		Mean	5,197	14.7	5.4	32.4
LSD$_{0.05}$	Ir		232	1.1	0.29	0.78
	N		241	ns	ns	ns
	Ir x N		341	ns	ns	2.26
SR2000	Rainfed	0	6,157	16.6	4.9	36.8
		50	6,015	17.0	5.0	35.0
		100	6,038	16.8	5.2	34.5
		Mean	6,070	16.8	5.0	35.4
	Irrigated	0	5,215	15.7	4.5	36.0
		50	6,372	16.7	5.1	37.0
		100	6,362	16.8	4.8	38.3
		Mean	5,983	16.4	4.8	37.1
LSD$_{0.05}$	Ir		Ns	ns	ns	ns
	N		462	ns	ns	ns
	Ir x N		653	ns	ns	ns

Data pooled for P

4.4 Discussion

4.4.1 Climate

In SR1999 water deficit in rainfed treatments occurred at the critical grain filling phase (Figure 4.14). Water stress during the reproductive phase can reduce grain yield by up to 50 % (Mengel and Kirkby, 1982; Saka, 1985). In LR2000 water deficit in rainfed treatments occurred from vegetative phase to the end of the season (Figure 4.14). The low rainfall during vegetative phase was compensated by high rainfall in the establishment phase in SR2000 (Figure 4.14).

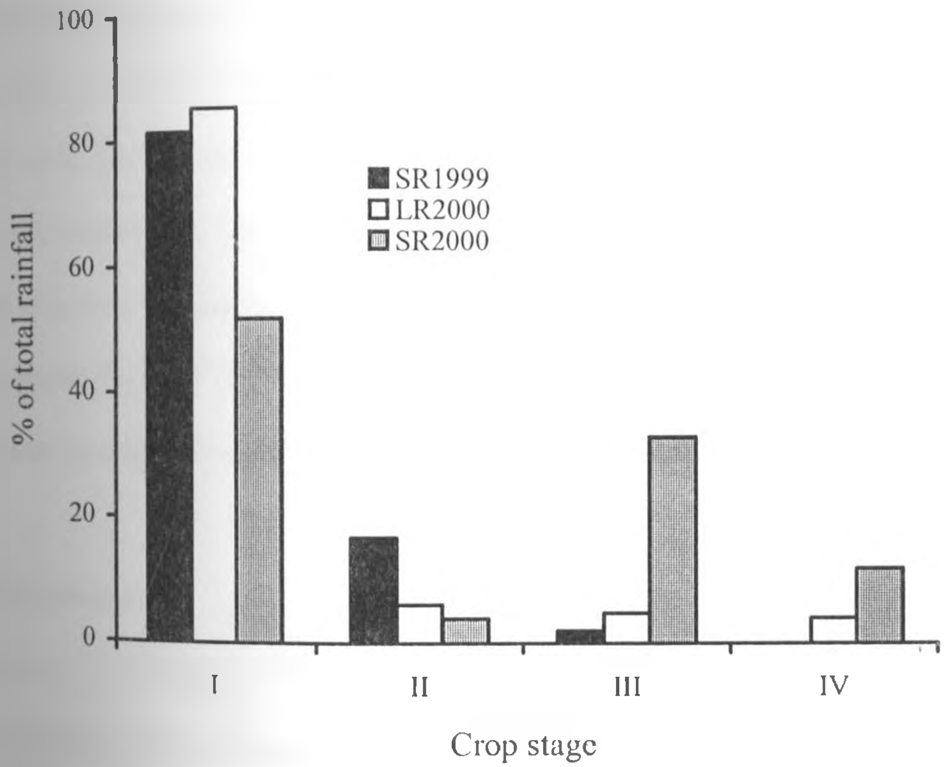


Figure 4.14. Percent rainfall distribution, SR1999, LR2000 and SR2000 seasons at Katumani, Kenya.

Higher and better rainfall distribution combined with higher mean temperatures in SR2000 compared to LR2000 (Figure 4.1 and Figure 4.2) resulted in higher growth rate in SR2000 (Figure 4.12) compared to LR2000. Flowering occured at DAE 46 and physiological maturity at DAE 100 compared to DAE 48 and 107 respectively for LR2000 (Table 4.2).

4.4.2 Crop Phenology

Under dry conditions in LR2000, nitrogen was not fully utilized resulting in lack of N response on 8th leaf stage. The lack of irrigation and nitrogen response on duration to tasseling and flowering is not clear. Both water and N stress have been found to lengthen the time from emergence to tasseling and silking (Bennet *et al*, 1989). The degree days to flowering were 538, 527 and 490 degree days for SR1999, LR2000 and SR2000 respectively while the total accumulated degree days to physiological maturity were 1127, 1028 and 1072 respectively. The lower degree days in SR2000 can be attributed to faster growth rate (Figure 4.13) due to higher and better distributed rainfall compared with the other two seasons (Figure 4.2). Temperature in SR1999 and SR2000 were comparable but the former had less rainfall hence growth and development was water limited.

4.4.3 Leaf area index

Leaf area index is a function of leaf growth and the later is sensitive to water supply (Mengel and Kirkby, 1982). Irrigation increased leaf length and width in the dry season of LR2000 while N increased them in the two wet seasons (SR1999 and SR2000) and under irrigation in LR2000 (Figure 4.7, 4.8 and 4.9). Similar to leaf length and

Higher and better rainfall distribution combined with higher mean temperatures in SR2000 compared to LR2000 (Figure 4.1 and Figure 4.2) resulted in higher growth rate in SR2000 (Figure 4.12) compared to LR2000. Flowering occured at DAE 46 and physiological maturity at DAE 100 compared to DAE 48 and 107 respectively for LR2000 (Table 4.2).

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Leaf area index is also increased by N supply (Novoa and Loomis, 1981; Muchow, 1994; Sergio and Andrade, 1995). The applied N in LR2000 rainfed treatments was not fully utilized due to insufficient rainfall possibly because of water limitation effect on uptake (Novoa and Loomis, 1981) hence N effect on LAI was not observed. The maximum LAI attained in the three seasons (2.8 in SR1999 and LR2000 and 3.1 in SR2000) was similar to that obtained by Hunter *et al.* (1970) for short duration maize varieties. The highest average number of leaves per plant (12 - 13), leaf length (68 – 84 cm) and leaf width (9.4 - 9.9 cm) restricted the maximum LAI attained. This may be attributed to the fact that Katumani maize is both short duration and fast maturing variety.

4.4.4 Leaf length, width and height expansion

Irrigation significantly increased length, width and maize height in the dry season while N significantly increased them in the two wet seasons and under irrigation in LR2000. Since LAI is a function of leaf length, width and number of leaves per plant and height depends on vegetative growth, the explanation for the irrigation and N responses on LAI also apply here. Similar irrigation and N effects on leaf expansion and maize height have been reported by various authors, "In an experiment with irrigation and various fertilizer N rates, irrigation increased maize plant height (Boquet *et al.*, 1987) while soil water stress during vegetative development reduced expansive growth of leaves and stems resulting in reduced maize height (Bennett, 1990)".

Nitrogen supply affects leaf area development and leaf senescence (Eik and Hanway, 1965; Lemcoff and Loomis, 1986; Muchow, 1994). Low soil N in rainfed LR2000 significantly reduced maize leaf area as a result of reduced leaf size Bennet *et al*. (1989) observed similar effects with maize.

Phosphorus had a significant effect on length, width and height between establishment and vegetative phases in all the seasons (Table 4.4). This may be possibly due to the fact that phosphorus is required by plant for proper root/shoot growth (Mengel and Kirkby, 1982).

4.4.5 Maize dry matter accumulation, partitioning and grain yield

Total dry matter (TDM) and grain yield were approximately two times higher in irrigated compared with rainfed treatments during SR1999 and 10.8 and 34.4 times higher respectively during LR2000. The higher values in LR2000 can be attributed to improved growth with irrigation because the rainfall was low and also to improved N uptake with supplementary irrigation. Lack of irrigation response on TDM and grain yield in SR2000 can be attributed to similar N uptake in rainfed and irrigated treatments as a result of the higher rainfall received in this season (Table 6.2). The effect of irrigation on grain yield in LR2000 was higher than in SR1999 (Table 4.6). This could have been due to higher soil evaporation rates in SR1999 because of higher solar radiation (Figure 4.1) compared to LR2000 resulting in lower net maize water uptake in irrigated SR1999 compared to irrigated LR2000. The lower irrigated grain yield in the nil treatment of SR2000 compared to the nil rainfed grain yield may have been due to nutrient leaching under irrigation.

Total dry matter and grain yield responded to N application only when water was not limiting in SR1999, SR2000 and in irrigated treatments of SR1999 and LR2000 but they were depressed by N application in rainfed LR2000. Similarly the grain size and cob length were depressed by N application in rainfed LR2000. The depression can be explained by lower N uptake under fertilized conditions in rainfed LR2000. Higher fertilizer application in conditions of limited water supply induces lower water potential in the immediate neighborhood of the roots compared to low fertilizer application thereby causing a lower net flow of water into the roots of the high fertilized crop (Van Keulen, 1981). The absence of maize growth and yield response above 50 kg N ha $^{-1}$ was similar to that reported by Nadar and Faught (1984) and FURP, (1990). Since the total water application levels were high (618 – 755 mm) in all seasons, the observed lack of N response at N application of 100 kg ha^{-1} may indicate that maize N demand was met at 50 kg N ha^{-1}.

Higher grain yield in irrigated treatments may be explained by increase in LAI and PAR interception and that the canopy remained photosythetically active for longer period compared to rainfed treatments. Irrigation increased the leaf area duration by 16 days and 10 days in SR1999 and LR2000 respectively compared to rainfed treatments. Increased leaf area duration and higher LAI increased cumulative seasonal solar radiation intercepted by the irrigated treatments (Figure 5.4 a), lengthened photosynthesis period (during the reproductive phase) and hence N uptake resulting in higher seed mass, larger cobs, more cobs m^{-2}, higher total dry matter and higher grain yield (Table 4.6). All yield components (cob length, cob number and grain size) were greatly reduced by water stress. Crop growth rate of between 22.9 to 32.5 g m^{-2} day^{-1} for high yielding corn (14 t ha^{-1}) have been reported (Bennett, 1990). It was only in SR2000 when crop growth rate approached this values (25 g m^{-2} day^{-1}). This may be explained by the fact that Katumani maize is a short duration, low yielding variety maize therefore its photosynthetic capacity is also lower compared to the high yielding varieties.

Irrigation decreased the proportion of dry matter partitioned to leaves and stems and increased the proportion partitioned to the reproductive organs (Figure 4.13 a, b and c). Under water stress, application of nitrogenous fertilizers lead to vegetative growth (Figure 4.13 a) early use of available moisture, and hence to water shortage in the most economically important part of the life cycle (Figure 4.13 c) (van Keulen, 1981). With irrigation this negative aspect may have been reversed.

CHAPTER 5

CANOPY RADIATION INTERCEPTION AND USE

5.1 Fractional PAR interception

Phosphorus had no effect on fractional PAR interception (f) in the three seasons probably because of high P levels in the soil (Appendix 2). Irrigation significantly increased PAR interception in the dry season (LR2000) (Figure 5.1 b and Appendix 14). Nitrogen effect was positive and significant when water supply was not limiting during SR1999 (Figure 5.1 a) but in the wettest season (SR2000) all treatments were similar. Application of N beyond 50 kg N ha^{-1} did not result in higher fractional PAR interception in the three seasons. The highest PAR interception (74 and 71 %) were attained in SR2000 and LR2000 irrigated treatments with N application of 100 kg N ha^{-1} while 57 % was attained in SR1999. A plot of leaf area index verses % PAR interception gave a linear relationship with LAI = 0.0439 * % PAR interception and R^2 of 0.94 (Figure 5.2) while a plot of ln(1-f) verses LAI gave equations with k (extinction coefficient) ranging from 0.30 to 0.37 (Figure 5.3). N did not significantly influence the slope so data was pooled.

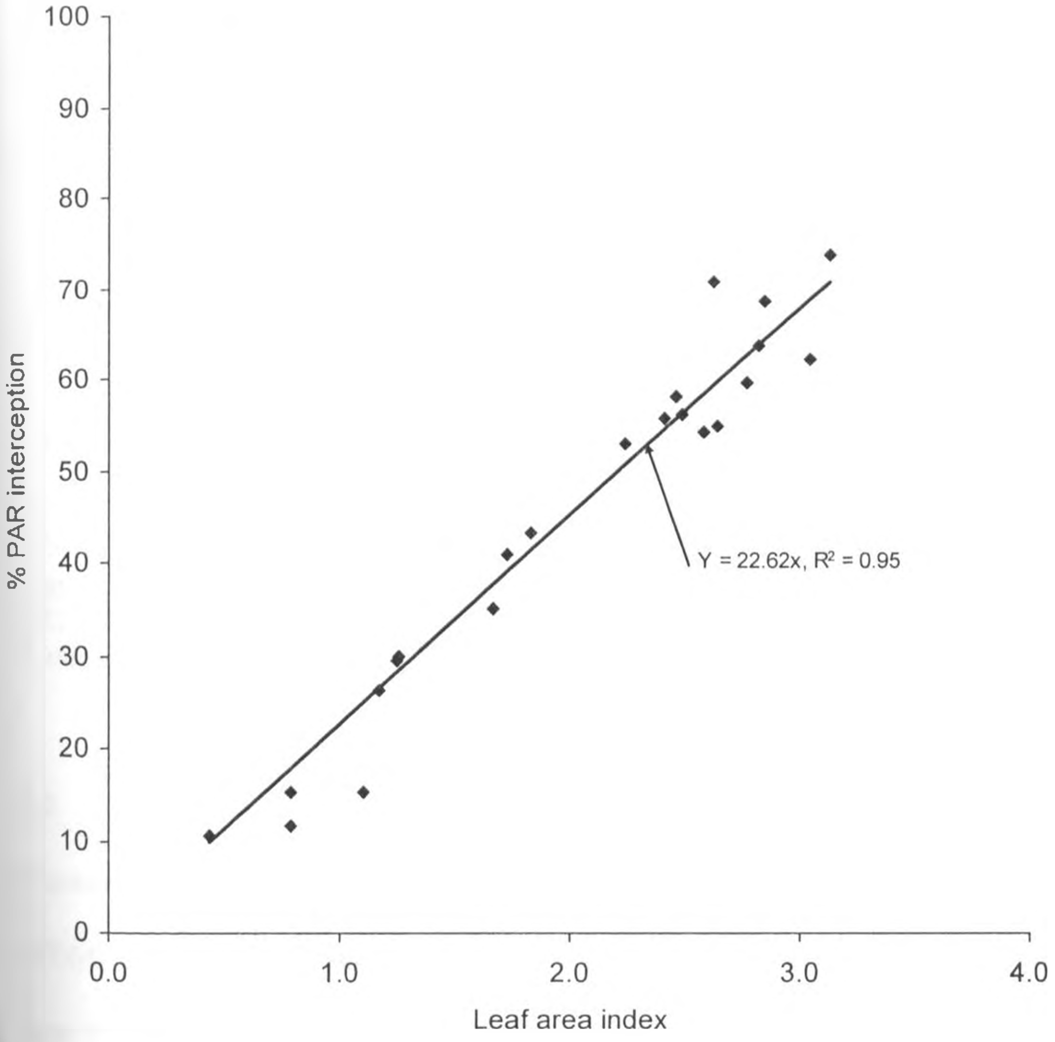


Figure 5.2 Percent PAR interception verses Leaf area index , all data pooled for SR1999, LR2000 and SR2000 at Katumani, Kenya.

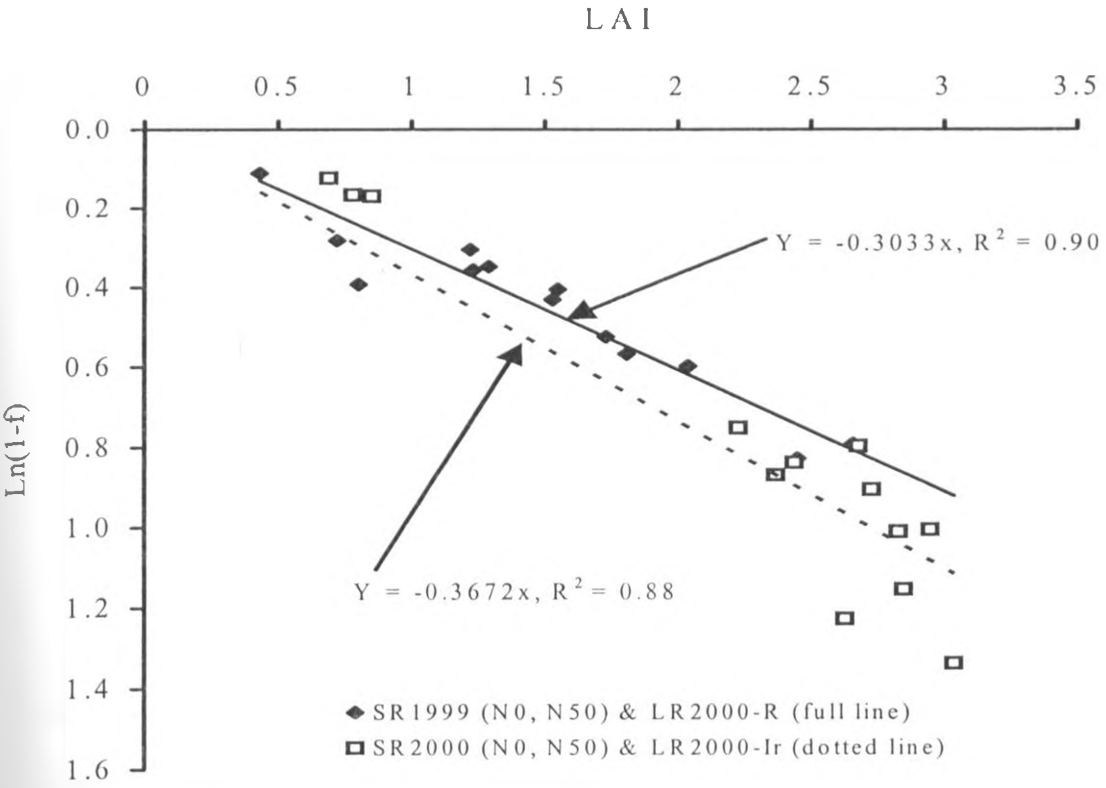


Figure 5.3. Natural log of fraction of transmitted PAR (ln(1-f)) and leaf area index (LAI), SR1999 pooled with LR2000 rainfed and SR2000 pooled with LR2000 irrigated, at Katumani, Kenya, f = fraction of intercepted PAR (range 0 to 1).

5.2 Cumulative PAR interception

Cumulative PAR interception was calculated in order to relate to dry matter accumulation (TDM) with time and hence derive the light use efficiency. For short rains 1999, TDM over time data were not available hence there was no need of working out cumulative PAR interception for SR1999. Nitrogen and phosphorus individually or collectively did not affect cumulative PAR interception in LR2000. Irrigation significantly increased cumulative PAR interception throughout the dry season (LR2000) (Figure 5.4 a and Appendix 15 a and b). There was a significant positive interaction of irrigation and nitrogen in SR2000 (Appendix 15). Irrigation effect on cumulative PAR interception was limited in SR2000 (21 DAE and 62 DAE only) (Figure 5.4 b and Appendix 15). The total mean seasonal cumulative PAR interception under rainfed conditions was 2.8 times higher in SR2000 (591 MJ m^{-2}) compared to LR2000 (210 MJ m^{-2}) and 1.2 times higher under irrigated conditions (560 MJ m^{-2} verses 448 MJ m^{-2} respectively). Nitrogen significantly increased cumulative PAR interception in the irrigated treatments in SR2000 (Figure 5.4 c and Appendix 15) but N application above 50 kg N ha^{-1} resulted in no further increase in cumulative PAR interception. Regression of dry matter against cumulative PAR interception resulted in linear relationships with light use efficiencies (RUE) of 2.45 and 2.23 g MJ^{-1} under good moisture conditions (irrigated LR2000 (Ir) and SR2000 respectively (Figure 5.5). Under water stressed rainfed LR2000 conditions the light use efficiency was 1.04 with R^2 of 0.98. Irrigation significantly increased RUE in the dry season of LR2000 but had no effect in the wet SR2000 season (Figure 5.5). Nitrogen had no effect RUE so data was pooled in SR2000.

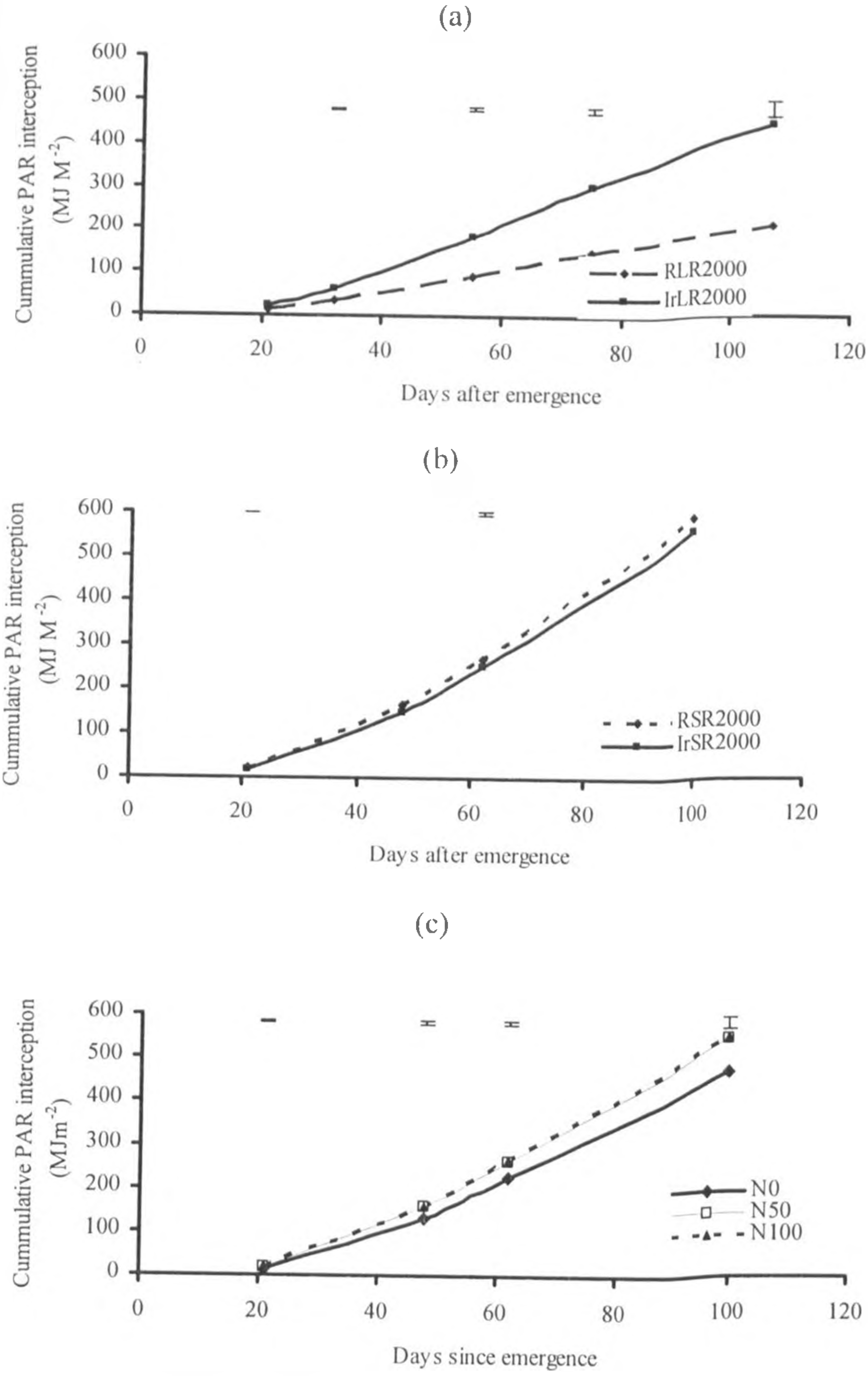


Figure 5.4. Cumulative PAR interception by maize under different water regime (LR2000 (a) and SR2000 (b)) and N levels (SR2000 irrigated treatment (c)), at Katumani, Kenya. R = rainfed, Ir = irrigated, (N0, N50, N100) = N application levels.

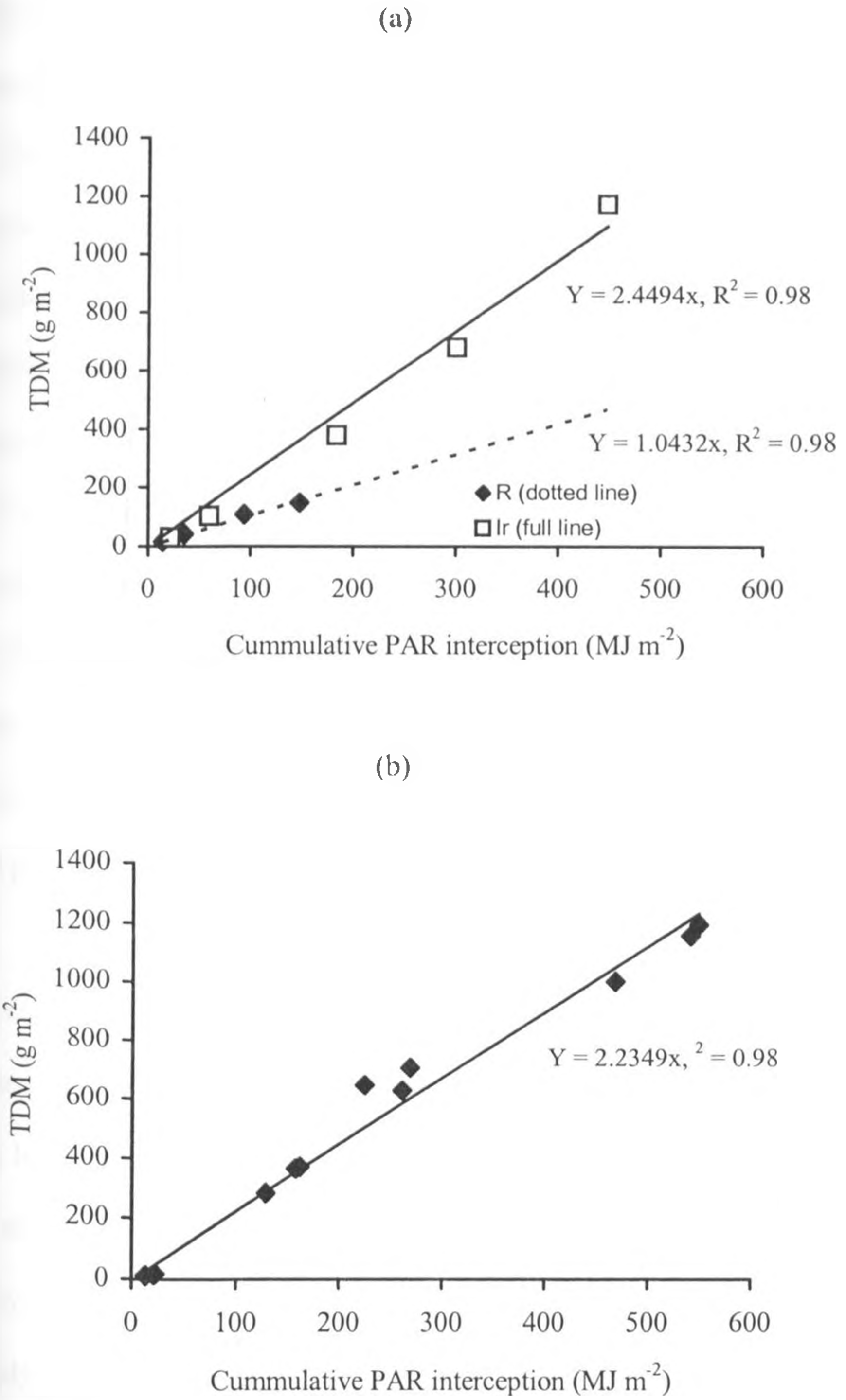


Figure 5.5. Total dry matter versus cumulative PAR interception by maize, LR2000 (a) and SR2000 (b) at Katumani, Kenya. (all data pooled), R = rainfed, Ir = irrigated.

5.3 Discussion

5.3.1 PAR interception

Irrigation had no significant effect on percentage PAR interception during SR1999 and SR2000 since PAR interception is a function of LAI (Gallo, 1985; Muchow, 1994; Sergio and Andrade, 1995). Irrigation in the dry season increased LAI (Figure 4.6 b) and consequently increased PAR interception. The maximum fractional PAR attained in the three seasons were 57 % in SR1999, 71 % in LR2000 and 74 % in SR2000. Higher values of intercepted PAR (90 % to 98 %) have been reported for other maize varieties under irrigated conditions and higher population densities (Tetio-Kagho and Gardener, 1988; Tollenaar and Bruulsema, 1988). However the compact nature and short duration of Katumani composite B maize restricted its ability to respond to increased water and N application. Improvement of LAI, hence PAR interception can only be attained through increased plant density.

Water limitation under low rainfall (LR2000) may have limited N availability while high rainfall in SR2000 increased N availability, soil N mineralization and uptake in all N treatment levels resulting in lowering of response to N fertilizer. The linear relationship between shoot dry weight and cumulative PAR interception (Figure 5.5) conform to findings by Kiniry *et al.* (1989) and Otegui *et al.* (1995). The light use efficiencies observed in this study under adequate moisture conditions (2.23 to 2.45 g MJ^{-1}) fall within the ranges reported by Kiniry *et al.* (1989) (2.1 to 4.5 g MJ-1) for different maize cultivars. The observed extinction coefficients (0.30 to 0.37) are within the documented range (0.34 to 0.40) (Muchow *et al.*, 1990; Flenet *et al.*, 1996). Nitrogen did not significantly influence k but water had an effect on the extinction coefficient; 0.30 and 0.37 under rainfed and irrigated conditions respectively. The differences in k value may reflect leaf responses i.e. leaf orientation or rolling in response to water stress.

CHAPTER 6

MAIZE NITROGEN UPTAKE

6.1 Grain N uptake

P effect on grain N uptake was non significant hence data was pooled. The seasonal, irrigation and N effects were significant for the three seasons combined (Appendix 16). There was significant interaction between season and irrigation and between irrigation and nitrogen during the three seasons (Table 6.1 and Appendix 16).

Table 6.1. Seasonal mean grain N uptake and total N uptake (kg ha^{-1}) for maize, calculated from Table 6.2, SR1999, LR2000 and SR2000 at Katumani, Kenya.

Season	Grain-N concentration (%)	Grain-N uptake (kg ha^{-1})	Total N uptake (kg ha^{-1})
SR1999	1.533	57.6	75.1
LR2000	1.541	38.4	78.6
SR2000	1.725	104.7	158.0
LSD$_{(0.05)}$	0.074	6.4	9.3

The interaction of irrigation and nitrogen was not significant on grain N uptake in SR1999 but had a positive significant effect on grain N uptake in irrigated treatments in LR2000 and SR2000 (Table 6.2 and Appendix 17). Irrigation x P also had a positive significant effect on grain N in irrigated LR2000 (Appendix 17) (grain N uptake under rainfed conditions were 2.91 and 1.92 kg ha^{-1} at P0 and P25 and 71.06 and 77.82 kg ha^{-1} respectively under irrigated conditions, LSD$_{(0.05)}$ of 4.43). Irrigation significantly increased grain N compared to rainfed treatments during SR1999 and LR2000 but had no significant effect in the wet SR2000.

Table 6.2. Nitrogen uptake and partitioning for maize under different water regimes and N application rates, SR1999, LR2000 and SR2000 at Katumani, Kenya.

Season		Water regime	N Level	Total N uptake	Grain N uptake
				(kg ha^{-1})	
SR1999		Rainfed	0	28	20.2
			50	57	41.9
			100	55	39.6
			Mean	47	33.9
		Irrigated	0	67	54.1
			50	110	83.6
			100	132	94.4
			Mean	103	77.4
	LSD$_{0.05}$	Ir		15	9.1
		N		11	10.8
		Ir x N		16	ns
LR2000		Rainfed	0	15.1	3.5
			50	11.2	1.6
			100	16.1	2.1
			Mean	14.1	2.4
		Irrigated	0	94.1	50.2
			50	164.3	85.7
			100	171.0	87.5
			Mean	143.1	74.5
	LSD$_{0.01}$	Ir		3.5	5.0
		N		11.9	3.8
		Ir x N		16.8	5.4
SR2000		Rainfed	0	139	100
			50	166	101
			100	169	101
			Mean	158	101
		Irrigated	0	129	90
			50	175	117
			100	171	119
			Mean	158	109
	LSD$_{0.01}$	Ir		ns	ns
		N		15.1	8.2
		Ir x N		ns	11.5

Data pooled for P

Nitrogen significantly increased grain N in all the seasons (Table 6.2 and Appendix 17) except in rainfed treatments of LR2000 and SR2000. The mean grain N (with and without N) in irrigated SR1999 and irrigated LR2000 were similar. Nitrogen application beyond 50 kg ha^{-1} did not result in higher grain N uptake except in irrigated SR1999. The N concentration was significantly higher in SR2000 compared to SR1999 and LR2000 (table 6.1).

6.2 Total N uptake

The seasonal, irrigation and N effects were significant for the three seasons combined however there was no significant seasonal effect between season 1 and 2 (Table 6.1 and Appendix 18). There was a significant interaction between season and irrigation (Appendix 18). The interaction between irrigation and N was significant and positive in the drier seasons, SR1999 and LR2000 (Table 6.2 and Appendix 17) but not significant in the wetter SR2000. Irrigation significantly increased total N in the first two seasons but had no effect in the third season (Table 6.2 and Appendix 17). The mean total N in irrigated treatments was 103 and 143.1 kg ha^{-1} compared with rainfed treatments 47 and 14.1 kg ha^{-1} during SR1999 and LR2000 respectively. Nitrogen significantly increased total N in all the three seasons except in rainfed treatments of LR2000 (Table 6.2 and Appendix 18). Nitrogen application beyond 50 kg ha^{-1} did not result in higher total N uptake except in irrigated treatment of SR1999.

6.3 Fertilizer nitrogen recovery

Under rainfed conditions 54 - 58 % of applied fertilizer N at 50 kg N ha^{-1} was recovered in the wetter seasons (SR1999 and SR2000) (Table 6.3). No fertilizer N was recovered in the drier rainfed LR2000. Lower fertilizer N was recovered under rainfed conditions in the wetter seasons (27 – 42%) at 100 kg N ha^{-1}. Under irrigated conditions 86 - 92 % of fertilizer N was recovered at 50 kg N ha^{-1} in the three seasons while at 100 kg N ha^{-1} fertilizer N recovery ranged from 42 – 77 %. Under rainfed conditions 43, 0 and 2 % of the total fertilizer N was recovered in the grain in moderate, dry and wet seasons respectively at 50 kg N ha^{-1} and 19, 0 and 1 % respectively at 100 kg N ha^{-1} (Table 5.6). In the irrigated treatments 54 – 71 % of the total fertilizer N was recovered in grain at 50 kg N ha^{-1} while 29 – 40 % of the total fertilizer N was recovered in the grain at 100 kg N ha^{-1}. Irrigation increased total soil N recovery by between 2.4 to 6.2 times in season 1 and 2 but had no effect in season 3.

Table 6.3. Partitioning of Total and Grain plant N from soil (N_s) and fertilizer N (N_f), under rainfed (R) and irrigated (Ir) treatments, SR1999, LR2000 and SR2000 at Katumani, Kenya (Values computed from Table 6.3).

Season	Water regime	N Level	Total		Grain N			Total
			N_s	N_f	N_s	N_f	% N_f	% N_f
		---------------------------(kg ha^{-1})-----------------						
SR1999	R	0	28		20.2			
		50		29		21.7	43	58
		100		27		19.4	19	27
	Ir	0	67		54.1			
		50		43		29.5	59	86
		100		65		40.3	40	65
LR2000	R	0	15.1		3.5			
		50		-3.9		-1.9	0	none
		100		1		-1.4	0	1
	Ir	0	94.1		50.2			
		50		70.2		35.5	71	140
		100		76.9		37.3	37	76.9
SR2000	R	0	139		100			
		50		27		1	2	54
		100		30		1	1	30
	Ir	0	129		90			
		50		46		27	54	92
		100		42		29	29	42

Data pooled for P, Total N uptake represent uptake by all above ground parts i.e. stems, leaves, grain, husks and cobs)

6.4 Discussion

Maize N uptake was highest in the wettest SR2000 season and lowest in the driest LR2000 season. Low N uptake in LR2000 rainfed treatments was due to decreased nitrogen and water availability which resulted in slow growth rate (Figure 4.12). Increased soil water through rainfall and irrigation may have increased organic nitrogen mineralization in the soil thus increasing available N supply and uptake (Pilbeam *et al.*, 1995a and b; Jarvis *et al.*, 1996). Under drier conditions the applied fertilizer N was not utilized by the maize.

The total N uptake under dry and wet conditions in the three seasons (11 – 175 kg N ha $^{-1}$) were within the reported values of (24 – 180kg N ha^{-1} (Fox *et al.*, 1974; Glove *et al.*, 1983; Pilbeam *et al.*, 1995; Singunga, 1997 and Ma *et al.*, 1999) while Karlen *et al.* (1987) reported total N uptake of up to 264 kg N ha $^{-1}$ under irrigation and high N application rate of 268 kg N/ha). All these researchers except Fox *et al.* (1974) and Karlen *et al.* (1987), worked with N application rates of 0 and 100 kg/ha (Fox used 134 kg ha $^{-1}$ in place of 100 kg ha $^{-1}$). Fox *et al*, (1974) and Glove *et al*, (1983) also worked under high rainfall conditions of 1234 and 2000 mm respectively.

Increased water supply may have increased uptake of available soil N by increasing mineralization of organic N (Pilbeam *et al.*, 1995; Jarvis *et al.*, 1996). Higher total fertilizer N (Treatment N50 and N100) recovery under wetter seasons compared to drier season was due to more solubilization and hence higher availability of fertilizer N under wet conditions compared to under drier conditions. Higher percentage recovery of fertilizer N at 50 kg N ha^{-1} compared with at 100 kg N ha^{-1} indicate that higher rate of supplemental irrigation is necessary at application of 100 kg N ha^{-1}. Increased total N and soil N recovery (Treatment N0) under irrigation and wetter conditions indicate higher N- mineralization under these conditions compared to drier conditions. The observed total fertilizer N recovery under rainfed conditions (27 – 58 %) are within the reported ranges (15 – 60 %) for most arable soils (Reddy and Reddy, 1993; Hernandez *et al.*, 2000; Kumar and Goh, 2000; Vanlauwe *et al.*, 2000 a and b; Abdelrahman *et al.*, 2001 and Simard, 2001). The observed fertilizer N recovery under irrigated conditions (42 – 92 %) in this study was higher than those reported above under rainfed conditions.

CHAPTER 7

SOIL MOISTURE CONTENT, MAIZE WATER USE, WATER USE EFFICIENCY

7.1 Soil profile moisture

The interaction of irrigation and N on total stored soil moisture in SR1999 was significant from (84 to 95 DAE) while in LR2000 the interaction of irrigation and N, irrigation and P and N and P on total stored soil moisture were significant from establishment to vegetative phase (17 to 38 DAE) (Appendix 19). All interactions on total stored soil moisture were not significant in SR2000 (Appendix 19). In SR1999 irrigation had no significant effect on total stored soil moisture in the establishment period (0 -25 DAE) (Figure 7.1 and Appendix 19) but significantly increased total stored soil moisture between vegetative and grain filling-ripening phases (36 – 84 DAE). In LR2000 irrigation significantly increased stored soil moisture between establishment and early vegetative phases only (DAE 17 to 28) (Appendix 19) but had no significant effect in SR2000.

Nitrogen had no significant effect on total stored soil moisture in SR1999. In LR2000 nitrogen significantly decreased total stored soil moisture during establishment and vegetative phases (DAE 17 - 28) at N application of 50 kg ha^{-1} but not at 100 kg N ha^{-1} (Table 7.1). In SR2000 nitrogen at 50 kg ha^{-1} significantly decreased soil moisture from 76 to 100 DAE (Table 7.2) but had no effect at 100 kg N ha^{-1}.

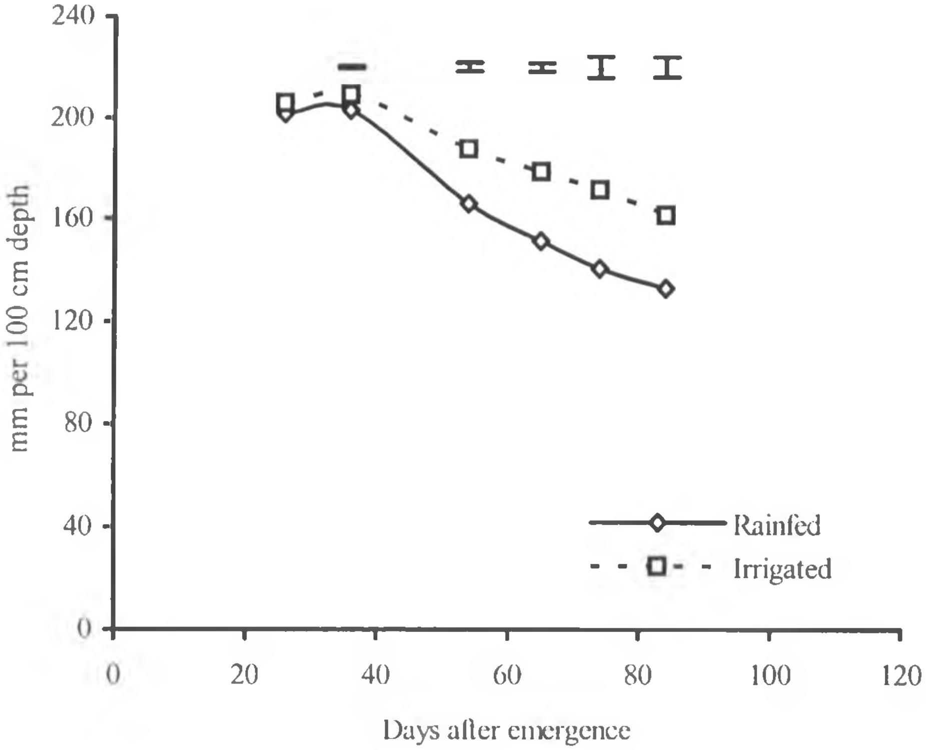


Figure 7.1. Total stored soil moisture (mm) under different water regimes, SR1999, at Katumani, Kenya. Bars represent irrigation effect, R = rainfed treatment, Ir = irrigated treatment.

Table 7.1 Total stored soil moisture mm per 100 cm depth under different N application levels, LR2000, at Katumani, Kenya.

N level (kg ha^{-1})	DAE		
	17	28	38
0	149	179	124
50	140	166	135
100	150	176	140
$LSD_{0.05}$	0.38	1.81	12.00

Table 7.2 Total stored soil moisture mm per 100 cm depth under different N application levels, SR2000, at Katumani, Kenya.

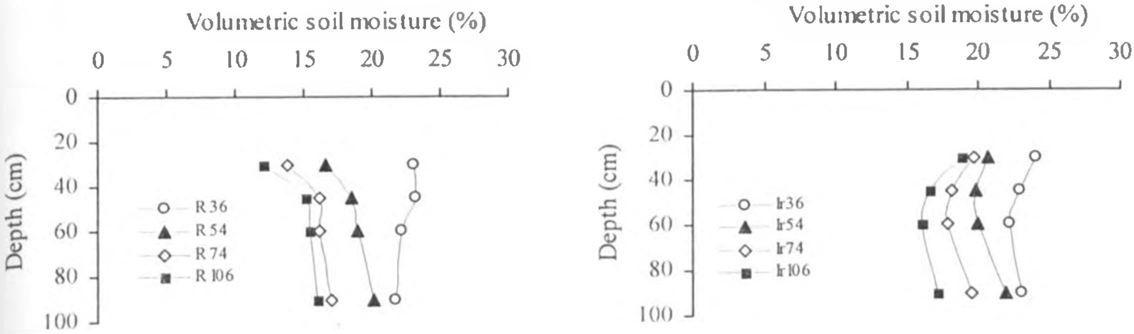
N level (kg ha^{-1})	DAE		
	78	89	100
0	182	160	152
50	170	148	140
100	183	159	149
LSD$_{0.05}$	9.6	10.1	9.3

Phosphorus had a significant effect on total stored soil moisture during establishment to early vegetative phases in LR2000 (Table 7.3 and Appendix 19) but had no effect in SR1999 and SR2000.

Table 7.3 Total stored soil moisture mm per 100 cm depth under different phosphorus application levels, LR2000, at Katumani, Kenya .

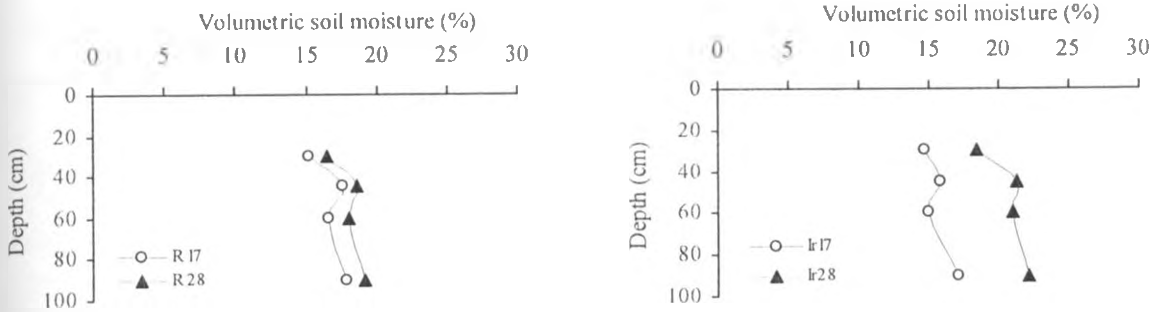
N level (kg ha^{-1})	DAE	
	17	28
P0	147	170
P25	146	178
LSD$_{0.05}$	0.31	1.48

The distribution of mean soil moisture with depth and time is shown in Figure 7.2 (rainfed and irrigated treatments). The moisture patterns were similar showing increase of soil moisture with depth from 30 cm to 45 cm (except SR1999 Figure 7.2 b) and little variation with deeper depth (Figure 7.2 a, c, d and e). There was however lower soil moisture at 60 cm depth compared to that at 45 cm depth in rainfed and irrigated LR2000. There was continuous soil moisture decrease with time in all the seasons.



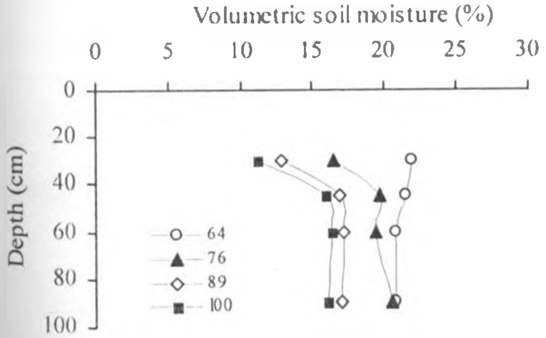
(a) SR1999 rainfed

(b) SR1999 irrigated



(c) LR2000 rainfed

(d) LR2000 irrigated



(e) SR2000

Figure 7.2. Mean volumetric soil moisture at various depths under different water regimes and time, SR1999 (a and b), LR2000 (c and d) and mean of rainfed and irrigated treaments SR2000 (e), at Katumani, Kenya. R = rainfed, Ir = irrigated, numbers 36, 54 = Days after emergence.

7.2 Maize water use (Cumulative evapotranspiration)

Nitrogen and phosphorus had no effect on cumulative evapotranspiration in SR1999. Irrigation was the dominant factor that influenced maize water use during SR1999 and LR2000. Irrigation effect on cumulative evapotranspiration was significant in all sampling dates in the drier seasons, SR1999 and LR2000 (Figure 7.3 a and b and Appendix 21) but not in the wet season (SR2000). In SR1999 cumulative evapotranspiration was on average 1.3 times higher (156 mm) at early vegetative (26 DAE) compared with rainfed, 1.8 times higher (379 mm) at flowering (54 DAE) and 2.4 times higher (637 mm) at maturity (100 DAE). With irrigation in LR2000, cumulative evapotranspiration was 7.6 times higher (96.7 mm) compared to rainfed treatment at establishment (17 DAE), 4.3 times higher (307 mm) at flowering and 5.0 times higher at maturity (108 DAE). In the dry season of LR2000 there was significant positive interaction of irrigation and P and Irrigation and nitrogen on cumulative evapotranspiration in the establishment and vegetative phases (Table 7.4 and Appendix 21). Other interactions were not significant. Nitrogen effect was also significant in these two phases. (Table 7.4). Cumulative evapotranspiration was on average 1.2 times higher with N compared with no N during the establishment phase and 1.1 times higher in the vegetative phase.

During SR2000 all factors had no significant effect on evapotranspiration except irrigation in the grain filling - ripening phases (76 – 100 DAE) (Figure 7.3 c and Appendix 21). Cumulative evapotranspiration was 1.1 times higher compared with rainfed during this grain filling - ripening phases.

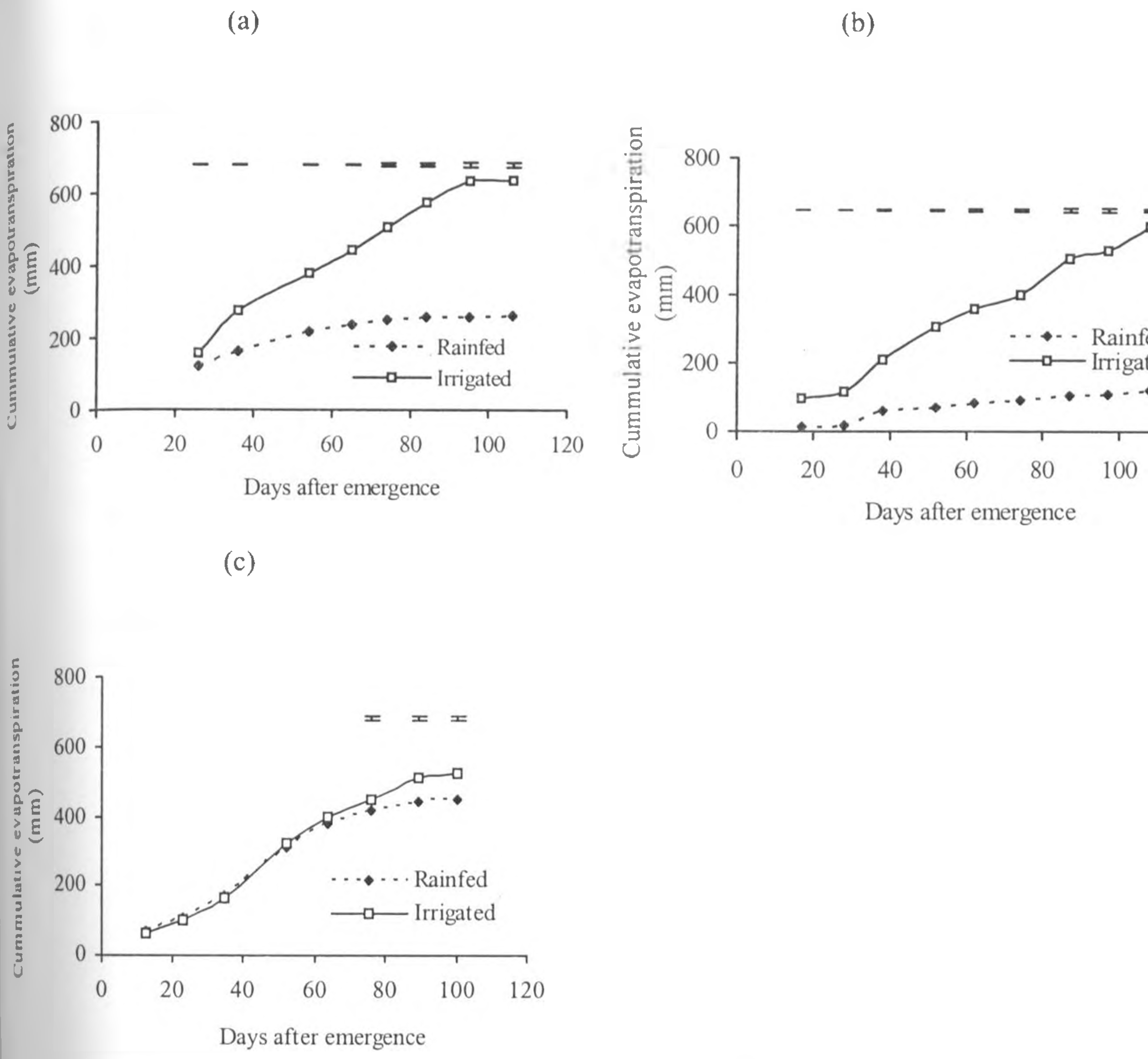


Figure 7.3. Cumulative evapotranspiration of maize, SR1999 (a), LR2000 (b) and SR2000 (c), at Katumani, Kenya. R = rainfed, Ir = irrigated.

Table 7.4. Cumulative evapotranspiration (ET) (mm) under different water regimes and N application rates, LR2000, at Katumani, Kenya.

Water regime	N level (kgha^{-1})	Days after emergence and growth phases		
		17 I	28 II	38 II
Rainfed	0	12	12	76
	50	11	27	46
	100	15	15	59
	Mean	12.7	18	60.3
Irrigated	0	86	105	202
	50	116	131	228
	100	88	114	197
	Mean	96.7	116.7	209
$LSD_{0.05}$				
Ir		0.71	3.45	20.06
N		0.39	4.55	ns
Ir x N		0.55	ns	19.18

Data pooled for P, I and II refer to establishment and vegetative phases, ns= non significant

7.3 Water use efficiency

Phosphorus had no effect on water use efficiency (WUE) in the three seasons. The interaction of irrigation and nitrogen was significant for grain water use efficiency and total dry matter water use efficiency in LR2000 (Table 7.6 and Appendix 22). Irrigation only increased WUE in the dry season of LR2000. Grain water use efficiency and total biomass water use efficiency ($WUE_{(gr)}$, $WUE_{(TDM)}$) were 6.7, and 2.2 times higher respectively compared with rainfed. The interaction of irrigation and nitrogen on $WUE_{(gr)}$ and irrigation and phosphorus on $WUE_{(TDM)}$ was significant in SR2000 (Table 7.6 and Appendix 22). Irrigation significantly decreased water use efficiency in SR2000 (Table 7.6). With irrigation $WUE_{(gr)}$, and $WUE_{(TDM)}$ were on average 0.8 times lower (11.4 and 21.8 kg $ha^{-1}mm^{-1}$ respectively) compared with rainfed (13.5 and 26.0 kg $ha^{-1}mm^{-1}$ respectively).

Nitrogen significantly increased water use efficiency throughout SR1999 (Table 7.5 and Appendix 22). Grain and total dry matter water use efficiency were 1.6 and 1.7 times higher respectively with N compared with no N. Nitrogen application beyond 50 kg ha^{-1} did not result in higher water use efficiency. With irrigation in LR2000 nitrogen significantly increased both grain and TDM water use efficiency by on average 60 and 40 % respectively (Table 7.6). Nitrogen significantly increased $WUE_{(TDM)}$ in the irrigated treatments during SR2000 (Table 7.6) by on average 20 %. N application beyond 50 kg ha^{-1} did not result in increased water use efficiencies in the three seasons except in rainfed LR2000.

Table 7.5. Grain and total biomass water use efficiency under different N application rates, SR1999 at Katumani, Kenya.

N level (kg/ha)	$WUE_{(gr)}$ (kg $ha^{-1}mm^{-1}$)	$WUE_{(TDM)}$ (kg $ha^{-1}mm^{-1}$)
0	5.9	12.1
50	9.1	20.3
100	9.1	20.6
$LSD_{0.05}$ (N)	1.44	2.58

Data pooled for P and water.

Table 7.6. Grain and total biomass water use efficiency under different water regimes and N application rates, LR2000 and SR2000, at Katumani, Kenya.

Water regime	N level (kg ha^{-1})	LR2000		SR2000	
		$WUE_{(gr)}$	$WUE_{(TDM)}$	$WUE_{(gr)}$	$WUE_{(TDM)}$
			(kg $ha^{-1}mm^{-1}$)		
Rainfed	0	1.9	9.0	13.8	25.9
	50	0.8	6.9	13.5	26.9
	100	1.2	11.1	13.3	25.3
	Mean	1.3	9.0	13.5	26.0
Irrigated	0	6.3	15.5	10.1	19.5
	50	9.9	21.1	12.1	23.2
	100	9.9	22.1	12.1	22.7
	Mean	8.7	19.6	11.4	21.8
$LSD_{0.05}$ Ir		0.97	1.83	0.77	1.86
N		0.75	2.67	ns	2.15
Ir x N		1.06	3.77	0.99	ns

Data pooled for P

7.4 Discussion

7.4.1 Soil profile moisture

The decrease in total stored soil moisture with N application in irrigated LR2000 and in SR2000 could have been due to increased growth as a result of higher N uptake under favourable moisture conditions. The lower total stored soil moisture with N at 50 kg ha^{-1} compared with no N (Figure 7.1 b and c) indicates higher water extraction by the fertilized maize compared with the unfertilized maize. Similar observations have been reported at Kabete, Kenya (Gachene *et al*, 1996). Since the initial soil N levels were low (0.07 – 0.08 %) (Chapter 3.1) full fertilizer N response at 100 kg N ha^{-1} could have been limited by physiological limitation of N utilization by Katumani composite B maize.

7.4.2 Maize water use (cumulative evapotranspiration)

Irrigation significantly increased maize water use in SR1999 and LR2000 because of the higher difference in water availability and hence higher uptake under irrigated compared with rainfed treatments. Lower irrigation response on water use compared to the other seasons in SR2000 was due to high rainfall in this season which resulted in similar water uptake in both rainfed and irrigated treatments. Low leaf area index in rainfed treatments of LR2000 as compared to irrigated treatments (Figure 4.7 b) could have resulted in differences in N use and utilization resulting in the observed positive N effect in this season.

7.4.3 Water use efficiency

The water use efficiencies were similar in the three seasons except in rainfed treatments of LR2000 when low rainfall resulted in decreased growth and hence low water use efficiency. The irrigation water added in SR2000 significantly increased maize water use (from 78 to 100 DAE) (Figure 7.3 c) compared to rainfed treatments but did not increase the grain yield significantly resulting in decreased water use efficiencies in the irrigated treatments. The resulting increase in maize N uptake (Table 6.2) due to the supplemental irrigation water (83.7 mm) was significant but did not result in significant increase in maize yield (Table 4.5). This suggest that more supplemental irrigation water than was used in this season (83.7 mm) may have been required to cause a significant increase in grain yield especially at N application of 100 kg ha^{-1}. The grain water use efficiencies under wet conditions (5.9 – 13.8 kg ha^{-1} mm^{-1}) are within the reported ranges for maize (4 - 28.8 kg ha^{-1} mm^{-1}) (Alessi *et al.*, 1998; Stone *et al.*, 1996) Tolk *et al.*, 1998), while $WUE_{(TDM)}$ of 12.1 – 27 kg ha^{-1} mm^{-1} are comparable to those observed by Alessi *et al.* (1998) and Tolk *et al.* (1998)

Water use efficiencies were significantly higher under fertilized compared with unfertilized conditions which conforms to findings by Van Keulen (1981) and Mengel and Kirby (1982) who observed that non limiting supply of nitrogen under favourable soil moisture conditions enhance crop water use due to improved crop growth as a result of higher N uptake. Poor maize growth in rainfed treatments of LR2000 due to low rainfall and hence poor uptake and utilization of the applied fertilizer resulted in low water use efficiency.

CHAPTER 8

PREDICTING MAIZE GROWTH AND YIELD BY USING THE WOFOST MODEL.

8.1 SUMMARY

WOFOST model predicted grain yield was 10 to 20 % higher than measured yield. The prediction of the various variables (LAI, soil profile moisture, leaves and stems dry matter, TDM and grain yield) were better under moderate to high rainfall (278 to 534 mm) or under irrigated conditions compared with low rainfall. Under dry conditions (143 mm seasonal rainfall, LR2000), the model overestimated the variables by a very high margin (30 - 765%). This could be due to the differences in dry matter partitioning under adequate water supply (SR2000) used in model calibration) and those under very dry conditions (rainfed LR2000) (Figure 4.13).

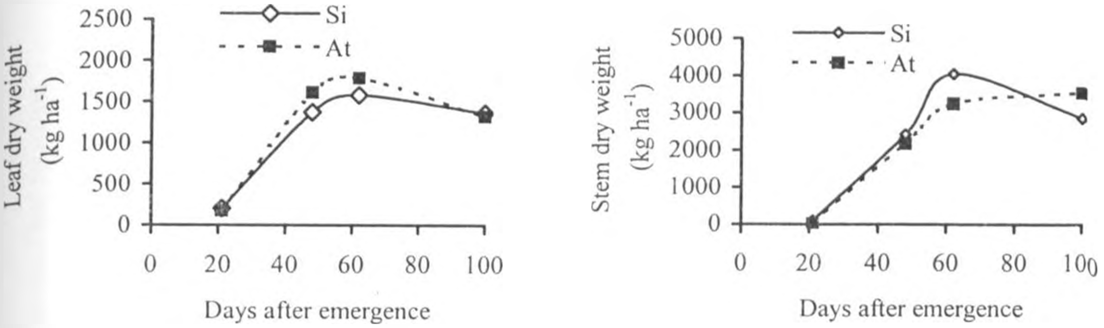
8.2 Model calibration

Calculation of temperature sum (degree days) for the three seasons from emergence to flowering (TSUM1) and emergence to maturity (TSUM2) using measured mean daily temperatures and a base temperature (threshold temperature (TBASE) of 9°C (van Keulen and Wolf, 1986; Rotter, 1993) yielded mean TSUM1 of 518 degree days and TSUM2 of 557 degree days (Table 4.1). Threshold temperature is the temperature below which phenological development stops and is crop specific (van Keulen and Wolf, 1986). TSUM1 and TSUM2 of 524 and 573 degree days respectively were used for the calibration. TSUM1 of 524 and TSUM2 of 573 degree days gave the best agreement between simulated and observed pre-anthesis (germination to flowering) and post-anthesis (flowering to physiological maturity respectively). So the value of TSUM1 of 810 degree days suggested by Rotter (1993) is too high for Katumani composite B maize (KCB) grown at Katumani. The difference is due to the fact that Rotter used observed KCB growth durations from Kitale research station (150 days from emergence to physiological maturity) compared to the 100 to 107 days observed at Katumani. Higher temperatures at Katumani (mean annual temperature of 20°C) compared to Kitale (mean annual temperature of 18.2°C) may explain the difference in growth durations. The calibration Rotter did should be considered as preliminary as the individual data sets for Katumani composite B maize were not fully adequate to make the adjusted parameters values very plausible (Rotter, 1993). Reported temperature sum values for three maize varieties (Ohio 401, Dekalb XL45 and Pioneer 3306) are 625, 640, 755°C days for the period from emergence to flowering and 650, 655 and 635°C days from flowering to maturity respectively (van Keulen and Wolf, 1986).

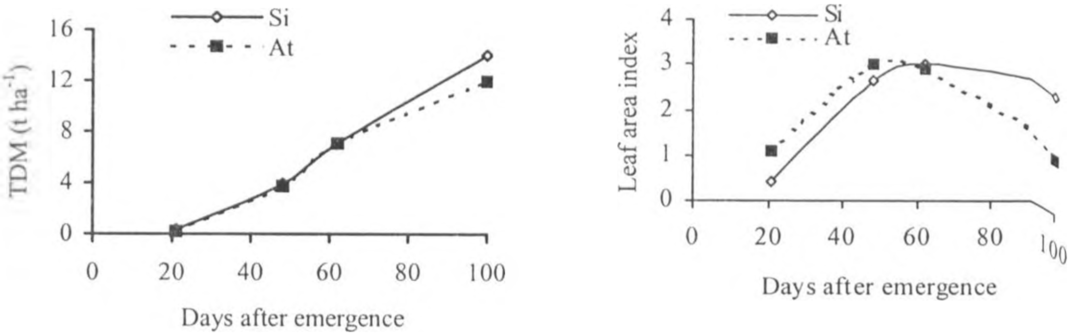
The determined specific leaf area (SLATB) at emergence and flowering were 0.0037 and 0.00186 ha kg^{-1} respectively. A lower value at emergence (0.0020 ha kg^{-1}) was however used to allow better fitting of simulated and measured values. Rotter (1993) used the same value for his simulations. Using the actual dry matter partitioning, TSUM1 and TSUM2 in the model resulted in LAI being overestimated by 2.8 times (actual measured mean maximum LAI was 3.0). The simulated leaf and stem dry weight was also too high compared to measured values. Lowering SLATB at emergence could not fully lower the LAI to measured values. This necessitated the re-adjustment of the actual partitioning factors (Appendix 3). The adjusted partitioning (Appendix 4) are part of the crop file

(Appendix 6, sub-titles FLTB, FSTB and FOTB). The adjusted partitioning factors lowered the dry matter partitioned to leaves. This combined with a lower SLATB at germination lowered the simulated LAI to values closest to measured values. The results of the calibration are indicated in Figures 8.1 and 8.2. The calibration indicated that the simulated leaves, stems and above ground total dry weights corresponded well with measured values (Figures 8.1 a, b, and c; Figures 8.2 a, b and c). There was also good agreement of simulated and measured leaf area index between establishment and flowering phases but poor agreement in the final phases (grain filling to ripening phases) (Figure 8.1 d). During post flowering growth periods the simulated LAI was too high compared to measured LAI. This may be due to the model under-estimating rate of leaf senescence after flowering.

The relationship between simulated and measured volumetric soil profile moisture content was poor in pre-anthesis but good in post-anthesis (Figure 8.1 e and 8.2). This could be due to the model underestimating infiltration and surface runoff. Underestimation of surface run-off by the model was observed in two out of three tested sites in Kenya (Rotter, 1993) and he attributed the problem to the approach used in calculating infiltration and run-off in the model.


(a) Leaves dry weight

(b) Stems dry weight


(c) Above ground total dry weight

(d) Leaf area index

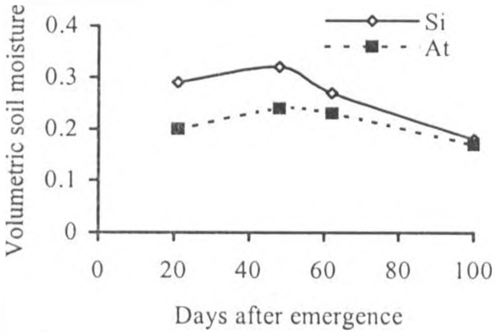
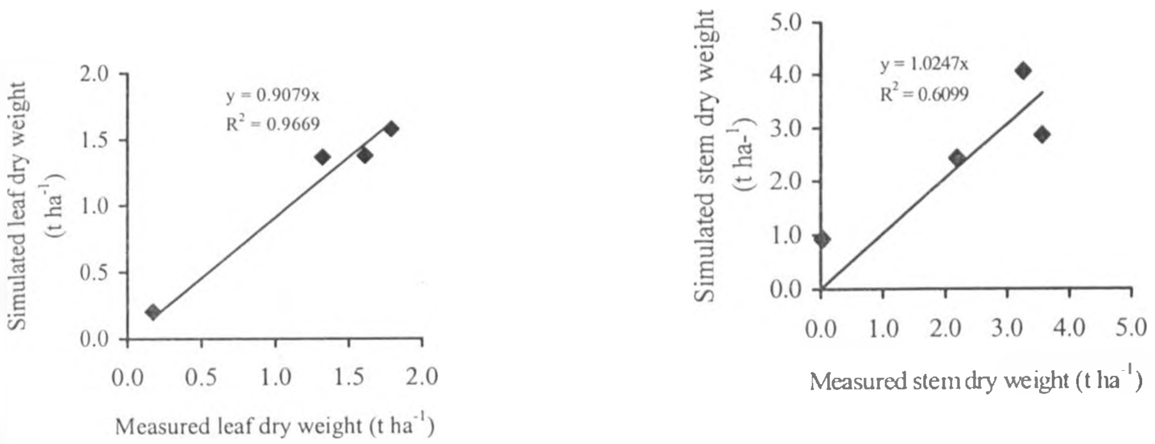
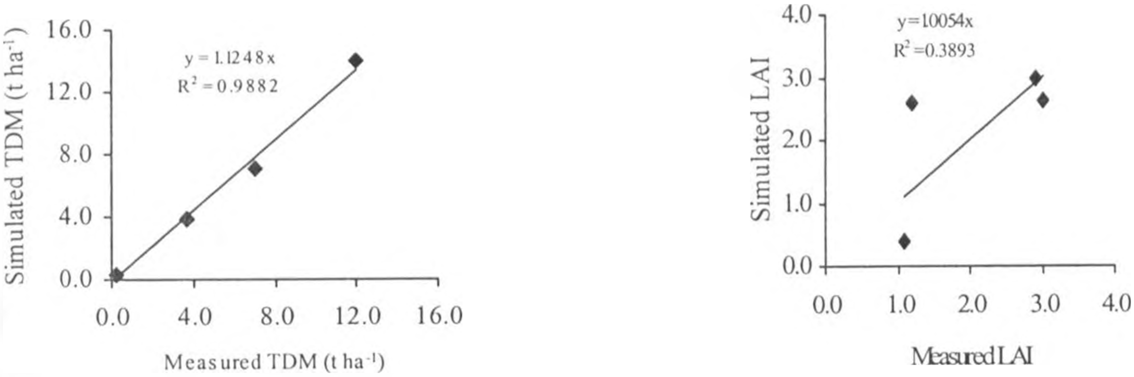

(e) Volumetric soil moisture

Figure 8.1. Simulated and measured variables for the data used in model calibration (rainfed SR2000) (Si = simulated, At = measured).


(a) Leaves dry weight

(b) Stems dry weight


(c) Above ground total dry matter

(d) Leaf area index

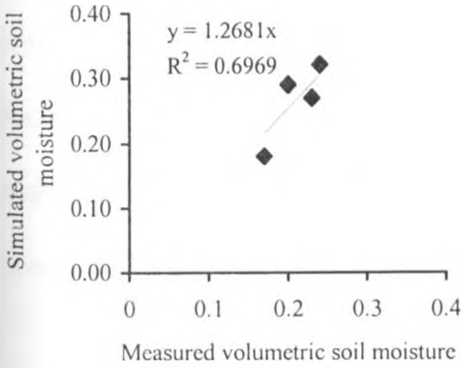

(e) Volumetric soil moisture

Figure 8.2. Relationship between simulated and measured variables for the data used in model calibration (rainfed SR2000).

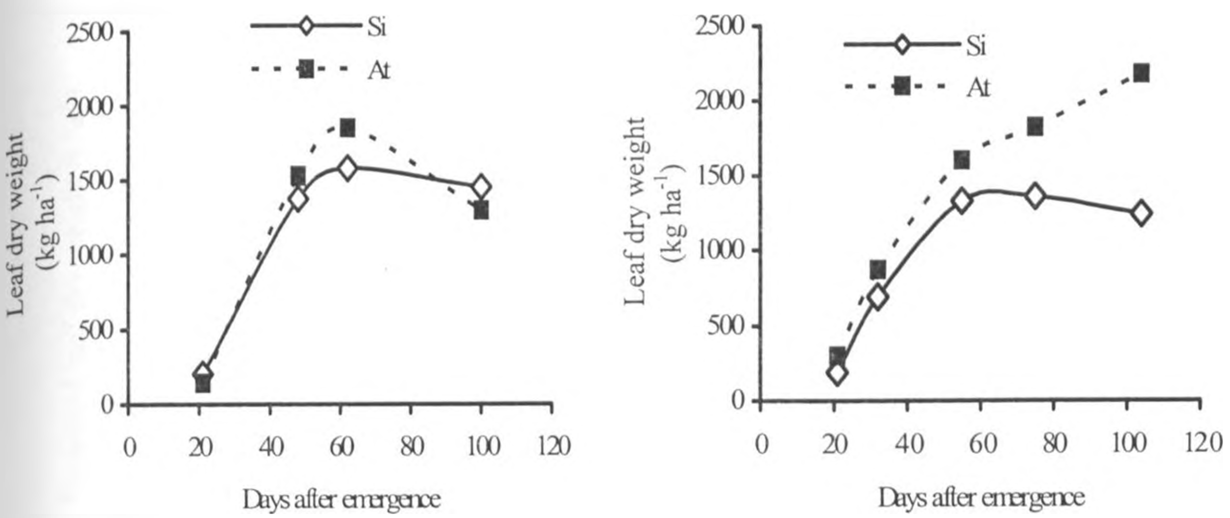
The simulated storage organs (grain + cobs) was 7,868 kg ha^{-1}. The measured cob weight was 15.5 % of the total storage organs. This implies the simulated grain yield was 84.5 % of 7,868 i.e. 6,648 kg ha^{-1} while the measured grain yield was 6,070 kg ha^{-1}. The simulated calibration final total dry matter was 14,019 kg ha^{-1} while the mean measured final dry matter was 11,892 kg ha^{-1} (approx. 15 % overestimate). Thus there was fair agreement of simulated TDM and grain yield to measured values.

8.3 Model validation

Figures 8.3 to Figure 8.12 show the results of model validation comparing simulated and measured outputs for other seasons (SR1999, LR2000, SR2000 and FURP rainfed grain yields between 1988 to 1991, five seasons).

8.3.1 Leaf dry matter

In the dry LR2000 rainfed treatments, there was poor agreement of simulated to measured leaves dry weight (89.6 % overestimation of leaf dry weight by the model). The poor agreement was between vegetative and flowering phases. (Figures 8.3 a and 8.4). In wet conditions (LR2000 and SR2000) irrigated treatments there was good agreement of simulated to measured leaves dry weight (30 to 10 % underestimation respectively) except in the period between grain filling and ripening phases (Figure 8.3 b and 8.4). The agreement was good in irrigated SR2000 (Figure 8.3 c and 8.4).



(a) LR2000 rainfed

(b) LR2000 irrigated

(c) SR2000 irrigated

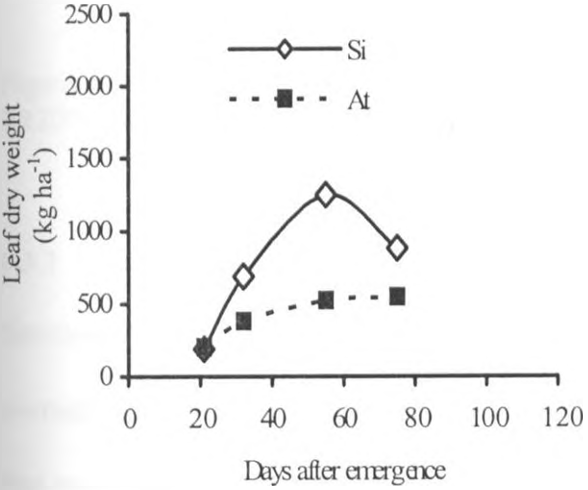


Figure 8.3. Simulated and measured leaf dry weight, LR2000 (a and b) and SR2000 (c). Si = simulated and At = measured leaf dry weight.

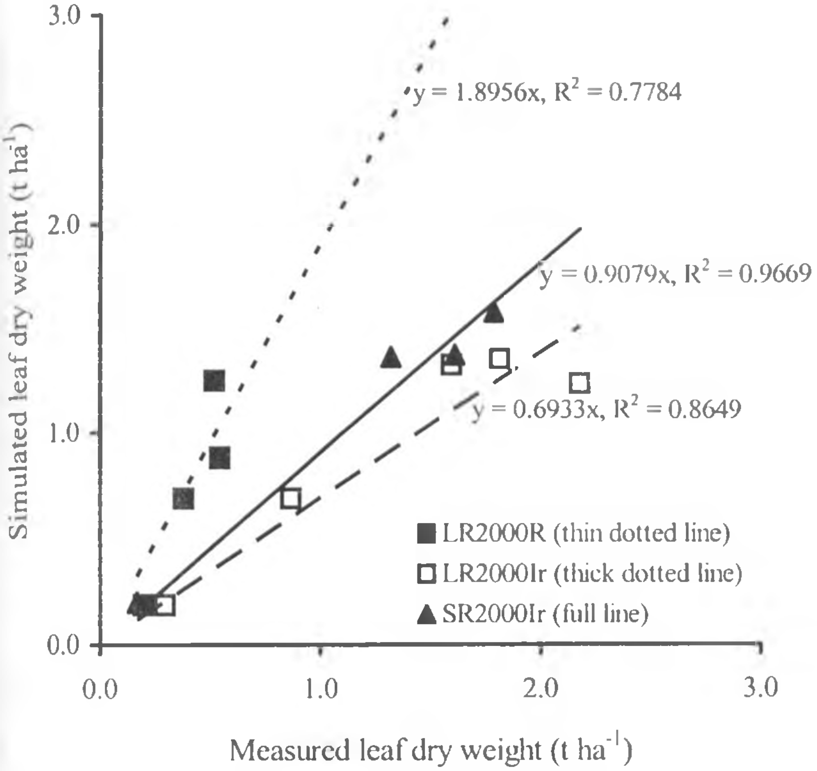
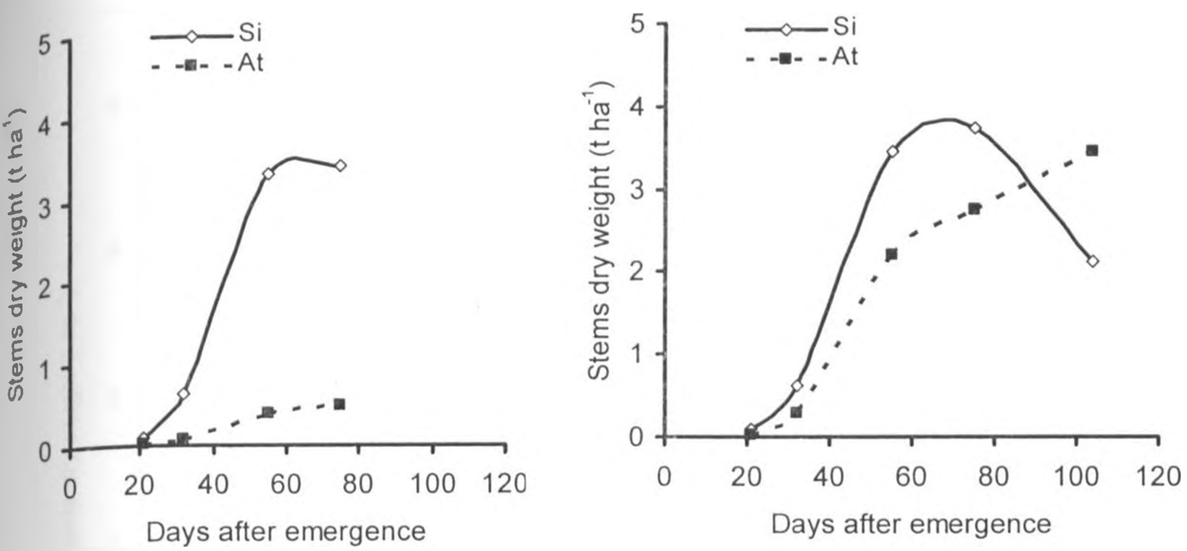


Figure 8.4. Validation relationships between simulated and measured leaf dry weight, LR2000 and SR2000. R = rainfed, Ir = irrigated.

8.3.2 Stem dry matter

Simulated stem dry weight in the dry LR2000 rainfed treatment was very high (765 % overestimate) compared to measured stems dry weight resulting in a regression line that was way off the 1:1 mark (Figure 8.5 a and 8.6). In wet conditions (irrigated SR2000 and LR2000) simulated stems dry weight was overestimated by between 2.4 to 4.3 % (Figure 8.5 b and c and 8.6).



(a) LR2000 rainfed

(b) LR2000 irrigated

(c) SR2000 irrigated

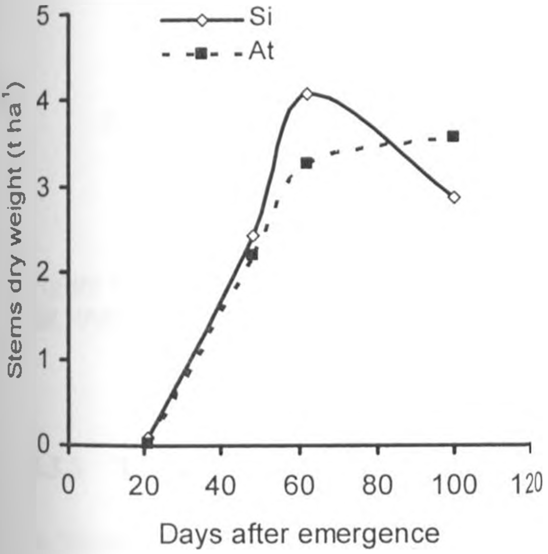


Figure 8.5. Simulated and measured stem dry weight, LR2000 (a and b) and SR2000 (c). Si = simulated, At = measured stem weight.

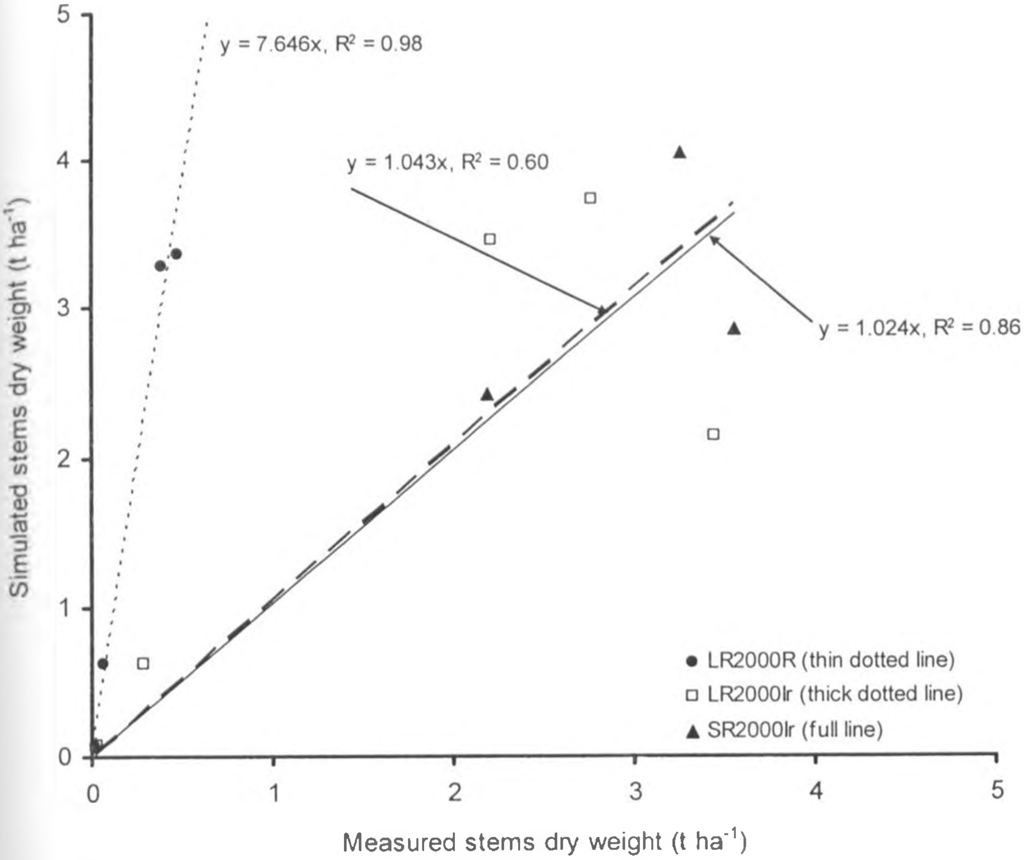


Figure 8.6. Validation relationships between simulated and measured stem dry weight, SR1999, LR2000 and SR2000. R = rainfed, Ir = irrigated.

8.3.3 Total dry matter

In SR1999 the measured final total dry matter 5,779 kg/ha (mean TDM for N_{50} and N_{100}) was 57 % of the simulated total dry matter (10,080 kg/ha). In LR2000 rainfed treatments, the simulated TDM was about 4.9 times higher compared to measured TDM while in the irrigated treatments simulated TDM was overestimated by 11.6 % and by 12.5 % in irrigated SR2000 (Figure 8.7 and 8.8 a, b and c).

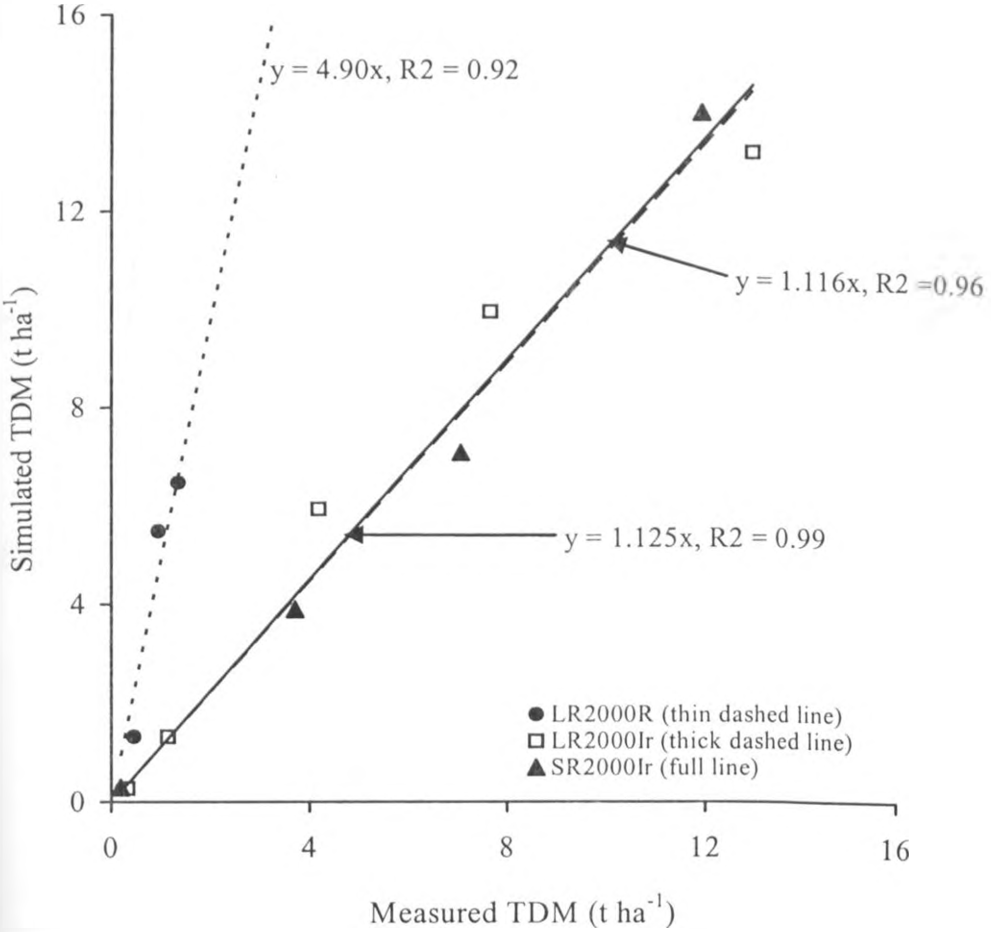
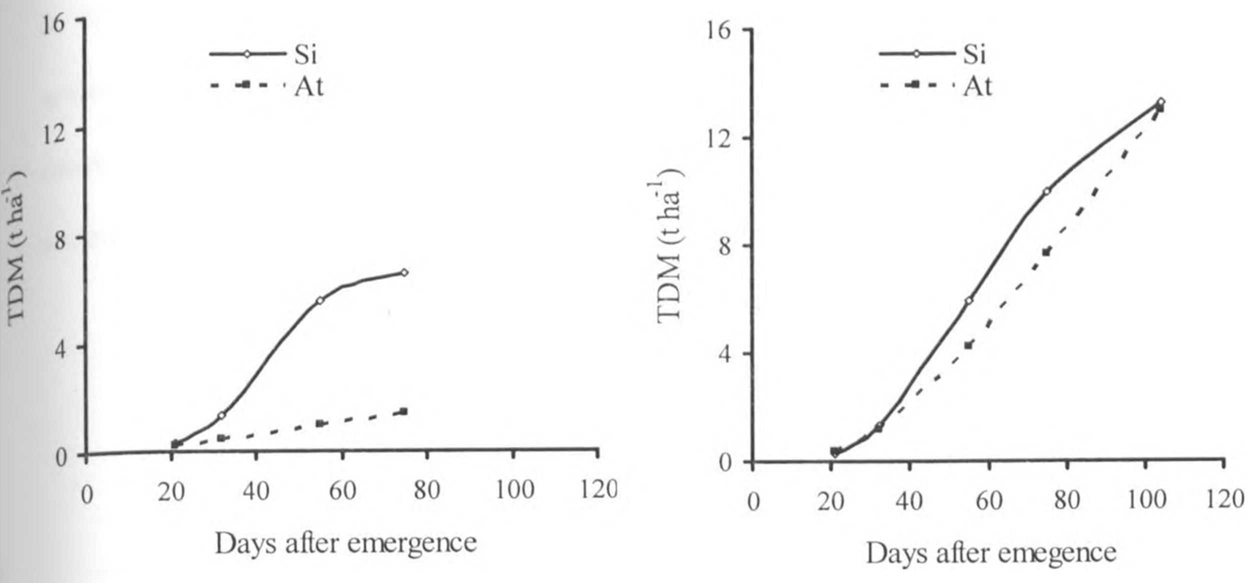


Figure 8.7. Validation relationships between simulated and measured TDM, SR1999, LR2000 and SR2000. R = rainfed, Ir = irrigated.



(a) LR2000 rainfed

(b) LR2000 irrigated

(c) SR2000 irrigated

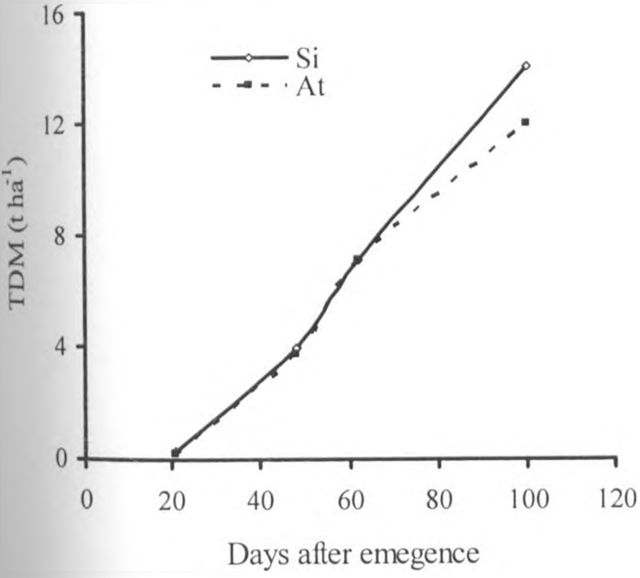


Figure 8.8. Simulated and measured TDM, LR2000 (a and b) and SR2000 (c). Si = simulated, At = measured TDM.

8.3.4 Leaf area index

In dry conditions (LR2000 rainfed) simulated LAI was overestimated by 57 % while under wet conditions (SR1999 rainfed and irrigated and irrigated SR2000) LAI was overestimated by between 5.3 to 7.1 % however in irrigated LR2000 LAI was underestimated by 20 % (Figure 8.9 and 8.10).

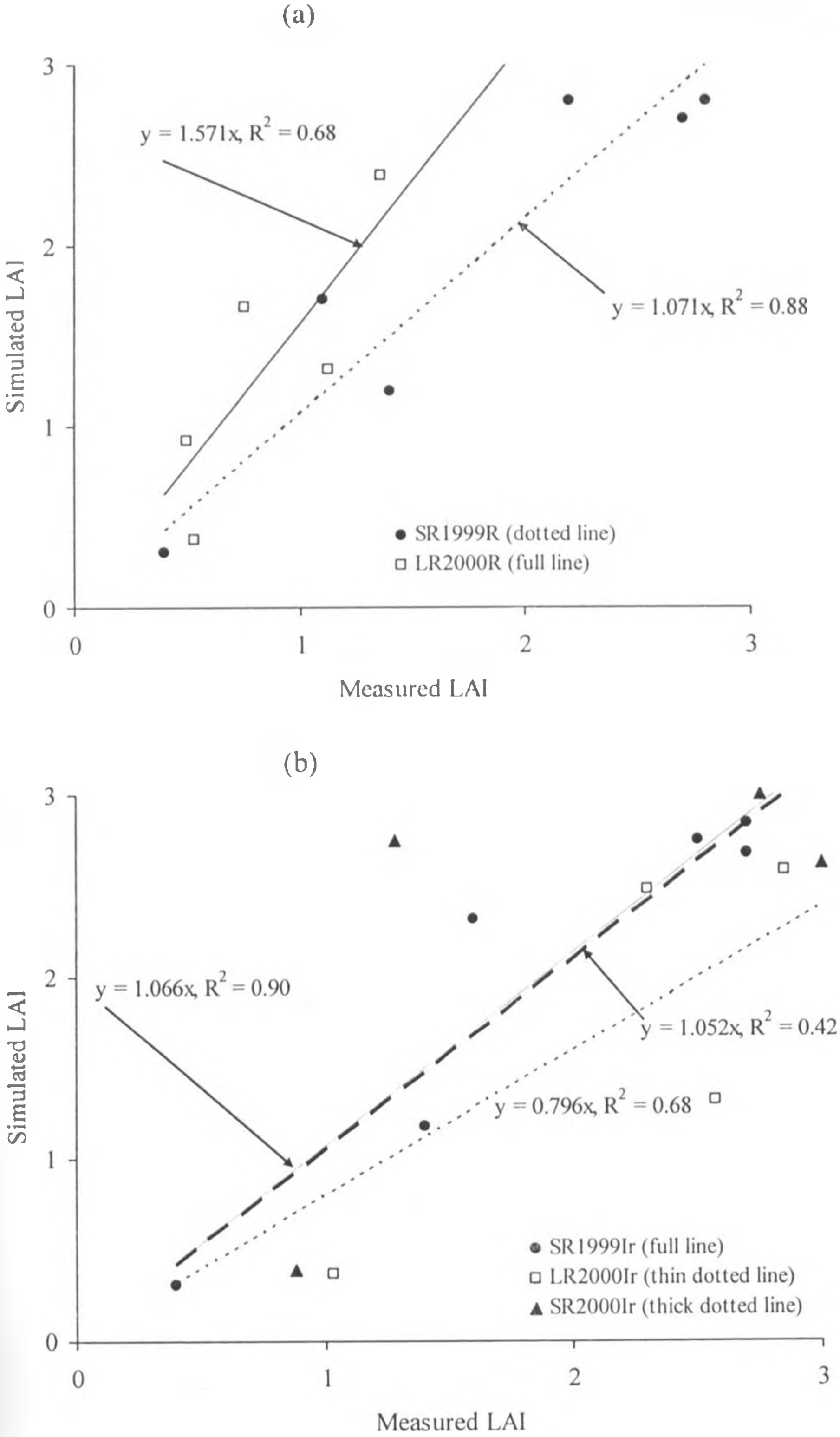


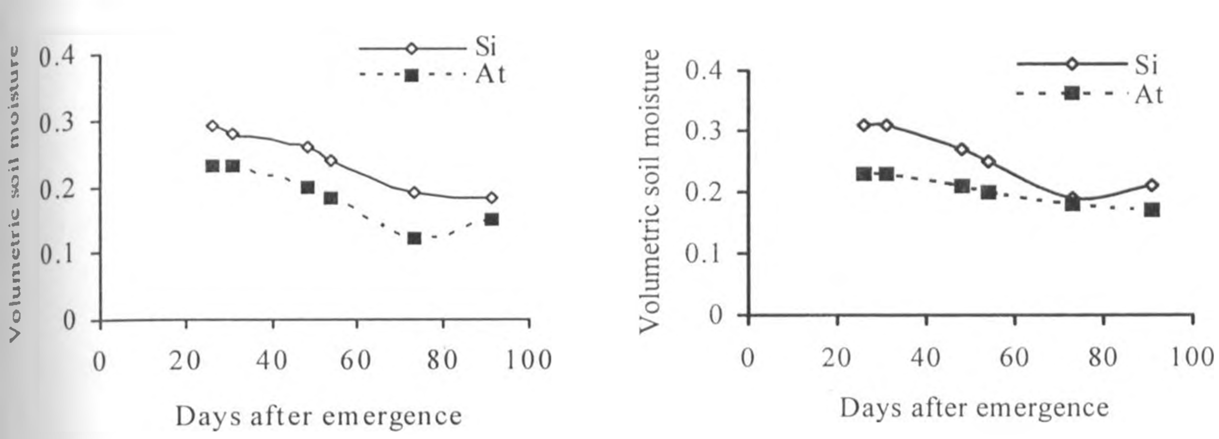
Figure 8.10. Validation relationships between simulated and measured LAI, SR1999, LR2000 and SR2000. (a) rainfed, (b) irrigated, (R = rainfed, Ir = irrigated).

8.3.5 Volumetric soil moisture

Under both rainfed and irrigated conditions simulated volumetric soil moisture was overestimated by between 27 to 29 % (Figures 8.11 and 8.12).

(a) SR1999 rainfed

(b) SR1999 irrigated



(c) LR2000 rainfed

(d) SR2000 irrigated

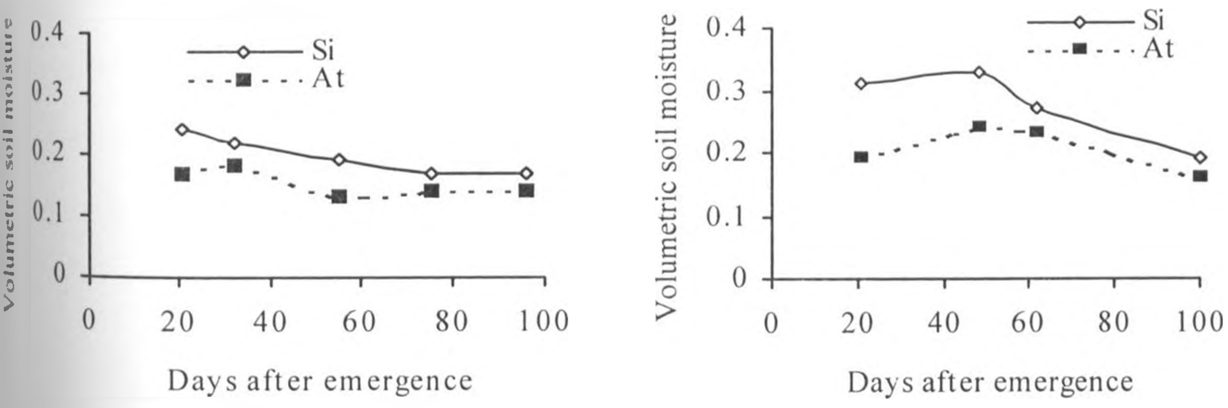


Figure 8.11. Simulated and measured volumetric soil moisture SR1999 (a) and (b), LR2000 (c) and SR2000 (d). Si = simulated, At = measured.

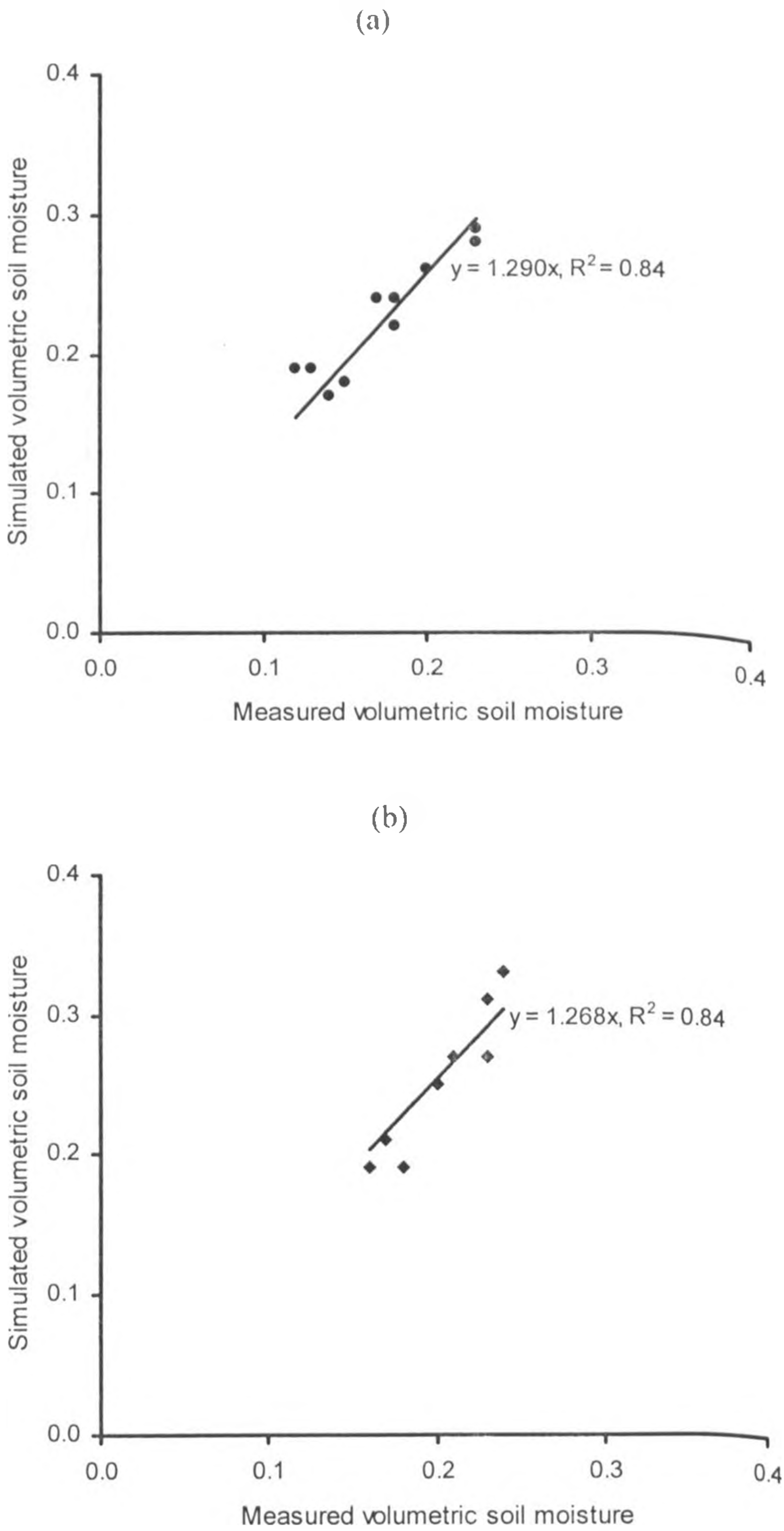


Figure 8.12. Validation relationships between simulated and measured volumetric soil moisture, (a) rainfed, SR1999 and LR2000 (b) irrigated, SR1999 and SR2000.

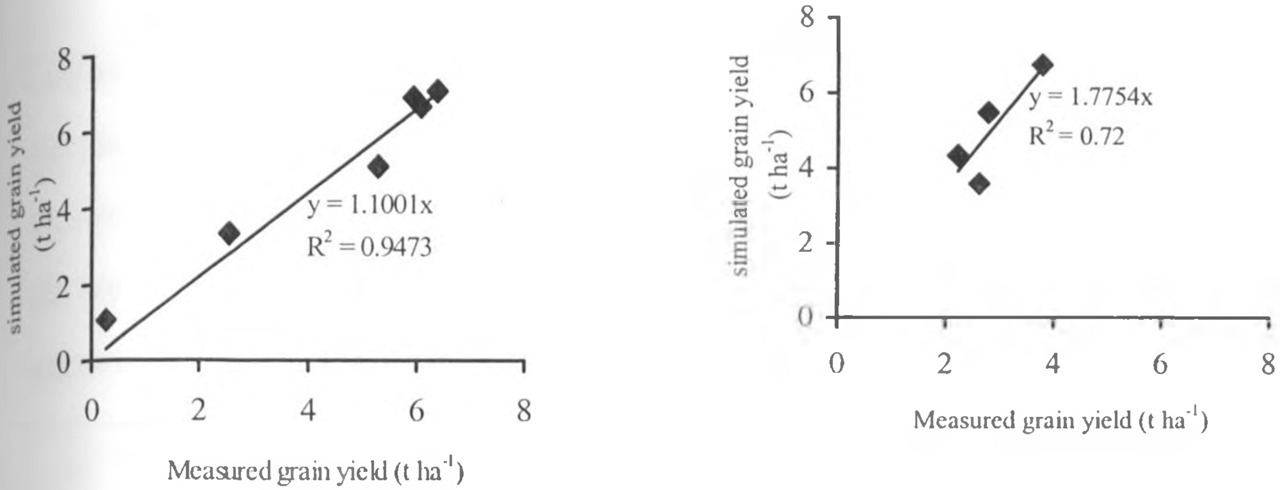
8.3.6 Grain yield

Simulated grain yield were first compared with measured grain yield on per season basis. Under dry conditions in LR2000 rainfed treatment, simulated grain yield (1056 kg ha^{-1}) was overestimated by 380 % while under wet conditions (SR1999 and SR2000 irrigated treatments) simulated grain yield of 5085 kg ha^{-1} and 7058 kg ha^{-1} respectively were underestimated by 4 % and overestimated by 10 % respectively. In moderately wet conditions (SR1999 rainfed) and in LR2000 irrigated treatment simulated grain yield of 3336 kg ha^{-1} and 6887 kg ha^{-1} respectively were 24 and 20 % higher respectively than measured grain yield.

Figure 8.13 shows the relationship between simulated and measured grain yield for 1999 to 2001 seasons and for those by FURP (1988 to 1991 seasons). When the seasons were treated together in this way the model predicted grain yield quite accurately between 1999 and 2001 seasons (Figure 8.13 a) with simulated grain yield being 10 % higher than measured grain yield. There was quite a bit of scattering for FURP data sets (1988 to 1991 seasons) with simulated grain yield being 77 % higher than measured grain yield (Figure 8.13 b). Table 8.1 shows simulated and measured grain yield for FURP seasons.

(a) SR1999-SR2000

(b)1988-1991



(c) All seasons combined

(d) All seasons-refined

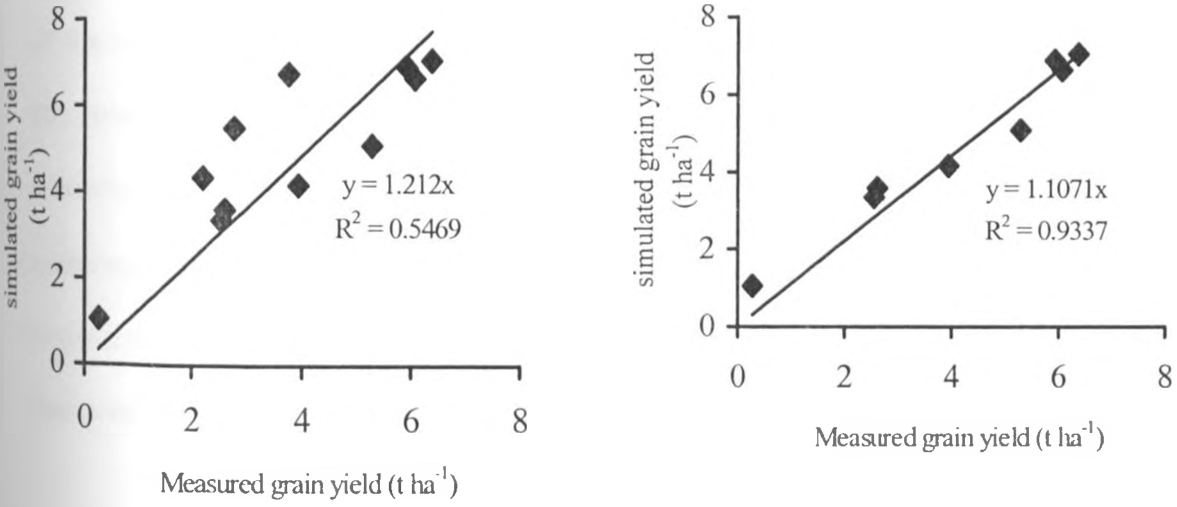


Figure 8.13. Validation relationship between simulated and measured grain yield (a) SR1999 to SR2000 seasons (rainfed and irrigated combined) (b) 1988 to 1991 seasons (rainfed, by FURP) and (c) all seasons combined (d) all seasons less some.

Table 8.1 Simulated and measured grain yield for FURP seasons.

Season	Simulated grain yield (kg ha^{-1})	Measured grain yield (kg ha^{-1})	Rainfall (mm)
LR1988	4334	2210	326
SR1988	6744	3760	382
LR1989	3587	2610	278
SR1989	4164	3940	342
SR1990	5484	2770	425

The table indicate that simulated grain yield corresponded well with measured values in two FURP seasons, i.e. LR1989 and SR1989 and the poor correlation was due to the three seasons LR1988, SR1988 and SR1990. As can be seen in this table rainfall was high in all the seasons so low yield in the latter seasons could have been due to other reasons. The combined graph for all seasons (Figure 8.13 c) indicate simulated grain yield was overestimated by 21 % compared to measured grain yield but there was higher data scattering than for 1999 to 2001 seasons. When the three doubtful FURP seasons data were omitted there was improved agreement between simulated (11 % overestimate) and measured grain yield for all seasons combined (Figure 8.13 d).

8.3.7 Summarized model results

Overall the leaf area index was overestimated by 7 % under wet conditions and by 57 % under dry conditions but the simulated verses measured LAI relationship were poor as indicated by the low R^2 (Table 8.2). The highest error in model estimation of LAI at calibration stage occurred from flowering to maturity while for soil moisture it occurred from emergence to flowering (Figure 8.1 d and 8.1 e). The simulated leaves, stems and TDM had an error at calibration stage of 2 to 12 % at calibration stage (Table 8.2). In the dry LR2000 rainfed season the simulated leaves, stems, TDM, LAI and grain yield at the validation stage were overestimated by a very high margin (57 to 765%). Under wetter conditions in irrigated SR1999, LR2000 and SR2000 the model predicted leaves, stems, TDM, LAI and grain yield were generally between - 20 to + 20 % of the measured values at validation stage. Soil moisture was overestimated by between 27 to 29 % at validation stage in all the seasons (Table 8.2).

Table 8.2. Summarized model calibration and validation results, SR1999, LR2000, SR2000 and Fertilizer Recommendation Project (FURP) seasons (1988 to 1991).

Variable	Calibration season	Validation seasons					
	SR2000-R	SR1999-R	SR1999-Ir	LR2000-R	LR2000-Ir	SR2000-Ir	FURP
Leaves	-9 (0.97)			+90 (0.78)	-31 (0.86)	-11 (0.96)	
stems	+2 (0.61)			+765 (0.97)	-4 (0.60)	-2 (0.86)	
TDM	+12 (0.99)			+490 (0.92)	+12 (0.96)	+13 (0.99)	
LAI	+0.5 (0.39)	+7(0.88)	+7 (0.90)	+57(0.68)	-20 (0.68)	+5 (0.42)	
Soil moisture	+27 (0.69)	+29 (0.84)	+27 (0.84)	+27 (0.84)		+29 (0.84)	
Grain yield		+24	-4	+380	+20	+10	+21 (0.55)
		Regression of simulated verses measured for 1999 - 2000 seasons combined -10 (0.95)					
		Regression of simulated verses measured for 1999 - 2000 seasons combined with FURP seasons -11 (0.93)					

R^2 values in brackets (+ or -) indicate overestimate or underestimate respectively

8.4 Discussion

The model was weak in the prediction of leaf area index and volumetric soil profile moisture. Even at the calibration stage it was not possible to make the simulated values agree well with the measured values in most of the growth stages. The simulated LAI started at a slightly lower value than measured LAI and ended with a quite higher value at maturity. This may be due to failure by the model to accurately cater for the senescence of the leaves after flowering. The maximum simulated LAI were however similar to measured LAI in both the calibration and validation cases (Figure 8.9). The simulated LAI was related to simulated leaves and stems dry weights in the model (i.e., LAI is a function of TDM). The relationships between specific leaf area (SLATB) with leaves, stems and total dry matter need to be re-examined so that when the measured SLATB at germination and flowering and measured partitioning factors are put into the model it produces reasonable LAI, leaves and stems dry weight comparable to measured values.

The relationship between simulated and measured volumetric profile soil moisture was poor during pre-anthesis (before flowering) period and good during post-anthesis (after flowering) (Figure 8.1e and 8.2). This could be due to the model underestimating infiltration and surface runoff and evaporation early in the season. Underestimation of surface run-off by the model was observed in two out of three tested sites in Kenya (Rotter, 1993) and he attributed them with the approach used in calculating infiltration and run-off in the model. Surface runoff was assumed to be zero when calculating evapotraspiration but this may not be true in some occasions during high intensity rains. Earlier intense adjustments within the model (Rotter, 1993) using calibration with lower dry matter values partitioned to leaves (Appendix 5) may be the reason why the model does not work properly with the more accurate partitioning factors measured during high ainfall SR2000 season.

he validation showed that reasonable estimations of grain yield, leaves, stems and total dry matter can be made only after adjustment of the measured partitioning factors which was a great weakness in the model. The results showed that under wet conditions and with good calibration (taking care of the partitioning weakness by slight adjustment of partitioning factors to obtain best fit between simulated and measured variables), grain yield can be predicted to an accuracy of between 80 and 90 %. The prediction of the various variables was better under moderate to high rainfall (278 to 534 mm) or under irrigated conditions compared with low rainfall. Under very dry conditions (143 mm seasonal rainfall, LR2000), the model tended to overestimate the various outputs by a very high margin (30 – 765 %). One possible reason for this may be that the model calibration requires that it be done under optimum (sufficient) moisture conditions. Under these conditions dry matter partitioning to leaves, stems and storage organs are higher than under dry conditions (see rainfed LR2000 and irrigated LR2000 partitioning, (chapter 4.3.5). Under dry conditions therefore (probably with rainfall below 200 mm) it may be advisable to use partitioning factors obtained under such dry conditions if accurate predictions of the various variables are to be attained.

CHAPTER 9

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS.

9.1 General discussion

N application above 50 kg ha $^{-1}$ did not result in increase in leaf area index, fractional PAR interception, N uptake, TDM and grain yield. There was improved N uptake from both soil and applied fertilizer with irrigation application because of improved soil moisture status which possibly increased N availability through mineralization and solubilization of fertilizer N in water. Higher fertilizer N recovery with irrigation (Table 6.3) suggested that response at N application of 100 kg N ha^{-1} could be expected with higher water supply than was used in this study. Since the initial soil N levels were low (0.07 – 0.08 %) (Chapter 3.1) full fertilizer N response at 100 kg N ha^{-1} could have been limited by either insufficient water or physiological limitation of N utilization by Katumani composite B maize. The physiological limitation is associated with Katumani composite B. characteristics i.e. short growth duration (100 to 110 days from emergence to physiological maturity) and few leaves (highest mean number of leaves was 12 – 13) and individual leaf size (Eik and Hanway, 1965; Lemcoff and Loomis, 1986; Muchow, 1994 and Bennet *et a*l, 1989). N fertilizer increased soil water extraction and water use efficiency in maize because of increased LAI and PAR interception (Figure 4.6 and 5.4 respectively).

These seasons had also the highest N uptake (164 to 175 kg N ha^{-1}), evapotranspiration (527 to 602 mm) and water use efficiency (21.1 to 26.9 kg ha^{-1} mm^{-1}). Irrigated fertilized SR1999 had slightly lower grain yield because of lower N uptake (110 to 132 kg N ha^{-1}) and slightly lower water use efficiency (20.3 to 20.6 kg ha^{-1} mm^{-1}). This was due to slightly lower net cumulative PAR interception in irrigated SR1999 compared to SR2000 and irrigated LR2000 (Figure 5.4) occasioned by lower total net leaf area in SR1999 (Figure 4.6). Low moisture supply resulted in low ET low N uptake low cumulative PAR interception and reduced TDM and grain yield.

Increased water supply increased uptake of available soil N by increasing mineralization of organic N (Pilbeam *et al.*, 1995; Jarvis *et al.*, 1996). This resulted in increased LAI and leaf duration hence increased cumulative PAR interception. Increased cumulative PAR interception resulted in higher TDM and grain yield due higher net photosynthesis.

Maize TDM and grain yields were related to N uptake, water and cumulative PAR interception. This indicated that the higher the water uptake, cumulative PAR intercepted and N uptake the higher the TDM and grain yield. The highest TDM and grain yield were obtained under N application in the wet SR2000 and higher water supply, i.e., under irrigation in LR2000.

9.2 EMPIRICAL RELATIONSHIPS BETWEEN TOTAL DRY MATTER, YIELD, NITROGEN, WATER AND LIGHT USE.

Assuming that water availability was the determining factor of N and PAR use in maize growth and yield, the relationships in Figures 9.1 to 9.3 were used to verify the assumption. Multiple regression analysis was used to derive the equations below relating TDM and grain yield to N uptake, ET and cumulative PAR interception. All the relationships were significant. The stars/lack of stars indicate significant/non significant contribution of each factor to the overall equation where,

*** = very highly significant (0.001 probability level)

* = significant (0.05 probability level)

Rainfed without N.

TDM = -532.807 + 70.961 x N*** + 6.909 x ET* – 1.578 x CUMPAR, R^2 = 1.000

Grain yield = -261.152 + 2.005 x N*** + 11.7 x ET*** + 4.676 x CUMPAR, R^2 = 1.000

Rainfed with N.

TDM = 2666.196 + 97.634 x N + 2.277 x ET – 15.007 x CUMPAR, R^2 =0.998

Grain yield = -889.573 + 21.178 x N + 10.589 x ET-2.513 x CUMPAR, R^2 = 1.000

Irrigated without N.

TDM = 4276.32 + 56.182 x N*** + 8.164 x ET*** – 12.181 x CUMPAR***, R^2 = 0.99

Grain yield = 3318.768 + 38.261 x N*** – 3.263 x ET – 2.9 x CUMPAR, R^2 = 0.97

Irrigated with N

TDM = 7028.841 + 34.092 x N*** + 4.783 x ET – 5.825 x CUMPAR, R^2 = 0.83

Grain yield = 1495.266 + 9.673 x N* + 1.703 x ET + 3.985 x CUMPAR, R^2 = 0.92

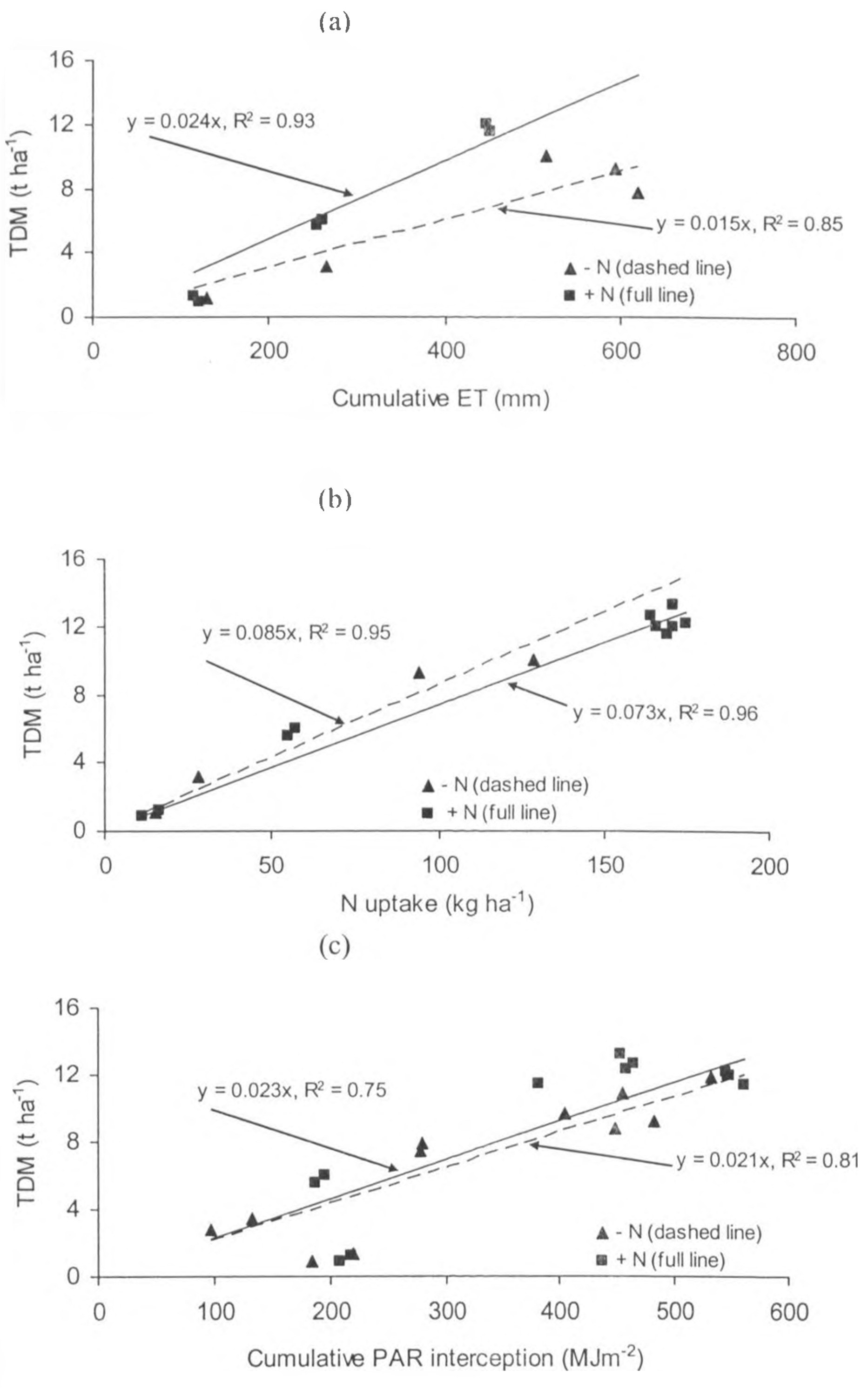


Figure 9.1. Relationship between maize (a) grain yield and cumulative evapotranspiration (b) TDM and total N uptake (c) TDM and cumulative PAR interception, at Katumani, Kenya (all seasons data pooled i.e. SR1999, LR2000 and SR2000). (- N , + N) = without and with N application.

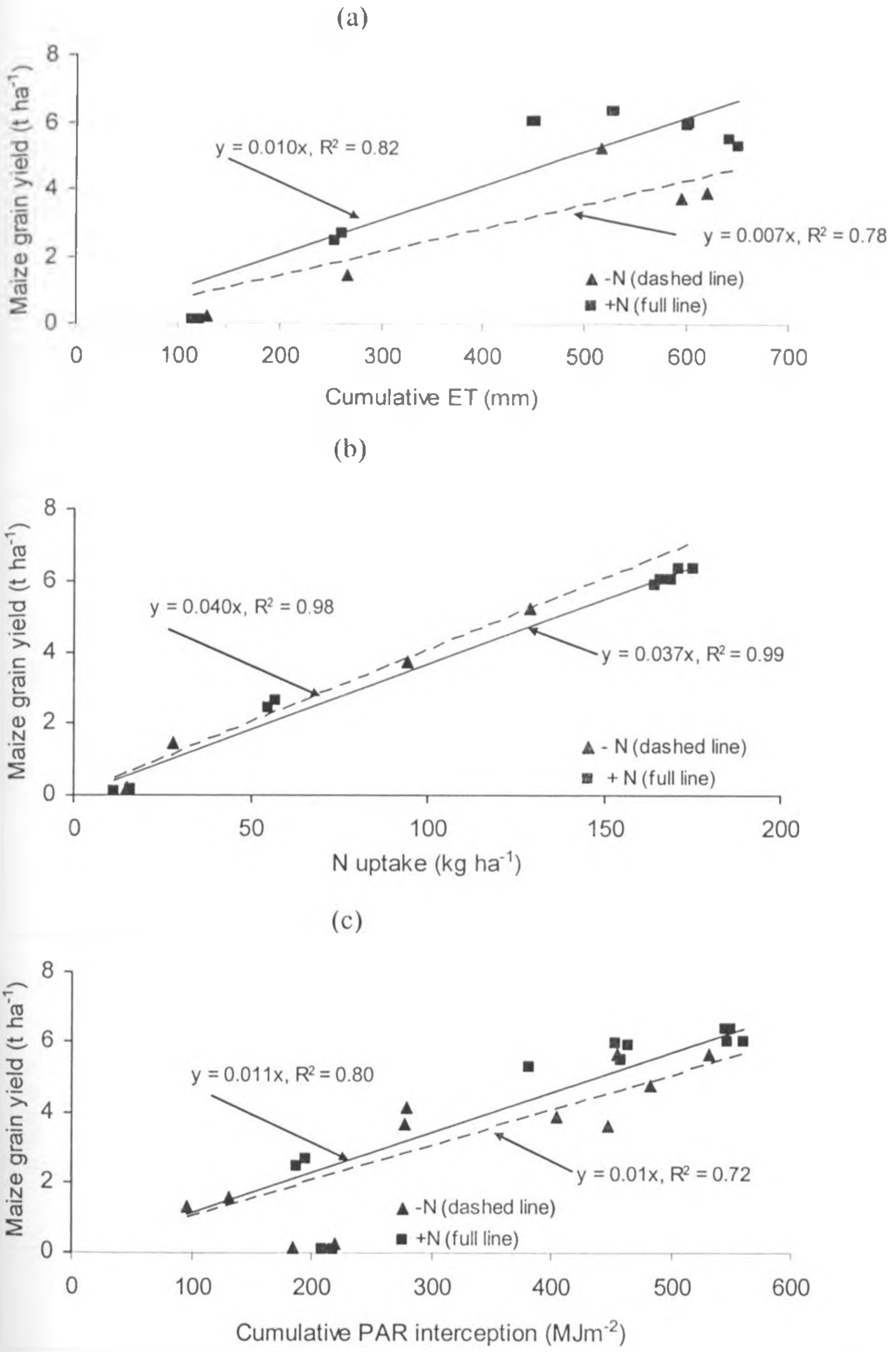


Figure 9.2. Relationship between Maize (a) Grain yield and cumulative evapotranspiration (b) Grain yield and total N uptake (c) grain yield and cumulative PAR interception at Katumani, Kenya (all seasons data pooled i.e. SR1999, LR2000 and SR2000). (- N, + N) = without and with N application.

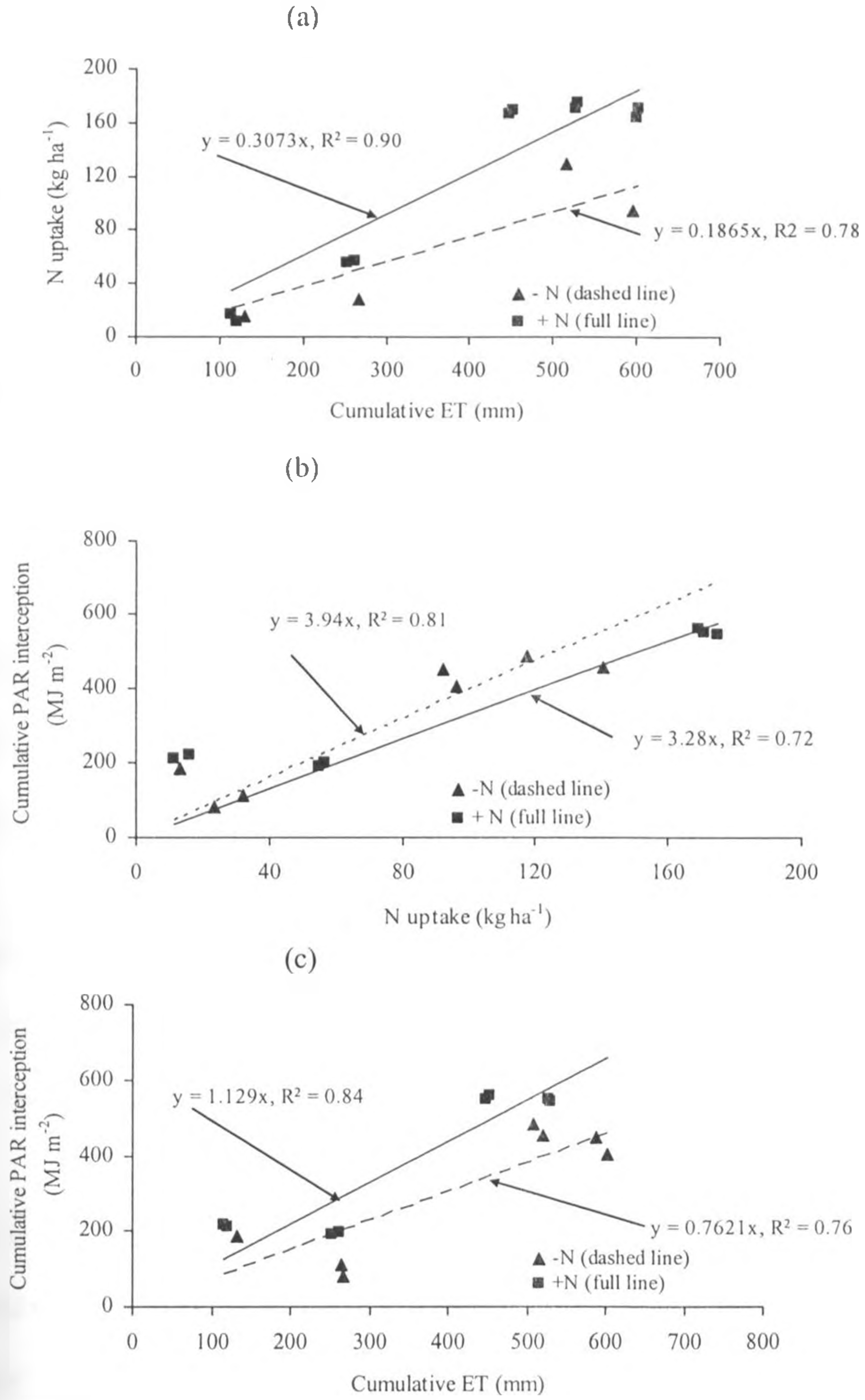


Figure 9.3. Relationship between Maize (a) Total N uptake and Cumulative evapotranspiration (b) cumulative PAR interception and total N uptake (c) cumulative PAR interception and Cumulative evapotranspiration at Katumani, Kenya (all seasons data pooled i.e. SR1999, LR2000 and SR2000). (- N, + N) = without and with N application.

9.2.2 Discussion

Total dry matter is related to water and solar radiation supply and to N uptake by the equations below (Pervez, 2004).

$$TDM = E_w \text{ x water supply (ET)} \qquad (1)$$

$$TDW = E_{light} \text{ x solar radiation supply} \qquad (2)$$

$$TDM = E_N \text{ x N uptake} \qquad (3)$$

Where,

E_w = water use efficiency (kg ha^{-1} mm^{-1})

E_{light} = light use efficiency

E_N = nitrogen use efficiency

The equations suggest that TDm is proportional to water, solar radiation supply and N uptake since the efficiencies are constant for each factor. Similarly grain yield is related to the three factors by:-

$$\text{Grain yield} = E_w \text{ x water supply (ET) x HI} \qquad (4)$$

$$\text{Grain yield} = E_{light} \text{ x solar radiation supply x HI} \qquad (5)$$

$$\text{Grain yield} = E_N \text{ x N uptake x HI} \qquad (6)$$

Where,

HI = harvest index

So grain yield like TDM is also proportional to water, solar radiation supply and N uptake. N influence both TDM and grain yield through its effect on leaf growth (i.e. LAI) and photosynthetic efficiency effect. The linear relationships in Figures 9.1 to 9.3 thus conform to the above equations (1 – 6). i.e TDM = f(($\sum$N uptake) + ($\sum$ET) +($\sum$PAR) and grain yield = TDM * HI, where,

$\sum$N uptake = total N

$\sum$ET = cumulative evapotranspiration

$\sum$PAR = cumulative PAR interception

HI = harvest index

The light interception per unit N uptake was 3.94 MJ m^{-2} kg^{-1}ha without N application and 3.28 MJ m^{-2} kg^{-1}ha with N application (Figure 9.3 b) which was 3 to 4 times the light interception per unit of ET (Figure 9.3 c). This explains the prominent role played by N (equations 1 to 6, page 126). N application increased water use and light use efficiency (Figure 9.1 and 9.2, a). N application increased light interception per unit of ET (Figure 9.3 c) because of increased LAI and photosynthetic efficiency while N fertilizer increased yield mainly by increasing LAI and photosynthetic efficiency (Squire, 1990; William, 1996).

Since E_w x water supply = E_N x N uptake = E_{light} x solar radiation supply and solar energy was reasonably supplied the major factor limiting photosynthesis was water supply and this also influenced N uptake. Both N uptake and PAR utilization depended on ET, which is an indicator of water supply. Increased evapotranspiration resulted in increased N uptake (Figure 9.3 a) possibly due to increased N availability, root and shoot growth (Eik and Hanway, 1965; Lemcoff and Loomis, 1986; Muchow, 1994). Fertilizer N application increased N uptake due to increased N supply resulting in increased leaf area index, leaf area duration, crop photosynthetic rate and hence increased radiation interception. N application decreased nitrogen use efficiency compared to control treatments (Figure 9.1 and 9.2, b). Except for legumes, nitrogen use efficiency is largest when no N is added and decreases as N application increases (Squire, 1990). This is because when N is not limiting yield the amount of N taken up by the crop is governed by the dry matter produced and there is no fixed ratio of dry matter to N uptake; more N will be taken up if more is available (Squire, 1990), thus decreasing N use efficiency.

In the semi-arid areas where water supply is often limited due to low and erratic rainfall, agronomic practices should aim at utilizing the available water for crop growth in an efficient way (Theib *et al.,* 2000). Improved production from a limited water supply can result from increasing the total amount of water used by the crop through supplemental irrigation and improving the efficiency of water use by minimizing losses, applying water only when there is a deficit and by N application. The good correlation between grain yield and cumulative evapotranspiration (crop water use) in this study indicates that grain yield is strongly influenced by the pattern of water use during the course of the season and emphasizes the importance of adequate water supply for higher yield and water use efficiency. Increased water use efficiency with increased water supply and N application (Table 7.5 and 7.6) indicates that water is used more efficiently if combined with N

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9.3 CONCLUSIONS AND RECOMMENDATIONS

- Water was the main limitation to maize yields at the experimental site and supplemental irrigation can improve fertilizer N use and availability to the maize and hence improve maize growth and yield even at low fertilizer input levels in semi arid Kenya. To attain a target maize yield of 6000 kg ha^{-1}, water supply of between 618 - 755 mm (rainfall + irrigation) and fertilizer N application of about 50 kg N ha ^{1} would be required.
- The conclusions above would also apply in most farmers fields in the area because the soil N levels are normally even lower than at the experimental site of this study. If one applies N and water, he/she can continue growing Katumani maize because it matures faster, has lower net water requirements and is better adapted for the semi arid environments than the other highland maize varieties.
- Maize total dry matter and grain yield can be derived quite accurately from information on N uptake, water use (evapotranspiration) and light use (cumulative PAR interception).
- In view of the water scarcity in semi-arid areas and from the experience of this study drip irrigation can play a very important role in enhancing crop production in these areas. To attain food sufficiency drip irrigation is certainly an option that need to be considered.

- The model needs to be re-examined so that it simulates dry leaves and hence LAI better using accurately determined partitioning factors. The soil profile moisture module in the model needs further re-examination to give more accurate pre-anthesis soil moisture levels.

9.4 Areas that need further research

Crop modeling in Kenya is inhibited by lack of relevant crop data on shoot and root dry matter accumulation with time. In view of the important role maize plays in Kenya's agriculture the following areas need further research to facilitate use of crop models:

1. Determination of root and shoot dry matter accumulation and shoot dry matter partitioning to leaves, stems and reproductive organs for other Kenyan maize cultivars.
2. Improvement of leaf area and soil profile moisture estimations by the WOFOST model.

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APPENDICES

Appendix 1. Input and output parameters for the WOFOST model.

Input parameters

For a simulation run the user first chooses the crop species, climate and soil type for which the corresponding sets of data are called from standard data files. Then the user has to provide some site specific information such as moisture conditions, depth of groundwater, physical properties of the soil surface, data on soil fertility, which are not included in these files and the starting date (the date of emergence or transplanting). The standard data files are generally not changed, but the user may edit them provided the file structure is maintained.

Climatic information

Minimum and maximum air temperatures, global radiation or sunshine hours, humidity or dew point temperature, wind speed, monthly rainfall and number of rainy days. The model uses the monthly climatic data of the CLIM41.DAT file and converts them to daily values for the simulation procedure.

Soil profile data

Variables to be specified by the user are soil type (i.e. soil texture class), maximum rooting depth, and presence of groundwater table with its initial depth.

Soil physical data

Soil moisture characteristics, soil hydraulic conductivity as a function of soil moisture tension, non-infiltrating fraction of rain and surface water capacity.

Soil fertility data

Base uptake of nitrogen, phosphorus and potassium from unfertilized soil and the recovery fractions of N-, P- and K- fertilizers. The base uptake is the nutrient uptake by a reference crop (e.g. maize) with a growth cycle of 120 days. For other crops the base uptake is related to the length of their growth cycle. Special constraints such as acidity, salinity, toxicities or micro-nutrient deficiencies are not considered in the model.

Crop data

Data required include initial dry weight, life span of leaves, rate of phenological development, death rates, fraction of assimilates partitioned to plant organs, and the minimum and maximum nutrient concentrations per plant organ. The data are already available in the CROP41.DAT file. The length of the growth cycle is the only crop characteristic that can be interactively adjusted by the user.

Output parameters

The model allows the user to modify the output specifications to suit specific requirements. The output for the whole growing period are total dry weight of roots (dead and living), total dry weight of leaves (dead and living), total dry weight of stems (dead and living), total dry weight of storage organs, total above-ground dry weight (dead and living), total gross assimilation in carbohydrates, total maintenance respiration, harvest index, transpiration coefficient (ratio of water use and dry matter production), water use or total transpiration during growth cycle. All these values are also calculated per decade basis and can be viewed or printed.

Summarized input data

Crop species, climate and soil type, moisture conditions, depth of groundwater, physical properties of the soil surface, data on soil fertility, starting date (the date of emergence or transplanting), minimum and maximum air temperatures, global radiation or sunshine hours, humidity or dew point temperature, wind speed, monthly rainfall and number of rainy days. soil texture class, maximum rooting depth, and presence of groundwater table with its initial depth, soil moisture characteristics, soil hydraulic conductivity as a function of soil moisture tension, non-infiltrating fraction of rain and surface water capacity, soil fertility data, base uptake of nitrogen, phosphorus and potassium from unfertilized soil and the recovery fractions of N-, P- and K- fertilizers, data required include initial dry weight, life span of leaves, rate of phenological development, death rates, fraction of assimilates partitioned to plant organs, and the minimum and maximum nutrient concentrations per plant organ.

Appendix 2. Soil chemical and physical properties of the experimental site.

Horizon	A	Bu1	Bu2	Bu3
Depth (cm)	0-27	27-48	48-118	118-136
Sand %	48	32	48	28
Silt %	4	24	4	10
Clay %	48	44	48	64
Texture class	SC	C	SC	C
pH-H_2O	6.6	6.2	6.2	6.5
% C	0.82	0.42	0.56	0.35
CEC (me/100g)	10.9	11.2	10.5	12.5
Total Ca(me/100g)	8.7	6.3	8.1	6.6
Total Mg "	2.0	2.6	2.4	2.7
Total K "	1.5	0.9	1.7	0.9
Total Na "	0.7	0.6	0.6	0.7
Sum of cations	12.9	10.4	10.0	10.9
Base sat. %, pH 7.0	100	93	80	87

Fertility aspects	0 - 30 cm
pH-H_2O	6.52
C %	0.82
Na me/100g	0.03
K me/100g	1.05
Ca me/100g	4.25
Mg me/100g	1.48
Mn me/100g	0.67
P p.p.m (Mehlic method)	29-46[*]

Appendix 3 Actual measured partitioning of added dry matter with time for Katumani composite b maize rainfed, short rains 2000.

Development stage*	DAE	Leaves	Stems	Storage organs
0.00	0	0.73	0.27	0.00
0.48	24	0.76	0.24	0.00
0.90	45	0.44	0.54	0.02
1.25	62.5	0.00	0.37	0.63
1.37	68.5	0.00	0.33	0.67
2.00	100	0.00	0.06	0.94

* *Expressed on a numerical scale, 0 = emergence, 1 = flowering and 2 = maturity.Partitioning values calculated from data on dry matter distribution.*

Appendix 4 Adjusted partitioning of added dry matter with time for Katumani composite b maize.

Development stage	DAE	Leaves	Stems	Storage organs
0.00	0	0.73	0.27	0.00
0.48	24	0.73	0.27	0.00
0.90	45	0.14	0.84	0.02
1.25	62.5	0.00	0.27	0.74
1.37	68.5	0.00	0.00	1.00
2.00	100	0.00	0.00	1.00

Appendix 5 Earlier partitioning of added dry matter with time for Katumani composite b maize (Rotter, 1993).

Development stage	DAE	Leaves	Stems	Storage organs
0.00	0	0.62	0.38	0.00
0.48	24	0.58	0.42	0.00
0.90	45	0.22	0.78	0.00
1.25	62.5	0.00	0.48	0.52
1.37	68.5	0.00	0.00	1.00
2.00	100	0.00	0.00	1.00

Appendix 6 Climatic, crop and soil files.

(1) CLIMATIC File "WOFOST-format"

```
** WCCDESCRIPTION=Kenya, Katumani/Machakos

** WCCFORMAT=0 indicates time series of monthly averages

** WCCYEARS=1999-2001, data period

* line 1 89 = station number

* line 2: year, latitude, altitude, the coefficients A and B for the

* Angstrom formula.

* Line 3 minimum temperature (°C), maximum temperature (°C),irradiation

* (MJm^-2d^-1), vapor pressure (hPa), wind speed (ms^-1), precipitation

* (mm. month-1),

* number of rainy days (d)

* Data from April 2001 not entered because it was not being used

* This data used in combination with daily rainfall

*

89 KATUMANI/ MACHAKOS

1999 -1.58 1600 0.25 0.45

14.0 27.6 24.3 13.8 1.6 16.1 1.0

13.7 28.9 25.0 12.4 1.6 2.2 14.0

15.5 27.2 22.9 18.8 1.4 126.1 16.0

14.8 25.0 20.5 16.1 1.2 113.8 16.0

13.6 24.8 19.1 14.1 1.5 9.8 3.0
```

12.1 23.7 16.7 13.0 1.2 5.0 2.0

12.0 22.4 17.8 12.6 1.3 2.4 2.0

12.6 23.1 15.1 13.0 1.6 4.1 2.0

12.1 25.5 20.8 12.1 2.0 0.0 0.0

13.3 26.6 22.5 12.6 1.9 20.6 2.0

14.7 24.4 22.5 16.0 1.5 234.5 23.0

14.6 23.5 23.0 16.5 1.3 108.6 20.0

89 KATUMANI/MACHAKOS

2000 -1.58 1600 0.25 0.45

12.5 25.8 26.5 12.9 1.4 7.0 2.0

12.1 28.7 27.5 10.9 1.4 0.0 0.0

15.1 28.8 26.7 14.3 1.7 53.3 6.0

14.5 26.5 23.6 14.9 1.4 68.5 6.0

13.5 25.2 21.4 13.8 1.7 15.1 7.0

12.5 23.6 18.7 13.0 1.5 5.7 3.0

11.6 22.4 17.8 12.6 1.5 0.3 1.0

11.9 23.8 19.7 11.8 1.8 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0

13.5 27.2 25.9 11.6 2.2 41.0 3.0

15.4 25.1 24.1 16.4 1.6 189.8 16.0

14.7 24.7 25.7 15.8 1.4 99.7 11.0

89 KATUMANI/MACHAKOS

2001 -1.58 1600 0.25 0.45

```
13.8 24.6 25.4 15.8 1.0 244.2 15.0

14.3 26.4 29.0 14.4 1.4 0.0 0.0

14.2 26.9 27.6 14.4 1.3 93.5 5.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0

0.0 0.0 0.0 0.0 0.0 0.0 0.0
```

(2) CROP FILE

```
** CROP DATA FILE for use with WOFOST, version 7.1, Dec. 2001.

** Purpose of application: Model calibration for simulation of

** maize yields in semi arid Kenya.

CRPNAM='Katumani B. Maize, P.T. Kamoni 2001'

** emergence

TBASEM   = 9.0 ! lower threshold temp. for emergence [cel]

TEFFMX   = 30.0 ! max. eff. temp. for emergence [cel]

TSUMEM   = 80. ! temperature sum from sowing to emergence [cel  d]

** phenology
```

```
IDSL     = 0 ! indicates whether pre-anthesis development depends
         ! on temp. (=0), daylength (=1) , or both (=2)
DLO      = 1.00 ! optimum daylength for development [hr]
DLC      = 0.00 ! critical daylength (lower threshold) [hr]
TSUM1    = 524 ! temperature sum from emergence to anthesis [cel d]
TSUM2    = 573 ! temperature sum from anthesis to maturity [cel d]
DTSMTB   = 0.00,  0.00, ! daily increase in temp. sum
       8.00, 0.00, ! as function of av. temp. [cel; cel d]
       30.00, 22.00,
       35.00, 22.00
DVSI     = 0. ! initial DVS
DVSEND   = 2.00 ! development stage at harvest (= 2.0 at maturity [-])
** initial
DWI      = 10.00 ! initial total crop dry weight [kg ha-1]
AIEM     = 0.02604 ! leaf area index at emergence [ha ha-1]
GRLAI    = 0.0503  ! maximum relative increase in LAI [ha ha-1 d-1]


* green area
LATB     = 0.00,  0.0020, ! specific leaf area
      1.00,  0.00186, ! as a function of DVS [ha kg-1]
      2.00,  0.00186
PA       = 0.000 ! specific pod area [ha kg-1]
SATB     = 0.0, 0., ! specific stem area [ha kg-1]
```

```
        2.0, 0. ! as function of DVS
SPAN     = 30. ! life span of leaves growing at 35 Celsius [d]
TBASE    = 9.0! lower threshold temp. for ageing of leaves [cel]
** assimilation
KDIFTB   = 0.0,  0.60, ! extinction coefficient for diffuse visible
        2.0,  0.60 ! light [- ] as function of DVS
EFFTB    = 0.,   0.45, ! light-use effic. single leaf [kg ha-1 hr-1 J-1
        40.,  0.45 ! m2 s] as function of daily mean temp.
AMAXTB   = 0.00, 70.00, ! max. leaf CO2 assim. rate
        1.25, 70.00, ! function of DVS [-; kg ha-1 hr-1]
        1.50, 63.00,
        1.75, 49.00,
        2.00,  0.00
TMPFTB   = 0.00,  0.00, ! reduction factor of AMAX
        6.00,  0.00, ! as function of av. temp. [cel; -]
        30.00, 1.00,
        42.00, 1.00,
        51.00, 0.00
TMNFTB   = 5.00,  0.00, ! red. factor of gross assim. rate
        12.00,  1.00 ! as function of low min. temp. [cel; -]
** conversion of assimilates into biomass
CVL      = 0.720 ! efficiency of conversion into leaves [kg kg-1]
CVO      = 0.720 ! efficiency of conversion into storage org. [kg kg-1]
```

```
CVR    = 0.720 ! efficiency of conversion into roots [kg kg-1]

CVS    = 0.690 ! efficiency of conversion into stems [kg kg-1]

** maintenance respiration

Q10    = 2.0 ! rel. incr. in resp. rate per 10 Cel temp. incr. [-]

RML    = 0.0300 ! rel. maint. resp. rate leaves [kg CH2O kg-1 d-1]

RMO    = 0.0100 ! rel. maint. resp. rate stor.org. [kg CH2O kg-1 d-1]

RMR    = 0.0100 ! rel. maint. resp. rate roots [kg CH2O kg-1 d-1]

RMS    = 0.0150 ! rel. maint. resp. rate stems [kg CH2O kg-1 d-1]

RFSETB   = 0.00,  1.00    ! red. factor for senescence

       2.00,  1.00    ! as function of DVS [-; -]

** partitioning

FRTB     = 0.00,  0.40, ! fraction of total dry matter to roots

       1.10,  0.00, ! as a function of DVS [-; kg kg-1],

       2.00,  0.00

FLTB     = 0.00,  0.73, ! fraction of above-gr. DM to leaves

       0.48,  0.73, ! as a function of DVS [-; kg kg-1]

       0.90,  0.14,

       1.25,  0.00,

       1.37,  0.00,

       2.00,  0.00

FSTB     = 0.00,  0.27, ! fraction of above-gr. DM to stems

       0.48,  0.27, ! as a function of DVS [-; kg kg-1]

       0.90,  0.84,
```

```
         1.25,  0.26,
         1.37,  0.00,
         2.00,  0.00
FOTB    = 0.00,  0.00, ! fraction of above-gr. DM to stor. org.
         0.48,  0.00, ! as a function of DVS [-; kg kg-1]
         0.90,  0.02,
         1.25,  0.74,
         1.37,  1.00,
         2.00,  1.00
** death rates
PERDL    = 0.030 ! max. rel. death rate of leaves due to water stress
RDRRTB    = 0.00,   0.000, ! rel. death rate of roots
         1.50,   0.000, ! as a function of DVS [-; kg kg-1 d-1]
         1.5001, 0.020,
         2.00,   0.020
RDRSTB    = 0.00,   0.000, ! rel. death rate of stems
         1.50,   0.000, ! as a function of DVS [-; kg kg-1 d-1]
         1.5001, 0.020,
         2.00,   0.020
** water use
CFET      = 1.00   ! correction factor transpiration rate [-]
DEPNR     = 4.5    ! crop group number for soil water depletion [-]
IAIRDU    = 0      ! air ducts in roots present (=1) or not (=0)
```

```
** rooting
RDI     = 10. ! initial rooting depth [cm]
RRI     = 1.4 ! maximum daily increase in rooting depth [cm d-1]
RDMCR     = 90. ! maximum rooting depth [cm]
** nutrients
** maximum and minimum concentrations of N, P, and K
** in storage organs in vegetative organs [kg kg-1]
NMINSO   = 0.0095;     NMINVE    = 0.0040
NMAXSO    = 0.0220;     NMAXVE    = 0.0125
PMINSO   = 0.0017;     PMINVE    = 0.0004
PMAXSO    = 0.0075;     PMAXVE    = 0.0030
KMINSO   = 0.0020;     KMINVE    = 0.0050
KMAXSO    = 0.0060;     KMAXVE    = 0.0200
YZERO    = 400. ! max. amount veg. organs at zero yield [kg ha-1]
NFIX    = 0.00  ! fraction of N-uptake from biol. fixation [kg kg-1]
```

(3) SOIL FILE

```
** SOIL DATA FILE for use with WOFOST version 7.1, sept. 2001
** soil data for Katumani Ph.D site, KENYA
SOLNAM='clay  (chr. Luv. Katumani)'
** soil physical soil characteristics
SMTAB  =  -1.000,   0.506, ! vol. soil moisture content
          1.000,   0.444, ! as function of pF [log (cm); cm3 cm-3]
```

```
        1.300,  0.416,
        1.491,  0.395,
        2.000,  0.341,
        2.400,  0.288,
        2.700,  0.269,
        3.400,  0.203,
        4.204,  0.160,
        6.000,  0.076
SMW    =  0.167   !  soil moisture content at wilting point [cm3/cm3]
SMFCF  =  0.296   !  soil moisture content at field capacity [cm3/cm3]
SM0    =  0.506   !  soil moisture content at saturation [cm3/cm3]
CRAIRC =  0.090   ! critical soil air content for aeration [cm3/cm3]
** hydraulic conductivity
CONTAB =  0.000,  1.421, ! 10-log hydraulic conductivity
        1.000,  0.603, ! as function of pF [log (cm); log (cm/day)]
        1.300,  0.326,
        1.491,  0.117,
        1.700, -0.125,
        2.000, -0.745,
        2.400, -2.292,
        2.700, -2.854,
        3.000, -3.237,
        3.400, -3.745,
```

Appendix 7. Mean square variance of maize height at Katumani, Kenya.

Season	Source	MSE	maize height						
		df/ DAE	23	28	33	44	50	68	81
SR1999	Replication	2	73.8	129	200	579	835	473	464
	Irrigation (Ir)	1	11	18	138	789	1940	2687	3010
	Error a	2	22.8	114.8	167	507	623	284	303
	N	2	188.7***	423***	751***	3383***	5593***	2971***	2067***
	P	1	76.8*	65*	62	189	182	24	1.2
	Ir x N	2	0.29	4.32	17.5	104	189	58	3715
	Ir x P	1	11.79	11.33	5.44	4.77	31.55	6.3	90.3
	N x P	2	32.83	24	25.96	172	210	114	65.6
	Ir x N x P	2	0.39	4.66	6.31	68	117.7	84	196
	Error b	20	11.9	11.6	20.4	83.6	144	71.6	79
LR2000			19	30	42	48	54	63	84
	Replication	2	3.63	46.7	393	1013	1459	1965	1924
	Irrigation (Ir)	1	652*	7236**	29532**	47176**	59203**	56731**	55617**
	Error a	2	11.4	72	177	380	475	429	381
	N	2	44.9**	188*	68.8*	41.9	6.2	94	16.2
	P	1	15	36.4	1.73	0.32	9.5	51.6	49.5
	Ir x N	2	16.4	126	317*	406	355	332	221
	Ir x P	1	5.9	55.8	74.2	26.7	1.9	9.7	0.07
	N x P	2	6.4	11.5	117.7	209	199.8	227	311
	Ir x N x P	2	3.9	18	52.9	67	34.5	28.8	68.7
	Error b	20	5.23	39.1	64.6	122.6	183	234	285
SR2000			16	28	36	42	47	65	83
	Replication	2	2.57	20.6	207	147	316	6.8	309
	Irrigation (Ir)	1	2.51	224.5*	160	589*	1284*	112	785
	Error a	2	0.88	6.49	42	29.1	15	84	679
	N	2	64.7***	328***	826***	1494***	1372***	168*	889
	P	1	14.8*	108.5*	119	53.8	56.8	20	140
	Ir x N	2	0.51	2.2	8.3	4.5	100	249*	801
	Ir x P	1	2.95	40.7	75	212	108	9.2	360
	N x P	2	1.98	21.9	4.3	52.6	33.5	54.6	203
	Ir x N x P	2	1.6	4.4	1.2	4.2	14.3	46.6	491
	Error b	20	1.92	15.6	35.7	48.4	86.3	45.7	387

Appendix 7. Mean square variance of maize height at Katumani, Kenya.

Season	Source	MSE	maize height						
		df/ DAE	23	28	33	44	50	68	81
SR1999	Replication	2	73.8	129	200	579	835	473	464
	Irrigation (Ir)	1	11	18	138	789	1940	2687	3010
	Error a	2	22.8	114.8	167	507	623	284	303
	N	2	188.7***	423***	751***	3383***	5593***	2971***	2067***
	P	1	76.8*	65*	62	189	182	24	1.2
	Ir x N	2	0.29	4.32	17.5	104	189	58	3715
	Ir x P	1	11.79	11.33	5.44	4.77	31.55	6.3	90.3
	N x P	2	32.83	24	25.96	172	210	114	65.6
	Ir x N x P	2	0.39	4.66	6.31	68	117.7	84	196
	Error b	20	11.9	11.6	20.4	83.6	144	71.6	79
LR2000			19	30	42	48	54	63	84
	Replication	2	3.63	46.7	393	1013	1459	1965	1924
	Irrigation (Ir)	1	652*	7236**	29532**	47176**	59203**	56731**	55617**
	Error a	2	11.4	72	177	380	475	429	381
	N	2	44.9**	188*	68.8*	41.9	6.2	94	16.2
	P	1	15	36.4	1.73	0.32	9.5	51.6	49.5
	Ir x N	2	16.4	126	317*	406	355	332	221
	Ir x P	1	5.9	55.8	74.2	26.7	1.9	9.7	0.07
	N x P	2	6.4	11.5	117.7	209	199.8	227	311
	Ir x N x P	2	3.9	18	52.9	67	34.5	28.8	68.7
	Error b	20	5.23	39.1	64.6	122.6	183	234	285
SR2000			16	28	36	42	47	65	83
	Replication	2	2.57	20.6	207	147	316	6.8	309
	Irrigation (Ir)	1	2.51	224.5*	160	589*	1284*	112	785
	Error a	2	0.88	6.49	42	29.1	15	84	679
	N	2	64.7***	328***	826***	1494***	1372***	168*	889
	P	1	14.8*	108.5*	119	53.8	56.8	20	140
	Ir x N	2	0.51	2.2	8.3	4.5	100	249*	801
	Ir x P	1	2.95	40.7	75	212	108	9.2	360
	N x P	2	1.98	21.9	4.3	52.6	33.5	54.6	203
	Ir x N x P	2	1.6	4.4	1.2	4.2	14.3	46.6	491
	Error b	20	1.92	15.6	35.7	48.4	86.3	45.7	387

Appendix 7. Mean square variance of maize height at Katumani, Kenya.

Season	Source	MSE df/ DAE	maize height 23	28	33	44	50	68	81
SR1999	Replication	2	73.8	129	200	579	835	473	464
	Irrigation (Ir)	1	11	18	138	789	1940	2687	3010
	Error a	2	22.8	114.8	167	507	623	284	303
	N	2	188.7***	423***	751***	3383***	5593***	2971***	2067***
	P	1	76.8*	65*	62	189	182	24	1.2
	Ir x N	2	0.29	4.32	17.5	104	189	58	3715
	Ir x P	1	11.79	11.33	5.44	4.77	31.55	6.3	90.3
	N x P	2	32.83	24	25.96	172	210	114	65.6
	Ir x N x P	2	0.39	4.66	6.31	68	117.7	84	196
	Error b	20	11.9	11.6	20.4	83.6	144	71.6	79
LR2000			19	30	42	48	54	63	84
	Replication	2	3.63	46.7	393	1013	1459	1965	1924
	Irrigation (Ir)	1	652*	7236**	29532**	47176**	59203**	56731**	55617**
	Error a	2	11.4	72	177	380	475	429	381
	N	2	44.9**	188*	68.8*	41.9	6.2	94	16.2
	P	1	15	36.4	1.73	0.32	9.5	51.6	49.5
	Ir x N	2	16.4	126	317*	406	355	332	221
	Ir x P	1	5.9	55.8	74.2	26.7	1.9	9.7	0.07
	N x P	2	6.4	11.5	117.7	209	199.8	227	311
	Ir x N x P	2	3.9	18	52.9	67	34.5	28.8	68.7
	Error b	20	5.23	39.1	64.6	122.6	183	234	285
SR2000			16	28	36	42	47	65	83
	Replication	2	2.57	20.6	207	147	316	6.8	309
	Irrigation (Ir)	1	2.51	224.5*	160	589*	1284*	112	785
	Error a	2	0.88	6.49	42	29.1	15	84	679
	N	2	64.7***	328***	826***	1494***	1372***	168*	889
	P	1	14.8*	108.5*	119	53.8	56.8	20	140
	Ir x N	2	0.51	2.2	8.3	4.5	100	249*	801
	Ir x P	1	2.95	40.7	75	212	108	9.2	360
	N x P	2	1.98	21.9	4.3	52.6	33.5	54.6	203
	Ir x N x P	2	1.6	4.4	1.2	4.2	14.3	46.6	491
	Error b	20	1.92	15.6	35.7	48.4	86.3	45.7	387

Appendix 9. Mean square variance of maize leaf length at Katumani, Kenya.

Season		MSE df/ DAE	leaf length						
			23	28	33	44	50	68	81
SR1999	Replication	2	205	323	507	326	173	65.8	37.7
	Irrigation (Ir)	1	119	10.8	6.0	20.7	53	12.6	75
	Error a	2	11.2	95	57	77	78.2	64	62.5
	N	2	518***	1007***	953***	926***	702***	431***	237***
	P	1	109	213**	36	6.5	6.0	29.7	42.3
	Ir x N	2	48	0.75	21	80.6**	27	8.6	3.7
	Ir x P	1	31.4	15.3	39.1	9.7	1.2	19.5	11.8
	N x P	2	36.8	20.5	4.1	7	11.9	2.8	13.7
	Ir x N x P	2	1.8	8.7	53	20.7	18	8.1	8.5
	Error b	20	25.2	18.7	24.2	13	17.8	6.57	6.89
LR2000			19	30	42	48	54	63	84
	Replication	2	11	21.1	121	95	117	77	137
	Irrigation (Ir)	1	1286*	4150**	5201**	4597**	4881**	5254***	4970*
	Error a	2	61.3	37.5	20.2	6.3	4.8	1.09	158
	N	2	66.4*	52	25	25	40	77	57
	P	1	46	19.5	18	9.0	11.6	0.38	172
	Ir x N	2	32.7	36	14	26	21	68	388
	Ir x P	1	1.2	35.8	23.5	29.5	14.4	38	9.2
	N x P	2	11.8	1.0	2.6	3.8	5.6	14.6	204
	Ir x N x P	2	3.4	31.7	12.7	6.8	14	30.5	92
	Error b	20	15.7	27	25	20.6	21.5	28.1	222
SR2000			16	28	36	42	47	65	83
	Replication	2	21.6	15.4	35	2.53	1.6	3.35	4.71
	Irrigation (Ir)	1	46.7	161	36	4.07	3.3	26.4	17.8
	Error a	2	2.92	10.1	3.0	4.2	1.4	1.5	2.5
	N	2	128.4***	181***	67.4**	29.2*	11.7	16.2	16.6
	P	1	32.1*	22.7	12.4	1.2	0.01	0.11	0.38
	Ir x N	2	4.5	1.3	3.0	2.4	5.8	15.6	8.7
	Ir x P	1	25.3	15	22.9	14.1	0.97	2.15	2.40
	N x P	2	4.8	11.6	7.0	6.4	4.14	3.88	0.31
	Ir x N x P	2	0.32	9.9	5.0	2.7	1.09	1.90	1.22
	Error b	20	7.33	12.6	8.32	7.99	5.91	6.7	5.15

Appendix 10. Mean square variance of maize leaf width at Katumani, Kenya.

		MSE	leaf width					
season	Source	df/ DAE	23	28	33	44	50	68	81
SR1999	Replication	2	2.83	5.94	3.73	2.25	2.44	1.45	1.07
	Irrigation (Ir)	1	1.56	0.054	0.23	0.84	0.81	0.13	0.87
	Error a	2	0.091	2.27	1.47	1.0	1.66	0.15	0.27
	N	2	5.03***	7.96***	9.05***	6.64***	8.35***	4.59***	2.21***
	P	1	1.56	2.15*	0.72	0.12	0.28	0.25	0.05
	Ir x N	2	0.64	0.17	0.04	0.27	0.006	0.11	0.17
	Ir x P	1	0.5	0.87	0.67	1.0	0.69	0.49	0.54
	N x P	2	0.6	0.6	0.55	0.22	0.03	0.28	0.29
	Ir x N x P	2	0.02	0.05	0.07	0.07	0.19	0.11	0.11
	Error b	20	0.436	0.37	0.53	0.40	0.54	0.30	0.34
LR2000			19	30	42	48	54	63	84
	Replication	2	0.09	0.068	0.76	0.52	1.08	0.94	0.53
	Irrigation (Ir)	1	8.51*	27.2*	47.6**	54.8**	44.7**	38.6**	55.3***
	Error a	2	0.20	0.43	0.35	0.43	0.08	0.31	0.05
	N	2	1.31***	1.13*	0.55	0.49	0.61	0.96	1.44
	P	1	0.30	0.08	0.04	0.01	0.02	0.06	0.001
	Ir x N	2	0.26	0.20	0.09	0.09	0.24	0.15	0.46
	Ir x P		0.007	0.000	0.07	0.11	0.42	0.06	0.13
	N x P		0.006	0.03	0.14	0.16	0.33	0.09	0.49
	Ir x N x P		0.079	0.38	0.06	0.10	0.15	0.003	0.88
	Error b	20	0.111	0.29	0.22	0.31	0.36	0.41	0.44
SR2000			16	28	36	42	47	65	83
	Replication	2	0.033	3.25	1.13	0.30	0.04	0.15	0.32
	Irrigation (Ir)	1	0.69	9.0	1.4	0.19	0.004	0.04	0.00
	Error a	2	0.42	1.6	0.59	0.35	0.19	0.093	0.40
	N	2	1.54***	0.65***	1.14**	0.85**	0.18	0.29	0.15
	P	1	0.44	0.54	0.05	1.28**	0.87*	0.59*	0.93**
	Ir x N	2	0.07	0.003	0.40	0.04	0.36	0.13	0.14
	Ir x P	1	0.04	0.028	0.38	0.004	0.004	0.09	0.018
	N x P	2	0.26	0.058	0.22	0.27	0.13	0.01	0.095
	Ir x N x P	2	0.04	1.35	0.25	0.22	0.09	0.49	0.35
	Error b	20	0.133	0.153	0.135	1.13	0.137	0.112	0.098

Appendix 11. Mean square variance of maize total dry matter accumulation over time at Katumani, Kenya.

Season	Source/DAE	df	MSE TDM 120		
SR1999	Replication	2	502878		
	Irrigation (Ir)	1	280339211*		
	Error a	2	3720141		
	N	2	47613952***		
	P	1	808800		
	Ir x N	2	3716587		
	Ir x P	1	92011		
	N x P	2	588668		
	Ir x N x P	2	727416		
	Error b	20	1713920		
LR2000			32	75	141
	Replication	2	14079	334405	1376371
	Irrigation (Ir)	1	3207681**	256032001**	1018822561**
	Error a	2	7184	1935684	1046014
	N	2	142646*	8504974*	14285511***
	P	1	20928	124139	363207
	Ir x N	2	177529*	6938329*	14251325***
	Ir x P	1	194775	1175056	1226187
	N x P	2	7221	421748	77463
	Ir x N x P	2	38424	2621513	188434
	Error b	20	44968	1640916	427568
SR2000			21	48	115
	Replication	2	200	404977	11273147
	Irrigation (Ir)	1	16727**	3014275	63205
	Error a	2	37	399243	918245
	N	2	9328*	1036628**	566376*
	P	1	3481	263340	10336
	Ir x N	2	1578	136983	3740960*
	Ir x P	1	2240	29871	7020733*
	N x P	2	446	725809	3717608
	Ir x N x P	2	9833	2078	158864
	Error b	20	1712	162654	1255759

** significant at 0.05 level, ** significant at 0.01 level, *** significant at 0.001 level.*

Appendix 13. Mean square variance of maize grain yield at Katumani, Kenya.

Season	Source	df	MSE Grain yield
SR1999	Replication	2	23065
	Irrigation (Ir)	1	66395336**
	Error a	2	495727
	N	2	6747249***
	P	1	42987
	Ir x N	2	281944
	Ir x P	1	61835
	N x P	2	308877
	Ir x N x P	2	201404
	Error b	20	532012
LR2000	Replication	2	102524
	Irrigation (Ir)	1	229123723***
	Error a	2	111061
	N	2	4330807***
	P	1	182471
	Ir x N	2	5335041***
	Ir x P	1	386677*
	N x P	2	30605
	Ir x N x P	2	13936
	Error b	20	80366
SR2000	Replication	2	315592
	Irrigation (Ir)	1	67860
	Error a	2	238018
	N	2	1043750*
	P	1	78120
	Ir x N	2	1645007*
	Ir x P	1	1209633
	N x P	2	612361
	Ir x N x P	2	96176
	Error b	20	294051

Appendix 14. Mean square variance of maize Photosynthetically Active Radiation (PAR) Interception, at Katumani, Kenya.

Seaon		df	MSE PAR interception				
	Source/DAE		57	78	88		
SR1999	Replication	2	0.056	0.012	0.043		
	Irrigation (Ir)	1	0.174 ns	0.134**	0.000		
	Error a	2	0.054	0.000	0.000		
	N	2	0.051**	0.054***	0.010*		
	P	1	0.023	0.001	0.018*		
	Ir x N	2	0.002	0.004	0.000		
	Ir x P	1	0.000	0.004	0.000		
	N x P	2	0.001	0.014	0.014		
	Ir x N x P	2	0.002	0.004	0.000		
	Error b	20	0.007	0.005	0.002		
LR2000			18	38	52	73	87
	Replication	2	0.000	0.001	0.005	0.006	0.006
	Irrigation (Ir)	1	0.020	0.734**	1.047**	1.311**	1.311**
	Error a	2	0.004	0.001	0.006	0.004	0.004
	N	2	0.004	0.004	0.004	0.005*	0.005*
	P	1	0.004	0.001	0.006	0.004	0.004
	Ir x N	2	0.003	0.010	0.001	0.002	0.002
	Ir x P	1	0.003	0.002	0.003	0.005	0.005
	N x P	2	0.001	0.001	0.001	0.003	0.003
	Ir x N x P	2	0.001	0.001	0.004	0.001	0.001
	Ir x P	1	0.003	0.002	0.003	0.005	0.005
	Error b	20	0.002	0.004	0.006	0.001	0.001
SR2000			20	47	56	84	
	Replication	2	0.001	0.003	0.012	0.008	
	Irrigation (Ir)	1	0.008*	0.011	0.012*	0.005	
	Error a	2	0.000	0.002	0.000	0.003	
	N	2	0.006*	0.011***	0.008	0.007	
	P	1	0.002	0.000	0.002	0.000	
	Ir x N	2	0.002	0.004*	0.002	0.007	
	Ir x P	1	0.003	0.000	0.004	0.001	
	N x P	2	0.002	0.000	0.004	0.003	
	Ir x N x P	2	0.001	0.000	0.001	0.003	
	Error b	20	0.001	0.001	0.003	0.003	

Appendix 15. Mean square variance of maize cumulative PAR interception at Katumani, Kenya.

Seaon		df	MSE Cumulative PAR interception		
	Source/DAE		32	55	100
LR2000	Replication	2	10.48	12.23	11.1
	Irrigation (Ir)	1	5607*	72995**	510427**
	Error a	2	48.69	162.7	265.8
	N	2	186	617	1871
	P	1	110	0.58	294
	Ir x N	2	269	914	724
	Ir x P	1	123	90.6	110
	N x P	2	28	109	2540
	Ir x N x P	2	44.9	73	221
	Ir x P	1	123	90.6	110
	Error b	20	86.1	313.6	1553
SR2000		df	21	48	100
	Replication	2	20.16	234.8	4683
	Irrigation (Ir)	1	163*	1835	7376
	Error a	2	6.2	126.7	592
	N	2	120*	1447***	8320**
	P	1	29.5	192	12.7
	Ir x N	2	37	492*	4594**
	Ir x P	1	56.2	311	564
	N x P	2	47	224	1811
	Ir x N x P	2	12	41	577
	Error b	20	21.4	90.8	951

Appendix 18. Mean square variance of maize nitrogen uptake at Katumani, Kenya.

	Source	df	MSE Grain N uptake	MSE Total Nuptake
SR1999	Replication	2	1.6	5.4
	Irrigation (Ir)	1	17005**	28900*
	Error a	2	171	449
	N	2	3128***	7116***
	P	1	73	158
	Ir x N	2	331	1116***
	Ir x P	1	0.000	0.87
	N x P	2	39	38.7
	Ir x N x P	2	57	55.3
	Error b	20	160	169
LR2000	Replication	2	84	44
	Irrigation (Ir)	1	46692**	149808***
	Error a	2	51	25
	N	2	1216***	5295***
	P	1	75	109
	Ir x N	2	1450***	5624***
	Ir x P	1	135*	299
	N x P	2	8.3	31.9
	Ir x N x P	2	4.1	24.4
	Error b	20	20	194
SR2000	Replication	2	3452	3076
	Irrigation (Ir)	1	595	1.44
	Error a	2	1664	4659
	N	2	824**	5258***
	P	1	18	72
	Ir x N	2	760**	275
	Ir x P	1	373	898
	N x P	2	176	40.7
	Ir x N x P	2	1.24	92.7
	Error b	20	92	312

Appendix 19. Mean square variance of total stored soil profile moisture under maize at Katumani, Kenya.

Season		df	MSE Soil profile moisture				
	Source/DAE		36	54	65	84	95
SR1999	Replication	2	349.69	22.09	43.91	115.07	156.14
	Irrigation (Ir)	1	360.05**	4163.48**	6658.56**	7323.08*	6662.64
	Error a	2	2.05	28.16	21.62	129.56	396.91
	N	2	312.90	167.67	205.59	327.11	496.14
	P	1	95.6	32.8	206	96	81
	Ir x N	2	28.30	145.09	220.21	727.45*	1035.65*
	Ir x P	1	154	176	215	24	0.77
	N x P	2	164	148	203	251	147
	Ir x N x P	2	239	292	366	237	56
	Error b	35	137.77	168.54	195.42	199.44	227.37
LR2000			17	28	38		
	Replication	2	0.466	0.066	2197.06		
	Irrigation (Ir)	1	463.72*	3239.19*	5664.80		
	Error a	2	1.26	0.889	1423.84		
	N	2	237.57***	410.92***	512.55*		
	P	1	16.51***	397.80***	137.28		
	Ir x N	2	364.06***	167.52***	1348.14**		
	Ir x P	1	8.88***	388.09***	28.93		
	N x P	2	422.35***	137.65***	166.48		
	Ir x N x P	2	25***	96.1***	87.6		
	Error b	23	0.116	2.65	116.70		
SR2000			64	76	89	100	
	Replication	2	103.08	236.59	299.52	353.78	
	Irrigation (Ir)	1	3505.64*	6204	5257.96	3464	
	Error a	2	39.17	122.11	318.14	462.99	
	N	2	317.5	625.37*	538.76*	436.48*	
	P	1	133	60.4	41.4	37.9	
	Ir x N	2	229.75	88.61	97.64	53.20	
	Ir x P	1	276	414	312	184	
	N x P	2	2.90	11.8	0.10	6.58	
	Ir x N x P	2	76.7	52.7	13.02	17.33	
	Error b	116	133.97	127.06	140.71	119.90	

Appendix 19. Mean square variance of total stored soil profile moisture under maize at Katumani, Kenya.

Season		df	MSE Soil profile moisture				
	Source/DAE		36	54	65	84	95
SR1999	Replication	2	349.69	22.09	43.91	115.07	156.14
	Irrigation (Ir)	1	360.05**	4163.48**	6658.56**	7323.08*	6662.64
	Error a	2	2.05	28.16	21.62	129.56	396.91
	N	2	312.90	167.67	205.59	327.11	496.14
	P	1	95.6	32.8	206	96	81
	Ir x N	2	28.30	145.09	220.21	727.45*	1035.65*
	Ir x P	1	154	176	215	24	0.77
	N x P	2	164	148	203	251	147
	Ir x N x P	2	239	292	366	237	56
	Error b	35	137.77	168.54	195.42	199.44	227.37
LR2000			17	28	38		
	Replication	2	0.466	0.066	2197.06		
	Irrigation (Ir)	1	463.72*	3239.19*	5664.80		
	Error a	2	1.26	0.889	1423.84		
	N	2	237.57***	410.92***	512.55*		
	P	1	16.51***	397.80***	137.28		
	Ir x N	2	364.06***	167.52***	1348.14**		
	Ir x P	1	8.88***	388.09***	28.93		
	N x P	2	422.35***	137.65***	166.48		
	Ir x N x P	2	25***	96.1***	87.6		
	Error b	23	0.116	2.65	116.70		
SR2000			64	76	89	100	
	Replication	2	103.08	236.59	299.52	353.78	
	Irrigation (Ir)	1	3505.64*	6204	5257.96	3464	
	Error a	2	39.17	122.11	318.14	462.99	
	N	2	317.5	625.37*	538.76*	436.48*	
	P	1	133	60.4	41.4	37.9	
	Ir x N	2	229.75	88.61	97.64	53.20	
	Ir x P	1	276	414	312	184	
	N x P	2	2.90	11.8	0.10	6.58	
	Ir x N x P	2	76.7	52.7	13.02	17.33	
	Error b	116	133.97	127.06	140.71	119.90	

Appendix 21. Mean square variance of maize water use (cumulative ET) at Katumani, Kenya.

Season	Source/ DAE	df	Mean Square Error of water use					
			26	36	54	84	106	
SR1999	Replication	2	401	348	22	117	153	
	Irrigation (Ir)	1	11356***	114232***	23791***	905067***	1275469***	
	Error a	2	4.14	1.95	28	132	362	
	N	2	320	312	167	363	491	
	P	1	243	96	33	117	86	
	Ir x N	2	100	28	145	696	1110*	
	Ir x P	1	109	154	176	15.3	0.44	
	N x P	2	215	164	147	277	154	
	Ir*N*P	2	191	240	292	220	47.6	
	Error b	20	123	138	169	204	231	
LR2000			17	28	38	52	74	108
	Replication	2	0.976	19.8	2795	3392	380	164
	Irrigation (Ir)	1	42393**	58418*	132803*	335624*	570102*	1369069**
	Error a	2	0.608	14.4	486	442	282	45
	N	2	490 ***	901***	258	898	192	26
	Ir x N	2	649***	64	1738**	699	21	209
	P	1	182***	439***	437	260	4.9	90
	Ir x P	1	12.1***	150*	0.001	85	1143	910
	N x P	2	560***	52ns	239	471	295	609
	Ir*N*P	2	11.8***	191**	50	168	181	372
	Error b	20	0.120	16.71	148	450	520	611
SR2000			76	89	100			
	Replication	2	50	51	55			
	Irrigation (Ir)	1	8360*	40140**	50169**			
	Error a	2	352	349	366			
	N	2	263	190	263			
	P	1	190	276	213			
	Ir x N	2	149	135	152			
	Ir x P	1	8.41	1.73	2.61			
	N x P	2	37.1	169	252			
	Ir*N*P	2	21.2	14.8	25.4			
	Error b	20	141	100	140			

Appendix 22. Mean square variance of maize water use efficiency at Katumani, Kenya (at harvest).

Season	Source	df	MSE $WUE_{(gr)}$	MSE $WUE_{(TDM)}$
SR1999	Replication	2	0.95	2.31
	Irrigation (Ir)	1	5.00	55.70
	Error a	2	5.27	32.29
	N	2	41.74**	278.87**
	P	1	1.08	9.92
	Ir x N	2	6.02	25.50
	Ir x P	1	1.10	4.55
	N x P	2	1.91	4.54
	Ir*N*P	2	1.99	8.27
	Error b	20	2.86	9.16
LR2000	Replication	2	1.49	5.94
	Irrigation (Ir)	1	489.88**	1010.18**
	Error a	2	1.95	7.91
	N	2	7.42**	56.65*
	P	1	0.004	9.30
	Ir x N	2	21.16**	45.81 *
	Ir x P	1	5.44 *	48.77
	N x P	2	0.299	1.11
	Ir*N*P	2	0.027	0.85
	Error b	20	0.77	9.81
SR2000	Replication	2	11.89	43.03
	Irrigation (Ir)	1	39.90*	161.71 *
	Error a	2	1.24	5.51
	N	2	2.48	16.84*
	P	1	0.00	1.82
	Ir x N	2	5.16*	11.58
	Ir x P	1	5.84	33.45*
	N x P	2	2.51	14.87
	Ir*N*P	2	0.63	1.069
	Error b	20	1.35	4.78

$WUE_{(gr)}$ = *grain water use efficiency*, $WUE_{(TDM)}$ = *Total biomass water use efficiency*

Appendix 23. Land use requirements for Katumani composite B maize.

Average number of days to physical maturity	85 - 105 days.
Average number of days to harvest	100 - 120 days.
Altitude	700 - 1500m
Rainfall	260 - 450mm, well distributed
pH	5.5 - 8.0
Drainage	free draining soils

Remark: Not on very acid soils, not on water logged soils, at least moderately fertile soils.

Appendix 24. List of acronyms.

ACIAR	Australian Centre for International Agricultural Reasearch
ASAL	Arid and semi arid lands
FAO	Food and Agriculture Organization of the united nations
ESP	Exchangeable sodium percentage
ISSS	International Soil Science Society
WOFOST	World Food Studies