ESTABLISHING OPTIMUM PLANT POPULATIONS AND WATER USE OF AN ULTRA FAST MAIZE HYBRID (*ZEA MAYS* L.) UNDER IRRIGATION

by

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Dedicated to my late mother
Faranje Gomosho

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ABSTRACT

For each grain production system, there is an optimum row spacing and plant density that optimises the use of available resources, allowing the expression of maximum attainable grain yield in that specific environment. Introduction of the ultra-fast maize hybrids raised the question whether existing guidelines for row spacing and plant density were still applicable. This necessitated the integration of optimum row spacing by plant density to maintain productivity and sustainability the yields with the intention to increase water use efficiency. Field experiments were conducted for two successive cropping seasons (2008/9 to 2009/10) at Kenilworth Experimental Station of the Department of Soil, Crop and Climate Sciences, University of the Free State to evaluate the growth, agronomic performance, phenological development and water use efficiency of an ultra-fast maize hybrid at varying row spacing and plant densities under irrigation. The treatments involved in this study were three row spacings (0.225, 0.45 and 0.90 m) and five plant densities (50 000, 75 000, 100 000, 125 000 and 150 000 plant ha^{-1}). The treatments were arranged in a factorial combination and laid out in a randomized complete block design (RCBD) with four replications. The largest block was used for periodic destructive sampling for growth analysis where a completely randomized design was adopted and replications consisted of five (5) single plants randomly selected. Regarding soil water monitoring, twenty neutron probe access tubes were installed prior to planting in the center of each plot in one of the three blocks of the agronomic study. Soil water content was measured at 0.3 m intervals to a depth of 1.8 m using a calibrated neutron probe. Measurements were made at weekly intervals from planting to crop physiological maturity where the volumetric reading was converted into depth of water per 1.8 m. Seasonal ET (water use) was determined by solving the ET components of the water balance equation. From this water use efficiency was computed as the ratio of total biomass/grain yield to seasonal ET. In each season crop growth, agronomic, phenologic and water use efficiency parameters were measured and the collected data were combined over seasons after carrying the homogeneity test of variances. Growth parameters, agronomic traits, phenology and water use efficiency of maize reacted differently to row spacing and plant density and the combination thereof.

In general a slow increase in growth parameters during establishment was followed by an exponential increase during the vegetative phase. At the reproductive phase growth ceased following the onset of flowering. Photosynthetic efficiency (NAR) and CGR, averaged over row spacing, were highest at a plant density of 100 000 plants ha^{-1} at all growth phases. Reducing row spacing from 0.45 to 0.225 m and a plant density below or above 100 000 plants ha^{-1} showed LAI outside the optimum with respect to NAR for optimum seed yield.

Row spacing, plant density and its interaction affected yield and yield components of maize significantly. Narrowing rows from 0.45 to 0.225 m and plant densities above 100 000 plants ha^{-1} as main or interaction effects led to the formation of smaller ears, a shorter ear length and diameter, low seed mass, favored plant lodging and development of barren plants with an obvious negative impact on grain yield. On other hand, plant densities below 100 000 plants ha^{-1} were insufficient to utilise growth-influencing factors optimally. Thus, growth analysis provided an opportunity to monitor the main effects and interaction effects of row spacing and plant density on crop growth at different growth and development phases.

Row spacing and plant density combinations affected the phenological development of maize. Increasing row spacing from 0.225 to 0.90 m relatively prolonged the number of days to anthesis and silking. Regarding anthesis-silking interval (ASI), the lowest plant density had the shortest ASI while the higher plant densities had relatively longer ASI. Wide row spacing coupled with low plant density increased the number of days to physiological maturity and vice versa.

Row spacing and plant density and their interaction affected water use efficiency of maize. Highest water use was observed at a plant density of 125 000 plants ha^{-1}. Biomass WUE was highest at a row spacing of 0.45 m with a plant density of 125 000 plants ha^{-1} while the highest grain yield WUE recorded was at a row spacing of 0.45 m with a plant density of 100 000 plants ha^{-1}.

The overall combined effect of row spacing and plant density revealed that a combination of 0.45 or 0.90 m with 100 000 plants ha^{-1} to be the optimum for the selected ultra-fast maize hybrid under irrigation.

Key words: row spacing, plant density, water use efficiency

CHAPTER 1

INTRODUCTION

1.1 Background

Maize (*Zea mays* L.) has become the third most important cereal crop in the world, because of its high adaptability and productivity (Mosisa *et al.*, 2002). Globally maize is grown under diverse climatic conditions but yields best under moderate temperatures with sufficient water (Aldrich *et al*., 1978). However, on the African continent, it is the most important food crop and mainstay of rural diets in the eastern and southern regions (FAO, 2003; Maredia, *et al.*, 2000; Pingali, & Pandey, 2001). Maize has a higher carbohydrate production potential per unit land than other cereals and was the first major cereal to undergo rapid and widespread technological transformation in its cultivation (Palwal, 2000). In developed countries, maize is grown mainly for animal feed and as raw materials for industrial products, such as starch, glucose, and dextrose and bio fuel. Therefore, maize occupies an important position in Africa and on the global economy where it is traded as a food, feed and industrial grain crop (Vasal, 2000).

On the African continent rainfed agriculture is confronted with unreliable or erratic rainfall and recurrent drought with subsequent production failures (Stroosnijder, 2003). On the other hand, exponential population growth and a diminishing resource base is the greatest global challenge for food security (Jensen *et al.*, 1990). The water requirements associated with producing food for the future world population are huge and almost certain to increase. For the near future, annual renewable freshwater resources are largely fixed. There may be some areas where freshwater resources could increase or decrease according to climatic changes. However, these are likely to be minor compared with the increased human demand for freshwater. Therefore, the problem of providing food for a much greater world population becomes focused on producing more with the existing water and land resources (Jensen *et al.*, 1990; Wallace, 2000).

It is estimated that maize demand in Sub-Saharan Africa would exceed 52 million tons in 2020 (Pingali & Pandey, 2001). To fulfil this projected demand, higher maize production has to be realized predominately on existing cultivated land, since an expansion of cultivated land is severely limited, because of population increase, environmental concerns, urbanization and diminishing water resources (Cakmak, 2001). According to Andrew and Kassam (1975), Beets (1982) and Mureithi (2005) production can be increased by:

- expanding the area planted to crops,
- raising the yield per unit area of individual crops,
- intercropping,
- or by growing more crops per year.

In the future, most of the additional food the world needs must come from larger yields on the lands already under cultivation and/or from lands now considered marginal (Chatterjee & Maiti, 1984). A major share of this increase will likely come from the use of commercial fertilizers, pesticides, and improved crop culture, mechanization of farm operations, irrigation and genetic improved varieties.

South Africa is a dry country with an annual average rainfall less than 500 mm with two-thirds of its area (Marais *et al.*, 2002). Agriculture and other economic activities are largely adapted to these semi-arid conditions. More than a million people are directly dependent on agriculture for their livelihood in South Africa. Maize is one of the staple food crops in South Africa and in recent years contributed 71% to the grain produced in the country (National Department of Agriculture, 2003). Maize production covered 58% of the cropping area in South Africa and 50% of the maize in the South African Development Community region in 2005 (SADC) which makes South Africa the major source of maize for the region (CEEPA, 2006). In South Africa, it was reported that grain yields, obtained by most smallholder irrigation farmers, are far below the mean potential of 3 ton maize ha^{-1} (Bembridge, 1996; Van Averbeke *et al*., 1998; Machethe *et al*., 2004; Fanadzo, 2007). This being the case, efficient crop water use in South Africa is of great importance. For this reason, there is a need to find appropriate, affordable solutions for particular circumstances that exists in different parts of the water scarce world including South Africa (Wallace, 2000).

Rainfall in South Africa is unpredictable and erratic. A mixture of dry spells and erratic rainfall, with annual variation that cannot be predicted accurately, consistently impact negatively on the growth and yield of maize in South Africa (Benhil, 2000). This necessitates the optimum and efficient use of water in a water scarce country. Under irrigation double cropping systems (maize-wheat) improved productivity, but it is difficult to manage with conventional cultivars. This led to the improvement of agronomic characteristics of maize cultivars and especially a decrease in the length of its growing season. Incorporation of fast and ultra-fast maize cultivars in a double cropping system eased management by increasing time for soil tillage.

Successful and sustainable maize production depends on the correct application of production inputs. These inputs are, inter alia, adapted cultivars, plant density, soil tillage, fertilisation, irrigation, herbicides, pesticides, harvesting, marketing and financial resources. From this list water, water and soil fertility are regarded as the most important constraints to increase food production. Considering water, the balance between the incessant demand for water by crops and its sporadic supply by precipitation that even short-term dry spells often reduce production significantly, and prolonged droughts can cause total crop failure and mass starvation (Hillel, 1980). Irrigation is the practice of supplying water artificially to permit farming in arid regions and to offset drought in semi-arid or semi-humid regions (Morrison *et al*., 2008). The controlled supply of water ensures increased biological productivity and therefore the yields of irrigated land can easily exceed that of un-irrigated ("rain-fed") land (Lety, 1994).

Finding the optimum distance between neighbouring rows and plants at any particular plant density has several advantages and is another attempt to further increase biological productivity. Firstly, it reduces competition among plants within rows for light, water and nutrients due to a more equidistant plant arrangement (Olson & Sander, 1988; Porter *et al*., 1997). The more favourable planting pattern provided by closer rows enhances maize growth rate early in the season (Bullock *et al*., 1988), leading to a better interception of sunlight, a higher radiation use efficiency and a greater grain yield (Westgate *et al*., 1997). Secondly, the maximization of light interception derived from early canopy closure also reduces light transmittance through the canopy (McLachlan *et al*., 1993). The smaller amount of sun light striking the ground reduces the potential for weed interference, especially for shade intolerant species (Gunsolus, 1990; Teasdale, 1995; Johnson *et al.,* 1998). Thirdly, quicker shading of the soil surface during the early part of the season results in less water lost by evaporation (Karlen & Camp, 1985a). This is especially important under favourable soil water conditions, because it allows maize plants to maximize photosynthesis and the proportion of water that is used in growth processes rather than evaporated from the soil (Lauer, 1994). Furthermore, earlier crop cover provided by narrower row widths enhance soil protection, diminish water runoff and hence, control soil erosion (Mannering & Johnson, 1969; Sangoi *et al*., 1998).

Grain yield per unit land area is the product of grain yield per plant and number of plants per unit land area. At low densities, grain yield is limited by the inadequate number of plants whereas at higher densities, yield declines mostly because of an increase in the number of aborted kernels and/or barren plants (Swank *et al*., 1982). Optimum plant density should be maintained to exploit natural resources, such as nutrients, sunlight and soil water fully to ensure satisfactory yields. Many studies were conducted with the aim of determining the optimum plant density for maize. There is no single recommendation for all conditions, because the optimum plant density varies depending on environmental factors such as soil fertility, water supply, crop management and genotype (ARC-GCI, 1999, Gonzalo *et al*., 2006). Hence, cultural practices such as row spacing and plant density, collectively known as spatial variation could influence water use efficiency. For each production system, there is a plant density that optimizes the use of available resources, allowing the expression of maximum attainable grain yield in that environment. Generally, irrigation farmers use a 0.915 m row spacing with plant densities that varies from 75 000 to 95 000 plant per hectare. Therefore, row spacing and plant density guidelines to maximize attainable potential yield of an ultra-fast maize hybrid have to be developed for specific conditions.

1.2 Hypotheses

Hypotheses formulated for this study were:

- Maize growth and development can be managed by monitoring independent and interaction effects of row spacing and plant density.
- Productivity of an ultra-fast maize hybrid can be optimised by integrating row spacing and plant density.
- Balanced phenological development can be achieved through appropriate combination of row spacing and plant density.
- Reduction of row width accompanied with varying plant density can result in a uniform distribution of plants over land area and increase water use efficiency.

1.3 Objectives

The main objective of this investigation was to evaluate the agronomic performance of an ultra-fast maize cultivar at varying row spacing and plant density combinations. To fully understand this objective, the specific objectives were:

- to evaluate growth and development of an ultra-fast maize hybrid at different row spacing and plant densities;
- to investigate yield and yield components performance of the hybrid at different row spacing and plant densities;
- to evaluate the phenological response of maize to varying row spacing and plant densities; and
- to quantify the water use efficiency at different row spacing and plant densities.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Maize is a member of the *Poaceae* family, a tall grass with a large stalk, long arching leaves with evenly ruffled edges. Its origin is from the American continent where it was cultivated by various Indian tribes and attained a high level of development centuries ago. Soon after the discovery of America the maize plant was rapidly distributed to other parts of the globe (Saunders, 1930). Although maize is often listed as one of many food crops introduced to Africa by the Portuguese, how and when it was brought to the continent could not be established with certainty. Data from the United Nations (UN) Food and Agriculture Organization (FAO) showed that worldwide 144 million hectares of land are cultivated for maize to produce 695 million metric ton (4.83 t ha^{-1}) per annum. The African continent contributed 7% (46 million metric ton) to the world maize production during this time (FAOSTAT, 2008). In eastern and southern Africa, maize is by far the dominant crop grown by the vast majority of rural households. Consumption of maize is high throughout most of the region, reflecting its role as the primary food staple and on average contributes to 40% of the calories consumed by people (Zambezi & Mwabula, 1996; Hassam *et al.*, 2001; Banziger & Diallo, 2004; Diallo *et al.*, 2004; Smalberger & Du Toit, 2004). In southern Africa the per capita annual consumption of maize averages more than 100 kg in several countries (Lesotho, 149 kg; Malawi, 181 kg; South Africa, 195 kg; Swaziland, 138 kg; Zambia, 168 kg and Zimbabwe, 153 kg) (CIMMYT, 1999).

In South Africa, maize is the main staple food and most extensively grown field crop, followed by wheat and sorghum (Ayisi & Poswell, 1997). Although maize is grown in almost all areas of South Africa, the main grain producing areas are in the so-called “maize triangle“ from Belfast in the east to the Lesotho highlands in the south, Setlagoli in the west and back to Belfast (Martin, 2006). In South Africa approximately 3.7 million hectares of land is annually planted by maize, and of this area 3.5 million hectares are cultivated under dry land conditions with a mean yield of 3.2 ton ha^{-1}. Irrigation contributes 0.19 million hectares to the area planted to maize with a mean yield of 8.5 ton ha^{-1} (Agric Stat, 2008). Dry land maize production mainly takes place in the Free State (34%), North West (32%), Mpumalanga (24%) and Kwazulu-Natal (3%) Provinces (Agric Stat, 2008).

In Sub-Saharan Africa, Kenya, Tanzania, South Africa, Ethiopia and Nigeria are the principal producers of maize but, South Africa is the only one, exporting maize (Polaszek & Khan, 1998). In South Africa maize is the second most important energy source in human diets and it is the most important source of energy in animal feed (De Jager, 1995).

2.2 Phenological development

2.2.1 Definition and concepts

Phenology, as defined by Leith (1970) and the International Biological Program (US/IBP) committee (1972), is the art of observing life cycle phases of plants and animals in their temporal occurrence throughout the year. Generally phenology refers to the study of seasonal appearances and timing of life-cycle events. The word is derived from the Greek word *Phainomai:*– to appear, come into view from scientific literature on ecology. Phenology is used to indicate the time frame of any seasonal biological phenomena, the causes of their time with regard to biotic and abiotic forces and the interrelation among phases of the same or different species. Phenology involves the study of the response of living organisms to seasonal and climatic changes of the environment in which they live. Seasonal changes include variations in the duration of sunlight, precipitation, temperature and other life-controlling factors (Murthy, 2005). Plants are adapted to the annual seasonal cycle and all the life-cycle stages are regulated by seasonal meteorological changes. It is important to keep track of cyclical events, such as appearance of buds, leaves, first bloom, pollination and fertilization and dispersal. Therefore, in crops, phenological development is characterized by the order and rate of appearance of vegetative and reproductive organs.

Phenology is a useful indicator of life phases of plants because it integrates agro-meteorological signals over a sustained period of time. Tollenaar (1993) indicated three reasons why good understanding of phenology is important in physiological and agronomic studies of the crop;

- Seasonal dry matter accumulation is a function of the duration of the life cycle of annual crops.
- Rates of physiological processes can differ substantially among phases of the life cycle. For instance, dry matter partitioning to the seeds, peaking of potential leaf photosynthesis when leaves are fully expanded and its subsequent decline after full leaf expansion.
- Susceptibility of most crops to adverse environmental conditions during one or more phases or stages of phenological development, such as high impact of adverse conditions on crop yield by affecting the initiation of florets and effects of growth regulators on crop development.

As the maize plant matures, changes take place in plant components. For instance, the number of leaves formed on a determinate plant species, such as maize, is dependent on the developmental processes. Initiation of the tassel at the elongated transitional stem tip also signals the beginning of reproductive development. Plant density impacts on synchrony of flowering where high plant densities may reduce the supply of nitrogen (Lemcoff & Loomis, 1994), photosynthates (Jacobs & Pearson, 1991) and water (Westgate, 1994) to the growing ear. Restrictions in carbon or nitrogen metabolism in dense stands may delay specific developmental events and reduce both spikelet number and silk extrusion, contributing to a decrease in the number of spikelets that can be fertilized through coincidence of pollen shed with silking of individual spiklets (Jacobs & Pearson, 1991). Thus, barrenness and the production of nubbin ears, associated with increasing plant density, have been linked with delayed silk or growth of ear premordia. Similarly, the prolific character of maize is also closely associated with plant density. Buren *et al*. (1974) and Anderson *et al.* (1984) observed that prolific maize lines that produced multiple ears at low plant densities, maintained a higher kernel number than did single-eared lines when grown at high plant densities. This was due to better synchronization between pollen shed of the tassel and silk extrusion of the ears. In maize, kernel number is a function of the rate and duration of differentiation of spikelet cessation prior to the initiation of the silk, fertilization which requires synchronization of flowering of tassel and ears, and kernel abortion after fertilization. Examination of spikelet production has been largely qualitative (Cheng *et al*., 1983; Stevens *et al.*, 1986). However, Edmeades and Daynard (1979) reported that a plant density of 200 000 plants ha^{-1} shortened the period of initiation of spikelet primordial, thereby reducing the number of spikelet premordia per row. Plant density (Buren *et al*., 1974), water stress (Herrero & Johnson, 1981; Hall *et al*., 1982) and nitrogen supply (Anderson *et al*., 1984) generally influence the synchrony of flowering and hence grain yield. This indicates that plant density has both a direct and indirect effect on synchronization of flowering.

2.2.2 Climate and phenological development

Climate encompasses temperature, humidity, atmospheric pressure, wind, rainfall and other meteorological variables in a given area/region over a period of time. It is defined as weather, averaged over a long period of time (Newman, 1994). Distribution of crop plants throughout the world is governed by many factors. Principally climate remains the determinant factor (Martin *et al*., 1976). Martin *et al*. (1976) further described that crop adaptation is determined primarily by genotype-environment interaction depending on the suitability of climatic features in relation to the crop requirements for normal growth and development. For instance, increase of leaf number in maize is linear with time in the 10-30^{o}C temperature range with an increased rate at higher temperatures (Thiagarah & Hunt, 1982). Global climate change has increased the length of the growing seasons of plants in temperate regions by as much as 12-18 days over the last two decades (Zhou *et al*., 2001). This includes an earlier onset of the growing season of approximately 2.5 days per decade in Europe (Menzel *et al*., 2006), as well as an extension of the growing season in autumn. Hence, global climate change may lead to changes in critical day length of plants (Bradshaw & Holzapfel, 2001; Van & Hautekeete, 2007) and changes in geographical distribution of crop plants (Walther *et al*., 2005). Climatic conditions also dictate the selection of maize genotypes (varieties) for a given area/temperature, because temperature affects the growth rate and development of the maize plant.

Timing of reproduction and maturity is a key component in fitness of plants to their respective environments (Stearns, 1992). Plant phenology change is associated with global climate alteration and will affect plant fitness by altering length of maturity. For example, a photoperiod-sensitive plant that germinates earlier as a result of spring warming might experience a longer vegetative growth. Such alterations in phenology would impact plant growth and resource acquisition. Plant phenology and timing of reproduction in particular, exhibit plastic responses to resource availability (Dorn *et al*., 2000; Gungula *et al*., 2003). Therefore, climate change obviously affects agriculture differently in different parts of the world (Parry *et al*., 1999). The resulting effects depend on current climatic and soil conditions, the direction of change and the availability of resources. Maize is grown in different agro-ecological and cropping s that differs in length of the growing season. Thus, there are different maturity groups of maize cultivars that were developed and are in use to meet the needs of growers with respect of climatic conditions of an area. Maturity grouping of maize cultivars is based on the number of days from planting to flowering or physiological maturity of kernels (Vasal *et al*., 1994). In South Africa maize cultivars are grouped into maturity classes based on their days to flowering *that is, short* (60-65), *medium* (65-70) and *long* (70-75) (Plessis & Bruwer, 2004).

2.3 Growth characteristics

2.3.1 Definition and concept of growth

Growth definitions range from unequivocal statements about change in specified dimensions to the abstract state of affairs in which the verb ‘to grow’ means nothing more than to live or even to exist (Hunt, 1990). The Concise Oxford Dictionary defines growth as (i) develop or exist as living plant and (ii) increase in size, height, quantity, degree and power. The latter part leans relatively more towards plant growth analysis aspects. Usually the term growth is applied to quantitative changes occurring during development with irreversible changes in the size of a cell, organ or whole organism. Thus, growth describes irreversible changes with time, which are mainly in size, form and occasionally in number. Growth is also defined as a process of cell division and elongation (Fussel *et al.*, 1980; Wareing & Phillips, 1981). Chiariello (1989) described growth as the capacity to change in size, mass, form, and/or number which is an essential feature of life referring the term 'growth' to any or all of these types of change. Boyer (1985) defined plant growth as an irreversible increase in size of organs, due to predominately increase in cellular water content accompanied by the simultaneous extension and synthesis of the cell wall and accumulation of the solutes. Agronomists generally define growth as an increase in dry matter (Fussel *et al*., 1980). This includes the diurnal reversible changes due to temperature, radiation and leaf water potential. According to Fournier and Andrieu (2000) the kinetics of stem/plant elongation in crop growth was found to be composed of four phases. Elongation rate rises exponentially during phase I, then increase sharply during phase II (a relative short period), followed by a major period of constant growth rate (phase III) before it enters the last period of decline (phase IV). During phase I, elongation appears to be integrated at the level of the whole apical cone. From phase II onwards elongation becomes determined at the level of phytomer (Fournier & Adnrieu, 2000). Gardner *et al*. (1985) concluded that plant growth and development are combinations of a host of complex processes of growth and differentiation that lead to the accumulation of dry matter. Growth and more specifically crop growth can generally be measured by biomass accumulation and an increase of LAI at the vegetative phase of maize (Walker, 1988).

2.3.2 Growth components

2.3.2.1 Plant height

Maize plant height is a genetic trait in maize and determined by the number and length of internodes. Plant height may vary from 0.3 to 7 m depending on the maize cultivar and environmental growing conditions (Gynes-Hegyi *et al*., 2002). Usually early maturing cultivars are shorter and late maturing ones taller. In the tropics where the growing season may be as long as 11 months, certain late maturing maize cultivars can grow to a height of 7 m (Koester *et al*., 1993). Yakozawa & Hara (1995) indicated that the final height of maize plants is strongly influenced by environmental conditions during stem elongation. Temperature and photoperiod may influence stalk height by affecting the number of internodes. However, other factors include water, nutrition, temperature, pest, diseases, light quality and quantity (Baggett & Kean, 1989). Moisture stress might simply affect the length of internodes by inhibiting the elongation of developing cells.

Previous research results involving different plant densities revealed that maize plants grew taller as mutual shading increased with a considerable cultivar variation in this characteristic (Yakozawa & Hara, 1995). Thus, plants that grow within a dense canopy or at a high plant density receive a different quality of light, enriched with far red (FR) and impoverished in red (R) radiation. High ratios of FR/R triggers a number of morphological alterations in plant architecture, stimulating stem elongation, favouring apical dominance and decrease in stem diameter (Rajcan & Swanton, 2001). Troyer & Rosenbrook (1991) also reported high stalk breakage and ear fall (ears fall from stem) in crowded maize plants having smaller diameter and shanks due to mutual shading. Such changes make maize stalks more susceptible to breakage before kernels reach physiological maturity. Stalk lodging represents one of the most serious constraints to the utilization of high plant densities in maize cultivation (Argenta *et al*., 2001). Thus, during breeding many high-yielding maize hybrids are often rejected during development because of stalk lodging.

2.3.2.2 Leaf area, leaf area index and crop growth

Watson (1997) defined leaf area index of a crop as the one-sided area of green leaf tissue per plant unit area of land occupied by that crop. That is the area of leaf per area of land. Leaf area index is a key plant growth parameter frequently measured and estimated from leaf shape characteristics (Stewart & Dwyer, 1999). Leaf area and its distribution over land area is one of the major factors that determine light interception, which affects photosynthesis, transpiration and dry matter accumulation. Leaf area index can be estimated and used in crop growth models to compute photosynthesis, assimilate partitioning, gas exchange and energy exchange (Fortin *et al*., 1994).

During the vegetative growth phase, leaf area determines the total amount of light interception. Thus, the amount of CO_2 fixed is proportional to leaf area available. It is reported that only 50% of incident solar radiation can be used as photosynthetically active radiation. The remaining energy is worthless with respect to photosynthesis and increases leaf temperature if absorbed (Monteith, 1981). Therefore, the efficient interception of radiant energy incident to the crop surface needs appropriate leaf area, uniformly distributed to provide complete ground cover which can be achieved by manipulating stand density and distribution over land surface (Modarres *et al*., 1998). The capacity of the crop to intercept photosynthetically active radiation and synthesis of carbohydrates for growth is a nonlinear function of LAI (Andrade *et al*., 2002). Kiniry & Knievel (1995) indicated that in the absence of nutrient deficiencies, temperature extremes or water stress, solar radiation intercepted by plants is the major limitation to growth, development and yield.

Plant density was recognized as a major factor determining the degree of competition between plants. In order to obtain a maximum crop growth rate (CGR), plant density in a cropping system needs to be adjusted in a manner that optimizes LAI for maximum solar radiation interception (Bavec & Bavec, 2002). The reason for this is that CGR is directly related to the amount of radiation intercepted by the crop (Jeffery *et al*., 2005). Hence, increasing plant density above an optimum may decrease CGR due to low dry matter accumulation on a per plant basis (Dehdashti & Riahinia, 2008). Moreover, increasing plant density results in a reduction of CGR due to mutual shading of leaves (Hashemi-Dezfouli & Herbert, 1992). Field crop growth was characterized by a system of growth analysis based mostly on dry matter accumulation rates. A meaningful analysis of crop growth is preferably based on a land area rather than an individual plant basis. Therefore, the most commonly used growth analysis is crop growth rate (g m^{-2} day^{-1}) defined as the dry matter accumulation rate per unit of land per unit time (Brown, 1984) and computed as:

$$CGR = \frac{1}{SA}\left\{\frac{(W2-W1)}{(T2-T1)}\right\} \tag{2.1}$$

Where:

CGR = Crop growth rate (g m^{-2} day^{-1})
W_2 = Dry weight at the end of interval (g $plant^{-1}$)
W_1 = Dry weight at the beginning of interval (g $plant^{-1}$)
SA = Soil area occupied by plants at each sampling (m^2)
T_2 = Time at end of interval (day)
T_1 = Time at beginning of interval (day)

Dry matter accumulation of crop plants is directly related to the utilization of solar radiation (Donald, 1963; Williams *et al*., 1968; Daughty *et al.*, 1983), which is influenced by canopy structure. Williams *et al.* (1968) observed that the effect of canopy architecture on vertical distribution of light within the maize canopy was a major determinant of photosynthetic efficiency and growth. Radiation is transmitted through and between leaves, and its flux density and spectral composition change rapidly with depth (Szeicz, 1974; Gardner *et al.*, 1985). Canopy light interception and photosynthesis are closely related to LAI up to the critical LAI, which is required to intercept 95% incident irradiance (Pearce *et al.*, 1965). Williams *et al*. (1968) found that light interception and CGR increased linearly as LAI increased up to 3, but CGR increased asymptotically as LAI was increased further to a maximum at 99% light interception. Plant density resulting in interplant competition affects both vegetative and reproductive growth. Effects of plant density normally refer to plant number per unit area, but spatial arrangement of plants should be considered regarding per unit area occupied by a single plant (Willey & Heath, 1970). Moreover, maize reproductive responses to plant density have generally shown that individual plant dry matter decreases with increasing plant density, whereas dry matter per unit area increases (Duncan, 1958, as cited by Gardner *et al*., 1985). Conversely, ear and kernel dry weight increased but total dry matter per unit land area decreased by reducing plant density. This reduction of total dry matter per unit land area was associated with the reduction of number of ears per plant as the plant density increased (Baenziger & Glover, 1980).

The photosynthetic capacity of crops is a function of leaf area index (LAI) and the photosynthetic efficiency can be described by the net assimilation rate (NAR = rate of increase of dry matter per unit of leaf area per unit time) (Watson, 1958, as cited by Shuting *et al*., 1993). Increasing plant density results in a reduction of net assimilation rate. Dwyer *et al.* (1991) reported that an increase of plant density from 20 000 to 130 000 plants ha^{-1} caused a NAR reduction from 0.85 to 0.11 g m^{-2} of CO_2. Therefore, crop growth can also be expressed on the basis of leaf area, because leaf surfaces intercept sunlight and absorb CO_2, releasing water during photosynthesis. The dry matter accumulation rate per unit of leaf area per unit of time is termed net assimilation rate (NAR) (Gardner *et al*., 1985) and is a measure of the photosynthetic efficiency of leaves per unit leaf area is computed as:

$$NAR = \frac{1}{LA}\left\{\frac{(W_2 - W_1)}{(T_2 - T_1)}\right\} \tag{2.2}$$

Where:

NAR = Net assimilation rate (g m^{-2} day^{-1})
W_2 = Dry weight at the end of interval (g plant^{-1})
W_1 = Dry weight at the beginning of interval (g plant^{-1})
LA = Leaf area (m^{-2})
T_2 = Time at end of interval (day)
T_1 = Time at beginning of interval (day)

2.3.3 Growth analysis

Plant growth and development are subjected to the action of physical and biological environment factors. Plant growth begins with germination, followed by a complex series of morphological and physiological events (Ting, 1982). Growth and development are continuous processes leading to morphologenic characteristics of species, where both are controlled by genotype by environment interactions. Hence, crop growth parameters, such as leaf number, leaf area index and dry matter accumulation, are very important indicators of growth and are affected by row spacing and plant density.

Growth analysis refers to quantitative methods of describing and interpreting the performance of plants grown under natural, semi-natural or controlled conditions (Hunt, 2003). Plant growth analysis provides an explanatory, holistic and integrated approach to interpreting plant form and function by using plant growth indicators such as dry matter, leaf area and plant height. The pattern of maize growth over a generation is typically characterized by a growth function referred to as the sigmoid curve (S-shaped curve) and results from differential rates of growth during the life cycle of the plant. Differential growth in maize is associated with the amount of dry matter accumulated at different stages of growth. Dry matter accumulation is the product of numerous interactions that include agro-meteorological conditions (temperature, photoperiod and light intensity), agronomic management (planting time, fertilizer, row spacing, plant density and harvest stage) and genetic factors (Graybill *et al.*, 1991). The effect of plant density on maize growth results from the onset of inter and intraplant competition during the growing period. Interplant competition commonly occurs earlier at higher densities whereas intraplant competition is more intense at low densities (Gardner *et al.*, 1985).

2.3.4 Growth phases

2.3.4.1 Establishment phase

Establishment begins with germination and leads to emergence of seedlings and is characterized by a slow increase in crop growth indicators due to the low LAI resulting in a low solar radiation interception. Basically the establishment of a plant mostly relies on viability and germination capacity of seed. It is a phase of growth characterized by a slow rate of growth where the newly emerged seedlings interact with a new habitat. The establishment phase usually involves a 21 day period from seeding/planting maize and depends on cultivar (Hunt, 1990). Smith (2006) reported that maize takes 15-25 days for establishment. The slight difference in establishment phase might be attributed to variations in viability of seeds, germination capacity of seed, soil temperature and moisture.

2.3.4.2 Vegetative phase

The vegetative phase follows establishment with a subsequent increase in photosynthesis. In essence, the vegetative phase represents the period between establishment and the beginning of sexual maturity. During this growth phase, a plant will be photosynthesizing as much as possible to grow as large as it can, before the onset of flowering (reproductive phase). The rate of maize growth between plant emergence and tassel emergence most significantly affects the total time required to maturity and establishes the date it will be ready for harvest. Smith (2006) reported that the vegetative growth phase of maize takes 25-40 days after establishment and is cultivar dependent. For instance, this period is shorter for 80-day hybrid maize than 120-day hybrids. In annual crops, the vegetative phase is generally terminated by the onset of flowering where leaves, stems and other vegetative parts fail to compete for current assimilate as grain filling requires a reserve as the main sink (Gardner *et al*., 1985).

2.3.4.3 Reproductive phase

The period from silking to physiological maturity is uniform and averages from 50 to 55 days for most hybrids. Pollination generally occurs within one to three days after silking and sufficient soil moisture levels, and optimum temperatures are critical for pollination. Cob growth also accelerates during this period with the onset of grain filling. Approximately 10 to 15 days after silking, depending on the maize cultivar, leaf and stalk growth is terminated and sugars produced by photosynthesis in the leaves move into the grain where they are converted into starches, protein and oils. Grain development is rapid during the next 30 to 35 days. Bewley & Black (1985) stated that the dry matter accumulation of maize kernels begins shortly after fertilization and progresses in a sigmoid pattern in which three phases can be distinguished. The first phase corresponds to the lag phase, which is a formative period during which sink capacity is set (Reddy & Daynard, 1983; Jones *et al*., 1996). It is characterized by a rapid increase in kernel water content with little dry matter deposition (Saini & Westgate, 2000). The second phase of seed growth is known as the effective grain filling period and involves active biomass accumulation, which is generally more important than the lag phase in actual size determination (Westgate *et al*., 2004). During this phase, kernel water content reaches its maximum and begins to decline, closely coordinated with dry matter deposition. In the third phase, kernels achieve their maximum dry weight (commonly referred to as physiological maturity) and enter a quiescent state (Saini & Westgate, 2000). Variation in final grain weight reflects the interaction between source capacity and sink strength (i.e., the source/sink ratio) during the effective grain filling period (Borras & Otegui, 2001; Westgate *et al*., 2004; Andrade *et al*., 2005). Maize grain yield is mainly determined by kernel size and number per unit land area (Otegui, 1995). These grain yield components are positively related to crop growth around silking (Anrade *et al*., 1999), and biomass allocation to the ears (Echarte *et al*., 2000).

2.4 Yield components

2.4.1 Number of kernels per row and ear

Kernel number per row and ear are yield components that have a profound impact on maize grain yield. In general, kernel number accounts for most of the differences in grain yield. Echarte *et al*. (2000) reported grain yield response to plant density to be positively and strongly related to number of kernels per ear and negatively and weakly related to weight per kernel. For instance, an increase in plant density from 50 000 to 145 000 plants ha^{-1} increased kernel number per ear by 38 to 56%. However, Tetio-kagho & Gardner (1988a) and Andrade *et al*. (1993) reported that the kernel number per row and ear declined sharply with increasing plant density. The decline of both yield components with increasing plant density was likely to be due to a decrease in photosynthetic rate per plant (Edmeades & Daynard, 1979) and hence plant growth rate. Both conditions reflected the reduction in interception of photosynthetically active radiation per plant. The highest reduction in kernel number per ear occurred in plants shaded during the lag phase of grain filling (Andrade *et al*., 1993).

Sangoi *et al.* (2002) indicated that the number of potential grain sites per ear measured when silking commenced and before pollination showed a decline from 550 to 474 grains per ear at a high plant density. This was ascribed to poor pollination for ears delayed in silking and abortion for some fertile grains thereafter (Hashemi-Dzefouli & Herbert, 1992). Tokatlidis & Koutroubas (2004) also reported that under high plant densities the reduced assimilate supply caused an abortion of kernels, especially at the tip. Carcova & Otegui (2001) and Maddonni & Otegui (2004) established that maize has a distinctive response to plant density beyond a certain threshold. This response to plant density derives from the combined effects of (i) a decrease in photosynthetic rate per plant and plant growth rate and (ii) a hierarchical pattern in reproductive development in which tassel growth dominates ear growth.

2.4.2 Kernel weight

Plant density has a prominent influence on kernel weight. The differences in kernel weight at variable plant densities may result from differences in the initial size of the spikelets and in the growth rate during the exponential and linear phases of grain accumulation. Lemcoff

& Loomis (1986) observed that the initial grain weight after pollination was a key factor in the early growth of the kernel. Thus, at a high plant density, the kernels was smaller, which could inturn be due to a delay in development (later initiation of spikelets) and a smaller initial size of the spikelets primordia. The final kernel weight correlates strongly with number of cells and starch granules formed, particularly in the endosperm tissue, representing about 80% of the mass of mature maize grains. Therefore, at high plant densities, yield may be restricted by limitations in the capacity for endosperm growth either by number, size or activity of endosperm cells (Salvador & Pearce, 1995). There is a possibility of interaction between kernel position and number in terms of competition for substrates required for growth, which is accentuated at high plant densities.

2.4.3 Ear length and diameter

Ear length and diameter are some of the dominant traits of grain yield of maize (Waezi *et al.*, 1998). Ross & Hallauer (2002) suggested that ear length and diameter are basic components affecting kernel yield. Plant density has a profound impact on ear length and ear diameter. Increased plant density, especially above a critical optimum on a particular environment reduces ear length and diameter, and ultimately the grain yield (EL-Lakany & Russel, 1971; Begna, 1996; Kgasago, 2006).

2.4.4 Prolificacy and barrenness

Plant density strongly affects the rate and duration of crop growth and ultimately the fate of multiple ears (Sarquis *et al*., 1998). These researchers also indicated that a 30% reduction in light interception by the canopy during the crop cycle was sufficient to completely suppress the development of a second ear. Apparently the reduction of light interception limits source capacity, which inturn could retard second-ear growth severely enough for the latter to be even totally repressed once the ovules in the apical ear have been fertilized (Tetio-Khago & Gardner, 1988b). High plant density results in a reduction of light interception per plant due to mutual shading that affects source capacity to supply a second ear with sufficient photoassimilates. Hence, apical ear yield seem to be sink limited, while source capacity seem to limit growth of the second ear. Edmeades *et al*. (1997) showed that assimilates moved preferentially from a leaf to its nearest sink. This implies that leaves above and immediately below the primary ear supply the majority of assimilates for grain filling while assimilates from the lower leaves are probably translocated into the root system and lower stem.

At high plant densities, the equilibrium between two ears seem to be affected by a stronger competition between the ears as evidenced by a more severe decrease in grain mass with increasing time between the two pollinations, regardless of which ear was pollinated first (Sarquis *et al.,*1998). The results indicated that in order to complete its growth, a second ear must reach a minimum stage of growth before active grain filling begins in the first ear (Tetio-Khago & Gardner, 1988a). The total yield per plant would be maximized when both ears were pollinated at the same time (Sarquis *et al.*, 1998). Researchers reported that plant density and arrangement of plants have an effect on prolificacy, where prolificacy is negatively correlated with plant density (Otegui, 1995).

Barrenness, the failure of plants to produce ears has been reported as one of the major factors limiting optimum conversion of solar radiation to grain in maize at high plant densities (Buren *et al*., 1974). Grain yield of many hybrids cultivated at high plant densities are considerably reduced as a result of barrenness. Therefore, factors influencing barrenness have to be determined and understood to carryout possible selection of genotypes that are tolerant to high plant densities (Buren *et al*., 1974). Ritchie & Alegarswamy (2003) reported that a high maize yield (kg ha^{-1}) at high plant densities ranging from 70 000 to 100 000 plants ha^{-1}, but barrenness was initiated more frequently at plant densities above 100 000 plants ha^{-1}. Increased plant density does not only affect barrenness positively, but also plant growth rate. Andrade *et al*. (1999) found that maize plants were barren when the plant growth rate averaged 1.0 g m^{-2} day^{-1} during the 30 day period bracketing silking. Maize genotypes also appear to have major genetic difference in barrenness. Another factor affecting barrenness leading to a greater proportion of barren plants is excessive population pressure. This could ultimately reduce grain yield (Van Averbeke & Marais, 1992). Tollenaar & Aquilera (1992) reported that lower barrenness in modern maize hybrids compared with older hybrids at higher plant densities was associated with higher plant growth rate from one week presilking to three weeks presilking. Moreover, Andrade *et al.* (1999) correlated average intercepted photosynthetically active radiation to barrenness and indicated that a threshold average intercepted photosynthetically active radiation of 0.34 MJ plant^{-1} during the ear development stage was necessary to avoid barrenness.

2.5 Yield

2.5.1 Biomass

Biomass is the dry mass of living material contained above and/or below a unit of ground surface area at a given time. Biomass is an integral part of crop growth rate in gram dry matter per m^2 of ground surface per day for the growing season. Crop growth rate is the product of the average NAR and the average leaf area index for a given growing season. Crop growth rate is influenced by soil properties, photosynthetic properties of leaves in the canopy, LAI and canopy architecture, length of the photosynthetic activity of the leaf area, climatic factors, absorption and synthetic activity of the root system (Petr *et al.*, 1988).

For any crop or stand of natural vegetation, four factors determine the net biomass gain or net productivity (Hall & Long, 1993). These are (i) the quantity of incident light (ii) the proportion of that light intercepted by green plant organs (iii) the efficiency of photosynthetic conversion of the intercepted light into biomass, and (iv) the respiratory losses of biomass. As leaves are the photosynthetic factory of the plant, the amount of photosynthate available for biomass production is related both to the current leaf area and photosynthetic rate of the leaves. Therefore, crop dry matter is a result of accumulated daily carbon gains from photosynthesis throughout the growing season. Leaf photosynthetic rates have sometimes been correlated with dry matter potential among genotypes (Izhar, 1967; Heichel, 1969; Moss, 1971). According to Dwyer & Tollenaar (1989) leaf photosynthesis of early maturing maize cultivars is less sensitive to stress. These hybrids also require higher plant densities to maximize grain yield due to their compact plant architecture (Derieum, 1987; Tollenaar, 1989). Moreover, there is some evidence that canopy CO_2 exchange is related to crop dry matter accumulation (Puckridge, 1971; Victor, 1979; Dong & Hu, 1993). However, these relationships are not clearly understood for stands of different plant types growing under different plant densities.

2.5.2 Grain yield

Grain yield refers to economic parts of the crop harvested per unit area of land (Forbes & Watson, 1992). Maize grain yield is a product of the yield components that include the number of plants per land area, number of ears per plant, seeds per ear and 1000-grain weight (Kmen *et al.*, 2001). The most important goal in any farming system is to minimize risk, maximize productivity and make profit. Maize production can also be described as a function of the rate and duration of dry matter accumulation by individual kernels multiplied by the number of kernels per plant (Westgate *et al.*, 1997). In simple terms, maize grain yield is a product of the number of ears produced and the average weight of the grain on the ears. Therefore, successful maize production requires an understanding of various management practices, as well as prevailing environmental conditions, that affect crop performance and productivity (Eckert, 1995). Selection of appropriate cultivars, planting dates, fertilization and plant densities are cultural practices that have been shown to affect maize yield potential and stability (Norwood, 2001).

Plant density is defined as the number of plants per unit area of ground. Plant density has a marked impact on crop yield and is regarded as an agricultural “input” in much the same way as fertilizer. An integral aspect of plant density is spatial arrangement, that is, the pattern of distribution of plants covering the ground area. As plant density increases, the yield per plant increases up to a threshold after which it decreases due to increasing competition for growth resources. On an area basis, however, the increased plant number gives greater utilization of resources and total biological yield increases in the form of a diminishing response curve that levels off when plant density is sufficient for maximum resource utilization. With further increases in plant density, the total biological yield of maize per unit area generally remains reasonably constant (Willey, 1982). Thus, a critical plant density is known to vary according to the level of soil fertility, soil water status, cultivar grown and planting date (Sangoi, 2000).

Grain yield in maize is also interrelated to LAI and hence canopy structure with respect to light interception (Tetio-Kagho and Gardner, 1988b; Cox, 1996). Basically to achieve optimum LAI, it requires an appropriate arrangement of row spacing by plant density combination for a particular genotype. Hunter (1980) reported that the grain yield of maize can be increased by increasing the leaf area per plant. He concluded that a large leaf area per plant produced more assimilate in the plant, resulting in increased yield. LAI can be improved in two ways: breeding for increased leaf area per plant and increasing plant density. One of the breeding strategies available for increasing leaf area per plant is to incorporate the leafy trait into inbred lines. Plants bearing the leafy trait are characterized by extra leaves above ears, low ear placement, highly lignified stalks and leaf parts, early maturities and high yield potential (Shaver, 1983). Increasing plant density is one management tool for increasing the capture of solar radiation within the canopy. Dewit (1967, as cited by Bos *et al.,* 2000) showed that crop canopies convert only 5% of incident solar radiation into chemical energy during the crop growing season. Pepper (1987) reported that increased plant densities can promote utilization of solar radiation by maize canopies. However, efficiency of conversion of intercepted solar radiation into economic yields decreases with a high plant density because of mutual shading of plants (Burnen, 1970).

Maize grain yield rises with planting density to some maximum value and then declines. The rate that produces maximum yield varies with varieties, environment, fertility and planting pattern. For a given hybrid, the yield of maize generally increases as plant density rises until one or more factors such as water supply, available plant nutrients and other growth influencing factors become limiting. According to Vega *et al.* (2001) maize grain yield is more affected by variations in plant density than other members of the grass family due to its low tillering capacity. Fancelli & Dourado (2000) also found a strong relationship between maize grain yield and plant density. They highlighted that for each production system there is a plant density that optimizes the use of available resources, thereby allowing the expression of maximum attainable grain yield in that environment.

A considerable amount of research showed that crop yield can be increased when row spacing is reduced (Olson & Sander, 1988; Porter *et al*., 1997; Westgate *et al*., 1997; Lee, 2006). The majority of research on crop row spacing was done from the early 1980's and focused on reducing row spacing to less than 0.76 m. Investigation in many areas of the northern United States indicated yield increases up to 9.9% by growing maize in rows narrower than 0.76 m (Paszkiewicz, 1998). In addition to improving crop yield, reduced row spacing can also provide the crop with a competitive advantage over weeds. Several studies have shown that narrow rows are more efficient at intercepting (0 to 11%) light than wide rows (Teasdale, 1995; Begna *et al.*, 2001; Stewart, 2001; Tharp & Kellers, 2001). Cardwell (1982) indicated that reduction of row spacing from 1.07 to 0.90 m in maize was estimated to result in an overall mean yield increase of 175 kg ha^{-1}. Maize yield may be further increased by reducing row spacing from 0.90 to 0.76 and even to 0.38 m (Neilsen, 1988; Widdicombe & Thelen, 2002). On the other hand, maize grain yield declines when plant density is increased beyond the optimum plant density primarily because of a decline in the harvest index and increased stem lodging (Tollenaar *et al.*, 1997). Such cases represent intense interplant competition for incident photosynthetic photon flux density, soil nutrients and soil water. When maize is planted in narrower rows at the same plant density, the plants are more uniformly distributed over the soil surface. This makes the crop more effective in intercepting solar radiation and shading weeds. The canopy will usually close sooner and result in lower soil temperatures, thus reducing evaporation from the soil surface. Studies on sorghum have shown that shading the soil sooner with narrow rows can reduce the sensible heat load, and subsequently lower the evaporation component of evapotranspiration (ET) (Choy & Kanemasu, 1974). This is probably also true for maize canopies where a more uniform distribution of plants will also assist in reducing the negative effect of rainfall impact on soil structure deterioration by intercepting more drops with leaves. This results in higher infiltration rates and more effective rainfall utilization with a positive impact on final grain yield (Pendleton, 1966; Mitchell, 1970).

Crop researchers conducted many studies on plant competition to determine the optimum plant density for maize (Olson & Sander, 1988). Unfortunately, there is no single recommendation for all environments, because optimum plant density varies depending on nearly all managed environmental factors such as soil fertility, hybrid selection, planting date, planting pattern, plant protection and time of harvest. Duncan (1984) reported that the yield of a single maize plant is affected by the proximity to adjacent plants. Plant density above a critical density has a negative effect on grain yield per plant. This yield reduction per plant is ascribed to the effects of interplant competition for light, water, nutrients and other potentially yield limiting environmental factors. Mock and Pearce (1975) proposed a maize ideotype that would maximally utilize an optimum production environment. Crop management for this environment includes high plant densities and narrow row spacings for maize ideotypes characterized by stiff, vertically oriented leaves above the ear, maximum photosynthesis efficiency, and efficient conversion of photosynthate to grain.

Plant density beyond an optimum limits the conversion of light energy to grain and initiates the development of barren plants (Sangoi, 1996). The mechanism of ear development needs clear understanding of its differentiation to silking. This enables to describe plant density impacts on the number of female inflorescence produced per plant and the number of viable differentiated spikelets. Barrenness is the physiological alteration that can be associated with high plant density which delays ear differentiation and growth of ear primordia (Jacobs & Pearson, 1991). The number of functional ear shoots differentiated per plant appears to depend upon the genetic programming for the time interval between the initiation of female inflorescences (lateral branches) and the differentiation of the shoot apex into a reproductive structure (male apical inflorescence). High rates of planting slow the rate of growth of axillary buds more than they do the shoot apex. The existence of this time interval permits the establishment of differential rates of polar transport of growth-promoting substances and nutrients into the shoot (Sangoi *et al.*, 1998). These growth-promoting substances and nutrients would regulate the rate and pattern of ear shoot development and the number of functional ear shoots per plant. Later-initiated ear shoots may receive smaller amounts of growth substances, thereby having less chance to become functional and produce grains. Thus, the lower absolute growth rate observed for ears in dense stands can also result from increased competition for assimilates between the ear and the rest of the plant organs. Besides the competition for assimilates among plant organs, there may be a hormonal mechanism accounting for the influence of plant density on ear development before flowering (Willson & Allison, 1978). The maize shoot apex is differentiated into a tassel premordium when the plant has six to seven expanded leaves and attains 40 to 50 cm plant height (Ritchie & Hanway, 1992). Once the growing point is transformed into a reproductive structure, it starts producing large amounts of phytohormones, especially auxins, which stimulate cell division and enlargement, triggering an intense increase in plant height and dry matter production. At high plant densities less solar radiation reaches the growing point as compared to lower plant densities (Gardner *et al*., 1985). Light in high intensity or amount may oxidize and inactivate auxins (Salisbury & Ross, 1992). Therefore, under high plant densities there is less auxin inactivation and a greater concentration of bioactive hormones which may promote hormonally-mediated apical dominance over the ears leading to the formation of barren plants with a corresponding reduction of grain yield (Sangoi & Salvador, 1998).

Plant density affects crop yields indirectly through an increased level of competition. Individual plant interference with the equal sharing of growth resources increases almost linearly with an increase of plant density. Most investigations assessed yield-density responses on the basis of observations made at the final harvest, but further insight into the origins of yield-density responses should be gained by following the development of those responses as a plant grows (Jolliffe *et al.*, 1985). To maximize crop yield, it is essential to optimize the stand uniformity by minimizing the plant to plant variation. Modern maize hybrids released for production have had increasing tolerance to the stress associated with high plant densities as compared with older hybrids (Hammer *et al.*, 2009). Furthermore, maize has a limited ability to take advantage of increased resources under suboptimal plant densities, indicating that future yield improvement will likely be related to greater stress tolerance, allowing for higher plant densities (Tollenaar & Lee, 2002). Thus, there is a need to regularly monitor the response of maize grain yield to plant density for new hybrids to maintain accurate recommendations for growth (Cox, 1997; Widdicombe & Thelen, 2002; Stranger & Lauer, 2006).

Yield increases in maize have become largely attributed to genetic gains made by breeders (50-70%) and superior agronomic management practices (30-50%) (Cardwell, 1982; Duvick, 2005; Lee & Tollenaar, 2007). However, in actuality nearly all prior yield advances in maize have resulted from the interactions between improved genetics and superior agronomic management practices (Tollenaar & Lee, 2002). Modern maize genotypes generally have greater tolerance to insect feeding, pathogen infection, drought, low soil fertility, saturated and/or cool soils, above and below average seasonal temperatures, low night temperatures during the grain filling period and inter- and intra species competition (maize-maize and maize-weed, respectively), solar radiation, water and soil nutrients (Dwyer & Tollenaar, 1989; Tollenaar *et al*., 1997; Tollenaar & Wu, 1999; Ying *et al.*, 2000; Duvick, 2005). The tolerance of modern maize hybrids to intense competition for available resources at high plant densities has improved much more than other environmental stress tolerance over the past 40 to 50 years (Russell, 1991; Tollenaar, 1991; Tollenaar & Lee, 2002; Tokatlidis & Koutroubas, 2004). Principally this progress has been driven by maize breeders selecting for grain yield and/or beneficial morpho-physiological traits in environments commonly encountered in commercial maize production. Thus, to optimize grain production and maximize grain yield potential in today's production systems, modern hybrids must be grown at higher plant densities than their predecessors (Tollenaar, 1989; Tokatlidis & Koutroubas, 2004).

2.5.3 Harvest index

The ratio of economic yield to above-ground dry matter yield is termed the harvest index and is a useful index in characterizing the physiological efficiency and ability of a crop for converting total dry matter into economic yield (Howell, 1990). Harvest index is a widely cited index and provides information on the relation of economic and biological yields. However, the harvest index gives no information on specific yield components, for example, head number and kernels per head (Kanemasu, 1983). Most of the yield increases in high yielding varieties is accredited to the increase in harvest index. According to Rhoads & Bennett (1990) many researchers reported that harvest indices of traditional maize varieties ranged from 0.32 to 0.48. In an experiment conducted by Howell *et al*. (1996), an average harvest index value of 0.52 was reported for all seasons, hybrids and fields in the experiment. Harvest index is highly positively correlated with grain yield and decreases with increasing plant density above a certain optimum due to consequent increase in plant barrenness and lodging (Tollenaar *et al*., 1997). This illustrates that the harvest index values are intimately correlated with grain yield and vary with environment. Hence, it was concluded that harvest indices obtained in one environment had no predictable relationship to grain yields in a different environment (Kanemasu, 1983).

2.6 Maize genotypes

Genotype describes the complete set of genes inherited by an individual that is important for the expression of a trait under consideration. Maize genotypes currently available were exposed to changes in their genetic make-up due to the cross pollination of maize. Thus, each genotype was a collection of individuals that were usually in a range of variability with distinctively different traits (Hallauer, 1987). Environment and human selection played important roles in the development of genotypes with specific needs and fitness to a corresponding habitat. Maize hybrids released for production have had increasing tolerance to the stress associated with high plant densities (Hammer *et al.*, 2009). Furthermore, maize has a ability to take advantage of increased resources under suboptimal plant densities, indicating that future yield improvement will likely be related to greater stress tolerance, allowing for higher plant densities (Tollenaar & Lee, 2002).

Compared with older hybrids, modern maize hybrids tolerate high plant densities, in part because of a higher LAI at silking, which results in more interception of photosynthetically active radiation and more dry matter accumulation during vegetative development (Dwyer *et al*., 1991; Tollenaar & Aquilera, 1992). Moreover, at high plant densities modern hybrids exhibit a higher CGR from one week before and two to three weeks after silking, which contributes to more kernels per plant and higher grain yield (Tollenaar, 1991). Tollenaar *et al*. (1992) and Tokatlidis & Koutroubas (2004) suggest that fast and ultra-fast maize hybrids, compared with older hybrids respond more positively to high plant densities because of increased stress tolerance. Prior & Russel (1975) found that prolific hybrids had a broad optimum plant density, whereas nonprolific, single eared hybrids had a narrower range of optimum plant density for grain yield. Furthermore, they suggested that prolific hybrids responded more positively than nonprolifc hybrids to high plant densities and/or stressful environmental conditions, because of greater resistance to barrenness. Graybill *et al*. (1991) in a study in New York reported that some commercial hybrids produced maximum forage yields at 80 000 plants ha^{-1}, whereas other hybrids produced maximum forage yields at 65 000 plants ha^{-1} which illustrates that different genotypes of maize demand variable plant density for maximum yield.

Mean agronomic traits of maize genotypes in maturity groups are summarized in Table 2.1. Generally late maturing genotypes showed higher values of agronomic traits while ultra-short genotypes exhibited lower values of agronomic traits. Late maturing maize genotypes need more days to taselling, silking, pollen shedding and physiological maturity. Similarly, the late maturing genotypes attained a higher plant height, ear height, leaf number, ear diameter, kernels per ear and leaf length. In contrast, ultra-short maize genotypes have the lowest values for almost all agronomic traits. Medium to short genotypes, on the other hand, has mostly agronomic traits values in between late and ultra-short genotypes. These phenotypic differences are the result of variations in genetic make-up. This illustrates that selection for different agronomic traits led to different physiological, morphological and anatomical alterations of genotypes. Hence, crop management to be practiced directly relates to morphological and agronomical traits of genotypes. Taller plants with a greater number of leaves require a lager growing area and lower plant density than shorter ones (Begna *et al*., 2000). The size of plants (height, leaf area, leaf length) is in positive correlation with the duration of the vegetative phase and dry matter production, that is, taller plants accumulate more dry matter. Mason *et al*. (1974) indicated that dry matter yield showed a significant positive association to plant and ear height. However, the translocation rate of assimilate to the kernels of shorter hybrids was found to be greater than that of taller ones (Begna *et al*., 2000).

Table 2.1 Mean agronomic traits of maize genotypes in maturity groups at their respective optimum plant densities

	Maize genotypes in maturity group					
Descriptor	**Late maturing**	**Medium to late**	**Medium**	**Medium to short**	**Short**	**Ultra-short**
Leaf number per plant	22	20	19	17	14	13
Leaf orientation	NA	NA	NA	NA	upright	Upright
Leaf length (cm)	85.4	84.6	83.1	80.9	80.2	80
Plant height (cm)	290	265	245	227	217	215
Ear height (cm)	143	132	122	113	103	102
Ear length (cm)	18	17.4	16.1	15.2	14.7	14.6
Ear diameter (cm)	5.19	5.13	5.05	4.97	4.94	4.93
Thousand seed weight (g)	252.4	251.5	251.2	250.6	250.2	250.2
Kernel number per row	39	37	36	35	35	35
Kernel number per ear	576	570	569	568	567	567
Days to tasseling (50%)	73	70	66	62	59	57
Days to pollen shedding (50%)	773	767	763	758	753	751
Days to silking (50%)	83	75	73	67	63	60
Days to physiological maturity	136	128	120	119	118	118

Source: CIMMYT, 1999; Salla *et al*., 2004; Beyene, 2005; Berzsenyi & Lap, 2005, NA= not available

Early maturing maize genotypes offer flexibility in planting dates which enables:

- multiple planting in a season to spread the risk of losing a single crop to mid-season droughts;
- late planting during delayed onset of rainfall;
- avoidance of known terminal drought during the cropping season; and
- cultivation at higher plant densities due to plant morphological characteristics such as less leaves, low plant height, low ear height and smaller leaf area (Pswarayi & Vivek, 2007).

Generally ultra-fast maize genotypes are characterized by fewer days to tasselling, silking and maturity, plant height, leaf length, ear length and diameter than medium and long maturing hybrids (Table 2.1). The plant height, ear length, and ear diameter are smaller than medium and long season hybrids. Moreover, the fast and ultra-fast hybrids are also characterised by leas leafs, upright leaves, smaller tassels and more synchronized floral development compared to the medium and long season hybrids. Such morphological traits enable them to withstand high plant density without presenting a higher percentage of barren plants (Sangoi, 2000). Therefore, under irrigation the fast and ultra-fast hybrids are planted at high plant densities to attain maximum yield with optimum integration of spatial arrangement of row spacing and plant density.

2.7 Water use and water use efficiency

2.7.1 Definition and concept

Any concept of efficiency is a measure of the output obtainable from a given input. Water use efficiency can be defined in different ways depending on the nature of the inputs and outputs considered. A widely applicable expression of efficiency is the agronomic or crop water-use efficiency, which has been defined as the amount of vegetative dry matter produced per unit volume of water taken up by the crop from the soil (Viets, 1962). Water use efficiency is the result of any measure that reduces the amount of water used per unit of any given activity. Most of the water taken up by plants in the field is transpired (in arid regions, as much as 99%) only a small amount is retained. Plant water use efficiency is in effect the reciprocal of what is known as the transpiration ratio (Briggs & Shantz, 1913, as cited by Hillel, 2004). On the other hand, water use also termed seasonal evapotranspiration (ET), refers to the quantity of water used in transpiration or building of plant tissue and that evaporated from the soil or from intercepted precipitation during a specific period of time (Thomas *et al*., 1975; Smith, 2000). The total ET requirement for a crop is usually taken from planting to crop physiological maturity. According to Hassan & Manaf (2006), water use encompasses the amount of water evaporated from soil surface and transpired from plants while runoff and drainage are often negligible per land area, but not in irrigated agriculture.

Crops consume water in the process of transpiration and water evaporates from the soil. Transpiration and evaporation are the combination of two separate processes, whereby water is lost from land. Evaporation is the process by which liquid water is converted to water vapour, while transpiration consists of the vaporization of liquid water contained in plant tissues and vapour removal to the atmosphere. Evaporation and transpiration occur simultaneously and there is no easy way of distinguishing between the two processes and they are collectively termed evapotranspiration (Thornthwaite, 1948). Only the transpiration portion of evaporation directly influences crop production (De Wit, 1958). Hence, WUE is the ratio of production to water used while production is the amount of marketable, total or above ground biomass and carbon dioxide fixed. Similarly, water use can be defined in terms of applied irrigation water, plant or leaf transpiration, or the sum of transpiration and evaporation from the soil surface (Thornthwaite, 1948). Clearly water use efficiency can be maximized by decreasing unproductive losses (evaporation, runoff, deep percolation) or increasing transpiration of crops. Improving water use efficiency is therefore, a twofold task. It requires that (a) water be conserved by avoidance of waste and (b) growth be maximized by using high yielding crop varieties, well adapted to local soil and climate and by optimizing agronomic practices.

2.7.2 Importance of water use efficiency

Water has always been a fundamental building block for a healthy economy. With the exception of soil fertility no other environmental factor limits crop productivity more severely than water deficits (Fischer & Turner, 1978; Boyer, 1982). Hence, soil water utilization is an important limiting factor to crop production since it is essential for every growth and development phase starting from seed germination to maturation. Yield potential in maize is closely related to water availability, either from rainfall or irrigation. The amount of water effectively utilized by the crops is less than 20% of the total water applied (Saeed, 1994). This indicates that sustainable and efficient use of water is of paramount importance for successful crop production (Balasubramaniaya & Palaniappan, 2001).

Plant growth and development can be affected by water deficits at any time during the crop life cycle, but the extent and nature of damage, the capacity for recovery and the impact on yield depends on the developmental stage at which a crop encounters stress. Moreover, the sensitivity to water deficits is particularly acute during the reproductive development because reproduction involves several processes that are extremely vulnerable to a change in the plant water status (Salter & Good, 1967; Saini, 1997).

Globally and locally, irrigated agriculture is vital in ensuring food security to meet the food requirement for a rapidly growing population (Morrison *et al*., 2008). The main emphasis of enhancing water use efficiency in irrigated cropping is to increase crop yield per unit of water applied. Therefore, irrigation scheduling can be an effective technique of improving water use efficiency of crops by increasing yield. Water requirements of a crop vary with genotype and environmental conditions. Basically water used by crops is related to the total dry matter production or economic yield (Taylor *et al*., 1983). Hence, the term water use efficiency originates in the economic concept of productivity which measures the amount of any given resource that must be expended to produce a unit of output. In simplest term, improved water use efficiency means lowering the water needs to achieve a unit of production. Therefore, in agricultural systems optimum water management should be established to maximize the water use efficiency which is associated with the economic yield produced with the corresponding total amount of water consumed (Kafkafi, 1997). This led to the concept of water use efficiency, which is a useful index to determine seasonal water requirements of a crop with the intention of increasing yield (Brown, 1999).

2.7.3 Estimation of water use efficiency

Generally, the term WUE (kg ha^{-1} mm^{-1}) has been used very loosely by plant scientists and agronomists to refer to observations ranging from gas exchange by individual leaves for a few minutes, to grain yield response to irrigation treatments through an entire season (Gregory, 1989; Khan *et al*., 2001). According to Jensen *et al.* (1990) the most common WUE expression is related to the ratio of crop yield, usually economic yield per unit area, to the water consumed by ET from planting to crop physiological maturity. Therefore, WUE has been expressed as:

$$\mathrm{WUE} = \frac{\textit{Dry matter/Crop yield}}{\textit{Evapotrnaspiration}} \tag{2.3}$$

Water use efficiency during a specific growing season, therefore, expresses the efficiency with which a particular crop converted the available water into biomass. Water use efficiency measurements can be made on plants in containers, on individual plants in the field or even on crop communities. It is important to emphasise that water use efficiency can be based either on evapotranspiration (ET, efficiency) or on crop transpiration (T, efficiency). The difference is important since suppression of soil evaporation and prevention of weed transpiration can improve the T efficiency, which is a measure of crop performance. These two water use efficiencies may be used either on the total dry matter production or the marketable yield, and thus the yield base should be given (Tanner & Sinclair, 1983).

2.7.4 Methods of increasing water use efficiency

Development of agronomic systems that are based on efficiency, rather than production will increase the sustainability of production systems (Hatfield, 2001). The main benefit will be for varying densitiessustained in most areas of the world and especially those in arid and semi-arid areas where population growth is the highest (Wallace, 2000). The water use efficiency expressed as dry matter production per unit evapotranspiration reflects on both genetic and environmental factors (Tanner & Sinclair, 1983). A higher water use efficiency of a certain hybrid, therefore, provides a potential explanation for its better yield performance compared with other hybrids (Khan *et al.,* 2001). Moreover, the choice of suitable varieties relies on a balance between water requirements, which is directly related to the yield potential, and water availability (Howell *et al*., 1998; Trooein *et al*., 1999). Allowing a crop to transpire freely appears to be the most promising option for increasing its water use efficiency. Thus, higher water use efficiencies can be achieved by preventing any shortage of water during the growing season, while avoiding the wastage of water and obviating all other environmental constraints. This will ensure the attainment of the maximum possible production of the crop. These considerations are particularly important for new and superior cultivars, which have been developed in recent years for a better yield and water use (Hillel, 1980; Botha *et al*., 1983; Fanadzo *et al*., 2010). Moreover, any strategic crop management that increases canopy closure favours the proportion of transpiration relative to evaporation and thereby increase dry matter production with corresponding maximization of water use efficiency (Turner *et al*., 1986).

Reduction of row spacing can maximize water use efficiency, because narrower rows can increase light interception and grain yield, and decrease ET, the net result is an indirect increase in transpiration and water use efficiency. Water use does not significantly change but the yield of grain per unit of water does increase significantly. On the other hand, under less than optimal moisture, narrow rows do not necessarily result in yield increases even though soil evaporation may be reduced with narrow rows and water use efficiency may increase (Mitchell, 1970). Thus, strategizing plant arrangement through manipulation and modification of row spacing is one of the crop management practices that enable plants to intercept sufficient photosynthetically active radiation that may lead to efficient water utilization (Argenta *et al*., 2001).

Although maize has high water requirements, it is still one of the most water efficient crops in producing dry matter. Water use efficiency in maize increases as yield increases, and higher plant densities result in a decreased efficiency during seasons of water deficits. The peak water use by maize occurs at the time of silking or shortly thereafter. Research has shown that water deficits at the time of tasseling and silking also cause the greatest reduction in yield. Water stress prior to silking reduces grain yield by 25%, 50% at silking and 21% after silking (Denmead & Shaw, 1960). Water stress at tasseling not only hinders the plant's ability to flower and shed pollen, but can also greatly affect the viability of maize pollen, especially when the drought is accompanied by high temperatures, as is usually the case. Water stress at silking can impair extrusion of the silks from the husks and cause desiccation of the silks, reducing the number of seeds set on the ear. Water stress before floral initiation can reduce the number of kernels that can potentially be produced by the plant and stress after floral initiation can reduce the potential size of the kernels (Waldren, 1983). Hence, matching of plant density with corresponding available soil water may maximize the efficient use of water by maize.

2.8 Factors affecting water use efficiency

Water use efficiency of maize is a function of multiple factors that include physiological characteristics, genotype, and soil characteristics such as soil water holding capacity, meteorological conditions and agronomic practices. Thus, to improve water use efficiency of maize, integrated measures should be taken to optimize cultivar selection and agronomic practices to be adopted. Hence, factors affecting water use efficiency are categorized as plant factors, soil factors, climatic factors and crop management factors and are dealt with briefly as follows.

2.8.1 Plant factors

Plant factors that affect WUE encompasses stomatal closure, number and size of stomata, leaf surface area, leaf rolling or folding, and root depth and proliferation. Plant factors modify the ET rate by affecting the resistance to water movement from soil to plant and from plant surface to the surrounding atmosphere. Variation in the length or duration of the growing season is one of the most obvious means for matching seasonal transpiration or evapotranspiration to water supply (Loomis, 1983). With a crop such as wheat, early maturing varieties generally yield better than late maturing varieties where the supply of water is limiting (Laing & Fischer, 1977). Although early maturing maize varieties produce less dry matter and grain yields, compared to late maturing ones, they have nearly the same grain water use efficiency while the seasonal evapotranspiration amount was less. Howell *et al*. (1996) found the seasonal ET amount of an early maturing cultivar to be almost 120 mm less than that of late maturing cultivar.

Stress during a particular crop growth phase is one of the plant factors that affect WUE, because each plant has a characteristic water use pattern throughout the growing season. As water use is minimal during germination and early growth of seedlings it increases during the vegetative phase and reaches a maximum during flowering to grain filling stages and decreases at maturity. Differences in canopy structure may affect WUE by affecting the amount of light intercepted and attenuated. Variations in canopy architecture have concomitant effects on light in interception and attenuation (Maddonni & Otegui, 1996), and affect the crop's response to plant spatial arrangement (Westgate *et al*., 1997). Greater leaf area results in more rapid ground cover and reduced penetration of radiated energy to the soil surface for evaporation of water. Pearson *et al*. (1984) hypothesized that: (i) cultivar differences in carbon dioxide exchange rate (CER) were the greatest during grain filling, i.e. they were related to sink mediation of CER; (ii) manipulation of source-sink relations should produce changes in CER within hours, not days, if the effect is primarily on stomatal metabolism; but (iii) the changes in CER would be relatively small, at least in the field. They also concluded that the differences among the genotypes in leaf CER was most likely due to stomatal conductance, because the genotypes had the same CO_2:H_2O exchange ratio.

2.8.2 Soil factors

Soil factors that affect water use efficiency include surface crusting, salinity, acidification, root distribution, soil depth, bulk density, texture and structure. Changing the soil nutrient status also influences water use efficiency as a result of the nutrient status of the soil that influences plant growth and ultimately the amount of biomass produced per unit of water consumed. It is known that proper nutrient levels in the soil will lead to increased yields and a better water use efficiency. Application of nitrogen fertilizers increases water use efficiency in grain maize due to the fact that nitrogen additions increased grain yield production (Gregory, 1989). Water stress that occurs during different growth and developmental stages influences WUE to a great extent. Water stress occurring during different development stages of maize may reduce final grain yield to different degrees, and the extent of yield reduction depends not only on the severity of the stress, but also on the stages of plant development (Cakir, 2004; Zaidi *et al*., 2004). Doorenbos & Kassam (1988) reported that maize appears to be relatively tolerant to water deficits during the vegetative and ripening periods, and that the greatest decrease in grain yield is caused by water deficits in the soil profile during the flowering period (Cakir, 2004; Zaidi *et al*., 2004). Thus, to alleviate yield reduction and maximize potential yield, adequate amount of water should be available during the flowering period (Neild & Newman, 1990; Van Averbeke, 1991).

2.8.3 Climatic factors

Climate is the driving force of crop production and crop water use. Increasing air temperature and precipitation patterns influence crop yield and WUE (Kattge & Knorr, 2007). The greater the atmospheric demand, the faster water evaporates from a free water surface. This atmospheric demand is influenced by climatic elements such as solar radiation, temperature, relative humidity and wind. The highest atmospheric demand occurs at the time of year when solar radiation and temperature are greatest. Climate change may modify transpiration, evaporation, runoff and soil water storage (Feddema & Freire, 2001; Nicholson, 2001). Crop water needs are higher when it is dry than when it is humid, and crops grown in windy climates use more water than those in calm climates (Brouwer & Heibloem 1986). The occurrence of water stress during flowering, pollination and grain filling is harmful to crops such as maize with obvious reduction of yield which results in a decline in WUE.

2.8.4 Crop management factors

Management of soils and crops has a large influence on WUE, mainly because of its effects on the proportion of water transpired. Water use efficiency is ration between water used and crop biomass or yield produced (Hatfield, 2001). It is not the same as drought resistance, but rather refers to yield in relation to the water used to produce the yield. In many arid and semi-arid regions evaporation directly from the soil surface is a large component of the total water use of crops grown. Essentially, any cropping or tillage practice that affects crop growth and development will have similar effects on transpiration and evaporation from the soil surface under comparable climatic conditions (Bennie & Hensley, 2001). Some practices increase the water use efficiency by reducing evaporation from the soil surface. These practices include the application of fertilizer, early sowing, modifying plant density and spacing, mulching and selecting varieties with rapid early growth (Bennie & Hensley, 2001). Others increase WUE by increasing the total water supply to crops that include cultivation to improve infiltration, fallowing, multiple/relay cropping, selecting varieties with deep roots, supplemental irrigation, water harvesting and weed control (Gregory, 1989).

Crop rotation affects WUE especially in semi-arid areas. A common practise is to rotate maize with wheat that includes a fallow period of approximately 11 months during which water conserved. Water use efficiency was primarily studied in semi-arid agricultural regions and generally ignored/excluded rainfall during the preceding fallow season of these studies (Hensley *et al*., 2000). In these regions the emphasis was on fallow periods in the crop rotation system to increase the amount of soil water stored in the profile at seeding. Secondary it also included crop health and weed management. There were some changes in this philosophy in the past ten years in an attempt to consider more intensive crop rotations. Some researchers showed that efficiency gains were due to reduced use of the fallow and using water for transpiration that otherwise is lost during fallow due to soil water evaporation, runoff, or deep percolation. In areas where fallowing is practiced, the efficiency of precipitation storage is often low, between 10 and 15% of the total rainfall partly due to disturbance of the soil surface to control weeds. Changing the intensity of crop rotation may have a significant increase in the overall water use efficiency. Water use efficiency in temperate climates is often twice as large as in semi-arid climates because of the reduced amount of water stress and wetter soil conditions (Hatfield, 2001). Management systems, such as deep cultivation operations affect and may even improve water use efficiency of maize. Deep cultivation ensures less runoff and improved infiltration as well as a better root system for maize, thereby enabling the crop to convert the absorbed water and nutrients more efficiently into biomass and grain production (Botha *et al*., 1983).

Time of water application affects water use efficiency. For maize, the most critical watering period is pollination. The highest seasonal water use occurs during the two weeks before and two weeks after silking. This reproductive stage is the single most important time to avoid water stress. Water stress during silking tends to desiccate the silks and pollen grains causing poor pollination and seed set, resulting in seedless ear tips. Therefore, water stress during silking will result in the highest yield reduction. Moreover, water requirements remain also high during early stages of grain development, often described as the blister kernel and milk stages. During this time, the grain develops rapidly and increases in weight. Since maize requires water up to the time of physiological maturity, the irrigation should usually be applied until two to four weeks before physiological maturity (Rhoads & Bennet, 1990).

Water use efficiency is regulated by plant water use which in turn is influenced by the evaporative potential of the atmosphere, amount of water available in the soil and certain plant characteristics. The available water supply is affected by precipitation and irrigation practices, drainage, certain inherent soil physical properties as well as water storage and movement (Hillel, 1987). Moreover, crop productivity is strongly influenced by nutrition and water availability. Viets (1962) investigated these interactions in terms of water use efficiency for crops with unlimited water supplies. When the water supply to a crop is fixed, any management factor that increases production, such as fertilizers, weed control, disease control, planting density and planting geometry, will increase the water use efficiency. Rhoads (1984) has summarized that literature dealing with water and N responses of crops which indicate that when N was limiting yield, the water use efficiency was improved by as much as 41% when higher rates of N were applied.

2.9 Relationship between crop production and water use efficiency as affected by evapotranspiration

Essentially all water on the earth is held in the oceans, lakes, and ice or snow fields. Only about 0.5% of the total water on earth is involved at any given time in the hydrologic cycle, that is, the cycle that includes the evaporation of water from the surface of the earth, transport of water vapour in the atmosphere, and the eventual return of the water to the land surfaces and water bodies (Blaine, 1983). Therefore, water scarcity is an important issue in many parts of the world. Climate change prediction of temperature increase and a decrease in rainfall means that water will become even scarcer. Since agriculture is the greatest water user, efficient use of water in agriculture is needed for the conservation of this limited resource. Increase in water use efficiency can be achieved by different strategies. One of these strategies is to change the crops capability to produce acceptable yields under deficit irrigation (Zwart & Bastiaanssen, 2004).

Severe water stress results in death of plants while its stress leads to reduced yields (Moss, 1984). Therefore, irrigation is increasingly important in the semi arid parts of the world and has become an important topic of discussion with respect to crop production. Erratic and unreliable rainfall has initiated the rapid increase of irrigation practices as an alternate means of crop production (Evette, 2006). In order to achieve sustainable crop production; matching current irrigation practices with management operations targeted with efficient water use is of paramount importance. Adjusting cultural practices such as row spacing and plant density on the basis of crop response in terms of increased plant growth is an opportunity to improve water use efficiency (Hatfield *et al*., 2001). Optimizing plant densities is crucial in areas where crop growth is constrained by precipitation. Thus, high plant densities may deplete most of the available water before the crop reaches maturity while low plant densities may leave water unutilized in the soil (Bayu *et al*., 2004).

Water use efficiency can be expressed in a number of ways, but for agronomic purposes it comprises of two major terms: (i) a biological component that expresses the amount of dry matter produced per unit of transpiration, referred to as the transpiration efficiency and (ii) a management term that specifies the fraction of the total water supply used for transpiration (Gregory, 1989). According to Hillel (1987) the first comprehensive analysis of the relation between transpiration and yield was offered by De Wit (1958). He found that in arid and semi-arid regions, the following relation was observed between yield and transpiration.

$$Y = \frac{m(T)}{Eo} \qquad (2.4)$$

Where:

Y = Dry matter or seed yield (kg ha^{-1})
T = Transpiration (mm)
Eo = Potential (free water) evaporation (mm)
m = Transpiration coefficient

The transpiration coefficient (m) is dependent only on variety and species. Using total biomass of maize and its transpiration, for the calculation of water use efficiency, Tanner & Sinclair (1983) reported a range of WUE of 2.0-5.4 g kg^{-1}. The main drawback of the relation was that transpiration could not be predicted exactly in the field from ET measurements.

The quantity of water required to produce a specific yield may also be expressed in several ways (Gregory, 1989; Bennie & Hensley, 2001). The seasonal above ground total biomass or dry matter (Y, kg ha^{-1}) produced per unit area is a function of the amount of water taken up (T, mm) during the corresponding season. The water balance equation (Bennie & Hensley, 2001) for a specific area of land is computed as:

$$(E + T) = P + I \pm R \pm D \pm \Delta W \tag{2.5}$$

Where:

P = Precipitation during the growing season (mm)
I = Applied irrigation (mm)
E = Amount of water evaporated from the soil surface during the growing season (mm)
T = Water uptake by the plant roots which for practical purposes equal to the transpiration loss through evaporation from the plant canopy (mm)
R = Runoff (-) from, or run-on (+) onto, the soil surface during the growing season (mm)
D = Deep water drainage below the rooting zone or beyond the deepest roots (-) or upward flux into the root zone (+) (mm), and
ΔW = Seasonal change in soil water content of the root zone (mm)

Evapotranspiration is calculated as the residual term (E + T) in the water balance equation, especially in seasonal studies. This equation is also used to calculate the evapotranspiration between two consecutive water content measurements, during the crop-growing season, when all the other terms have been measured. There are several methods of directly measuring the soil water content. The neutron probe has become the common technique for measuring the soil water content of the soil profile. Lysimeters can also be used as an indirect method of measuring evapotranspiration. Hanks (1983), Hillel (1987) and Hatfield (1990) reported that there is a strong relationship between ET and grain yield or dry matter yield. However, the relationship between yield and ET is more complicated than that between yield and transpiration, due to the variable component of evaporation from the soil surface.

In a field study by Hillel and Guron (1973), the total dry matter yield of maize per unit ET increased twofold and ET increased by 30% in a wetter irrigation regime where ET was nearly equal to maximum ET corresponding to maximum attainable dry matter yield when water is not limiting. The wettest treatment yielded 2.3 times as much grain as the driest treatment, while, consuming only 1.3 times as much water. Rhoads & Bennett (1990) reported that, as a result of the lower seasonal ET in the humid regions, WUE as high as 30 kg ha $^{-1}$ mm^{-1} was reported for maize grown in southern USA. Moreover, a WUE value of 3.0 kg ha^{-1} mm^{-1} was reported by Howell *et al.* (1998) for maize using its above-ground biomass and ET. Direct measurements of ET, maize dry matter and grain yields under field conditions and various irrigation treatments, have been the focus of numerous studies during the 1970's and the early 1980's. Maize yields are linearly related to the amount of ET, as can be noticed from linear relationships found between both maize dry matter and grain yield and ET (Tanner & Sinclair, 1983). Linear regressions performed on ET-yield data, resulted in R^2 values of 0.95 and 0.87 for maize dry matter yield and grain yield versus ET, respectively (Rhoads & Bennett, 1990). A linear relationship between grain yield and maize water use, with a R^2 value of 0.91, was reported over ET's ranging from 400 to nearly 1000 mm (Tanner & Sinclair, 1983).

2.10 Water availability and plant density relationship

Plants require water to sustain growth and development. From germination and emergence to the production of foliage, fruit or seed, large and varying quantities of water are moved through the plant to the atmosphere. Irrigation research and irrigation farm management require either the quantity of water in or its availability to plants, be measured. When water use is limiting, water use efficiency may drop below the maximum rate. Consequently crop yield is related functionally to crop water use, which in turn is dictated by the water supply. Due to increasing scarcity of water for irrigation the functional dependence of crop yields on water supply has become a major interest in the past (Hillel, 1987).

The number of plants required per unit area to achieve optimum yields will depend on the nature of the crop and on its environment. Maximum efficiency of growth factors is achieved only when the plant density exercises maximum pressure on all production factors (Donald, 1963). The relationship of seed production to plant density is different. As plant density increases, the yield of seed increases to a maximum, which remains constant within a certain range and then declines more or less steeply as plant density pressure increases still further even when water and nutrients are not limiting (Holliday, 1960). Plant density have to be adjusted to available soil water levels by adjusting inter-row or intra-row spacing or both to attain efficient water use.

2.11 Conclusion

The most important goal in any crop production system is to maximize productivity with the integration of crop management practices to alleviate production related constraints. Row spacing and plant density are important agronomic factors that affect growth, yield, yield components and water use of maize. Maize yield components decline with an increase in plant density over and above the threshold. Barrenness is associated with an increase in plant density beyond this threshold and may affect final grain yield. On the other hand, optimum plant density varies depending on environmental factors such as soil fertility, moisture supply and genotype. Therefore, adequate row spacing coupled with optimum plant density is important in order to maximize the potential yield of maize. This necessitates the need to determine the appropriate row spacing by plant density (in row spacing) combination to maximize yield and optimize water use for ultra-fast maize hybrids.

CHAPTER 3

MAIZE GROWTH RESPONSE TO ROW SPACING AND PLANT POPULATION DENSITY

3.1 Introduction

Maize growth is an essential process of life and propagation of the plant. Growth is a product of a combination of complex processes of differentiation during the crop life cycle and depends on the availability of assimilates hormones and environmental factors that lead to dry matter accumulation (Gardner *et al*., 1985). Maize growth is divided into three stages that is establishment, vegetative and reproductive. These phases are influenced by biotic and abiotic factors, like temperature, photoperiod, sowing date, row spacing and plant density. Row spacing is an important agronomic attribute since it is believed to have an effect on the growth of crop plants. Crop plants interfere with each other to a varying degree and compete for soil water, nutrients and solar radiation depending on the proximity of rows (Retta *et al.*, 1991). Row spacing has a special significance since it is ultimately related to root development, plant density and dry matter accumulation (Davi *et al*., 1995). Generally, the most appropriate row spacing enables the plants to make the best use of the resources at their disposal (Lawson & Topham, 1985; Obi, 1991; Mallik *et al*., 1993). Use of narrow rows hastens closure of the canopy and enhances canopy radiation interception, thereby increasing crop growth rates (Andrade *et al*., 2002). On the other hand, too wide rows may result in excessive vegetative weed growth due to reduced interplant competition for growth factors (Maqbool *et al*., 2006).

Plant density affects crop growth and yield of individual plants by influencing growth components such as leaf area, plant height, crop growth rate and photosynthetic activity. It also influences yield components such as number of ears, kernels per ear and kernel mass (Ahmad *et al.*, 1993; Sangoi *et al*., 2002). This necessitates genetic improvement of maize hybrids to be associated with an increase in the plant density at which, maximum grain yield can be attained. With increasing plant density, dry matter production in maize increases due to increased light interception and radiation use efficiency brought about by selection in plant structure (Gifford *et al*., 1984). According to Gallagher & Biscoe (1978), this increased dry matter accumulation was ultimately the result of the amount of radiation absorbed rather than the radiation use efficiency. Monteith, 1977 and Edwards, 1982 suggested that a physiological approach together with concepts of photoassimilate partitioning, can be used to predict and analyse crop yield.

Currently an arable land shortage with an increasing food demand necessitates the practice of double and multiple cropping systems to include extra fast maize hybrids due to their shorter growing period as compared to late maturing ones. In such conditions ultra-fast maize hybrids are preferable because of their smaller size, less number of leaves per plant, lower leaf area and fewer self-shading problems as well as a sufficient time gap for land preparation for the next crop. These hybrids require higher plant densities for maximum yield (Tollenaar, 1993). Optimum maize plant density is known to depending on the level of soil fertility, moisture status, cultivar grown and planting time (Sangoi, 2000). Generally, under irrigation, the practice in South Africa is to grow short season cultivars at plant densities of 80 000 to 90 000 plants ha^{-1} whereas medium to long season cultivars can be grown at plant densities of 45 000 to 65 000 plants ha^{-1} (Department of Agriculture, 2003). Hence, this study was initiated to evaluate the effect of row spacing and plant density on the growth and dry matter accumulation of an ultra-fast maize hybrid under irrigation.

3.2 Materials and methods

3.2.1 Experimental site

Two consecutive field trials, 2008/09 and 2009/10, were conducted at the Kenilworth Experimental Station (Latitude = 29^{o}02’00” S, Longitude = 26^{o}13’83” E, Altitude = 1372 meters above sea level) of the Department of Soil, Crop and Climate Sciences, University of the Free State (UFS), Bloemfontein. Agro-meteorological data obtained from records of the weather station at the experimental farm and the results are summarized in Table 3.1. At the experimental site the soil was classified as a deep sandy loam Bainsvlei Amalia and is regarded as suitable for irrigation (Soil Classification Working Group, 1991). Some physical and chemical properties, as well as particle distribution and bulk density of the soil are summarized in Table 3.2 and 3.3, respectively.

3.2.2 Field trial layout and treatments

Experimental treatments were allotted to the same plots for both seasons. The field trial was laid out in a completely randomized design. Treatments consisted of three row spacings (0.225, 0.45 and 0.90 m) and five plant densities (50 000, 75 000, 100 000, 125 000 and 150 000 plants ha^{-1}) and were combined in a complete factorial combination. Replications consisted of five single plants randomly selected in the plot to evaluate plant response tothe treatment combinations. The total land area used was 1296 m^{2} with each plot 5.4 m wide and 12 m long. The treatment combination with the theoretical and actual plant densities are summarized in Table 3.4. Spatial orientation of a single plant with respect to row width and plant density is shown in Figure 3.1.

Table 3.1 Agro-meteorological data for Kenilworth Experimental Station

Duration	Rainfall (mm)												
	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Total**
2003-2007	55.7	63.1	131.4	6.5	16.2	0.1	3.3	3.4	18	6.8	49.7	52.4	407
2008	63.2	56.7	45.3	38.9	37.4	23.6	6.9	4.4	6.9	4.4	2.4	11.1	301
2009	67.1	67.9	20.2	21.3	29.2	19.6	10.0	8.7	0.0	97.4	8.5	57.6	408
2010	133.3	34.9	32.0	30.1	39.2	7.6	0.0	0.0	0.1	27.9	52.9	55.3	413
2008-2010	87.9	53.2	32.5	30.1	35.3	16.9	5.6	4.4	2.3	43.2	21.3	41.3	374
	Temperature (^{o}C) from 2008-2010												**Mean**
Minimum	14.7	12.3	7.7	3.9	0.4	0.8	0.0	0.2	2.1	4.8	9.4	10.3	6
Maximum	34.6	34.6	34.6	31.3	29.6	23.0	20.6	20.1	28.8	31.3	32.3	33.5	30
Mean	24.7	23.5	21.2	17.6	14.9	11.9	10.3	10.2	15.4	18.0	20.9	21.9	18

Table 3.2 Some physical and chemical properties of the Bainsvlei Amalia topsoil

Physical properties			
Particle size distribution (%)			
Sand (0.02-2 mm)	83		
Silt (0.002-0.02 mm)	1		
Clay (< 0.002 mm)'	16		
Chemical properties			
	Cropping season		
	2008/2009	2009/2010	Norm (FSSA, 2007)
pH (KCl)	5.8	5.5	5.5-7.5
CEC ($cmol_C kg^{-1}$)	2.97	2.86	5.5-7.5
Nutrients (mg kg^{-1})			
P (Bray1)	25.9	29.1	21-27
K (NH_4OA_C)	150.4	155.3	80-160
Ca (NH_4OA_C)	310.0	306.0	300-2000
Mg (NH_4OA_C)	111.0	109.3	80-300
Na (NH_4OA_C)	28.2	8.9	≤ 15
Ca/Mg	1.71	1.71	1.5-4.5
(Ca + Mg)/K	6.40	6.11	10-20

Table 3.3 Summary of particle distribution and bulk density of the Bainsvlei Amalia soil (Chimungu, 2009)

Particles size (%)	**Horizons**					
	A	B1	B2	B3	B4	B5
Coarse sand (2-0.5 mm)	0.4	0.3	0.3	0.3	0.3	0.6
Medium sand (0.5-0.25 mm)	7.1	5.2	5.4	4.1	3.3	6.0
Fine sand (0.25-0.106 mm)	61.4	55.1	53.8	44.9	64.3	48.3
Very fine sand (0.106-0.53)	16.8	15.1	15.5	18.0	17.3	17.0
Silt	4.0	4.0	6.0	8.0	4.0	6.0
Clay	8.0	18.1	18.0	22.1	8.1	20.1
Bulk density (mg m^{-3})	1.66	1.68	1.66	1.67	1.68	1.67

Table 3.4 Summary of treatment combinations with theoretical and actual plant densities

Row spacing (m)	**Theoretical plant density (plants ha^{-1})**	**Actual plant density (plants ha^{-1})**	**Area per plant (m^2)**
0.225	50 000	49 382	0.204
	75 000	74 074	0.135
	100 000	101 010	0.099
	125 000	126 984	0.079
	150 000	148148	0.068
0.45	50 000	50 505	0.198
	75 000	74 074	0.135
	100 000	101 010	0.099
	125 000	123 457	0.081
	150 000	148 148	0.068
0.90	50 000	50 505	0.198
	75 000	74 074	0.135
	100 000	101 010	0.099
	125 000	123 456	0.081
	150 000	148 148	0.068

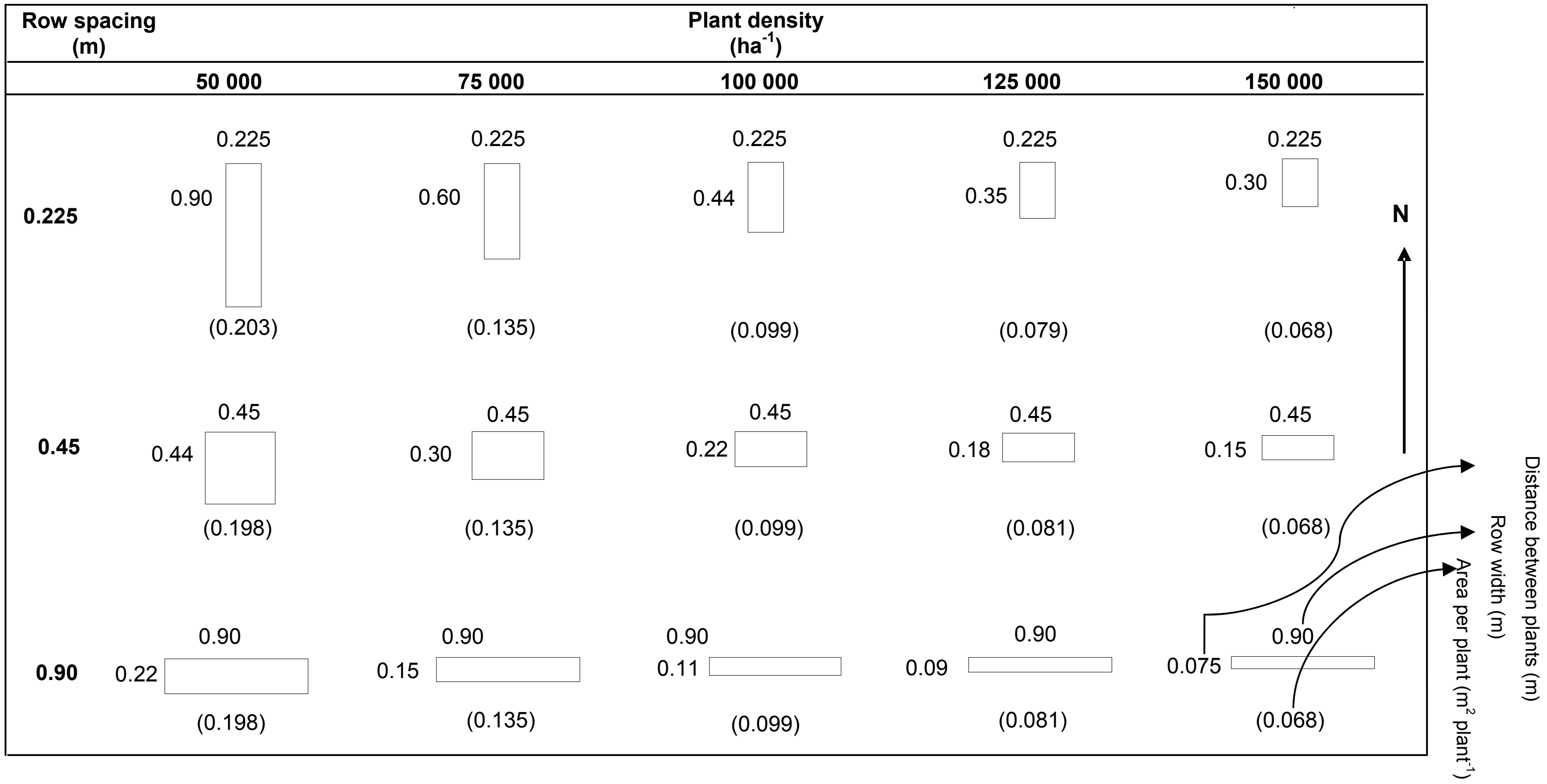

Figure 3.1 Summary of treatment combinations with dimensional representation of land area (m^2) occupied by a single plant at various row spacing and plant densities.

3.2.3 Agronomic practices

Before initiation of the trials representative soil samples were collected and analysed (Table 3.3). Fertilization was determined by the results of the soil analysis and a yield potential of 10 t ha^{-1}. The field was ploughed and a compound fertilizer (2:3:2(35)) was broadcasted at a rate of 450 kg ha^{-1} (45 kg ha^{-1} N, 67 kg ha^{-1} P and 45 kg ha^{-1} K) one day before planting. This was followed by a deep disk action disked and field span/tiller followed to level and firms the seed bed. In order to apply all the nitrogen 200 kg ha^{-1} urea (46% N) was top-dressed thirty days after planting with another top-dressing and the same amount of urea at fifty days after planting. The total amount of N applied per season was 229 kg ha^{-1}.

The selected cultivar for this trial was PAN 6236B. This cultivar is classified as an ultra-fast yellow maize hybrid. It is considered as an agronomic balanced hybrid performing excellently in the warmer irrigation areas of South Africa. The cultivar has a high yielding ability and very good yield stability. Furthermore, it is tolerant to corn blight and has a high resistance against stalk borer. Maize was planted on the 10th and 11th of December 2008 and 2009, respectively. Seeds were hand planted by placing two seeds per hill and rows were oriented in a north-south direction. After emergence seedlings were thinned to maintain the desired plant density per plot (Table 3.4).

The trial was irrigated with an one tower centre pivot irrigation system. All emitters were equipped with pressure regulators, which were checked before the onset of the experiment. The coefficient of uniformity was 90% and the application rate was measured as 12 mm day^{-1}, which is sufficient for the peak water use of maize for a target yield of 10 t ha^{-1} and 100 000 plants ha^{-1}. The crop was irrigated weekly and irrigation amounts were determined by measuring soil water with a neutron soil water meter. The difference between the predetermined refill point (PRP = 421 mm/1800 m) and the actual soil water content was taken as the irrigation amount to be applied for a particular week. The amount of 30 mm was subtracted when rainfall occurred immediately after irrigation to allow rain storage. The irrigated amounts and rainfall recorded are summarized in Table 3.5.

Weed control was carried out by hand or hand hoeing while insect damage was visually monitored during the crop growing season. Insignificant insect damage occurred and therefore no corrective measures were taken.

Table 3.5 Rainfall recoded and amount of water irrigated from planting to crop physiological maturity for two cropping seasons

2008/09			2009/10		
Date	**Irrigation (mm)**	**Rainfall (mm)**	**Date**	**Irrigation (mm)**	**Rainfall (mm)**
15/12/2008	-	15	10/12/2009	-	14
18/12/2008	19	-	11/12/2009	7	-
20/12/2008	-	9	14/12/2009	11	19
29/12/2008	26	10	17/12/2009	19	-
01/01/2009		11	21/12/2009	10	-
02/01/2009	-	5	24/12/2009	5	-
06/01/2009	17	2	31/12/2009	20	-
09/01/2009	-	1	02/01/2010	-	21
11/01/2009	-	20	07/01/2010	5	-
21/01/2009	-	18	10/01/2010		10
25/01/2009	23	2	14/01/2010	10	14
27/01/2009	-	7	19/01/2010		12
29/01/2009		28	22/01/2010		23
31/01/2009		-	23/01/2010		26
03/02/2009	20	-	26/01/2010		10
04/02/2009		-	31/01/2010		15
05/02/2009		-	03/02/2010		6
07/03/2009		-	08/02/2010		3
08/02/2009	-	3	10/02/2010	10	-
09/02/2009	-	3	11/02/2010		1
11/02/2009	18	3	14/02/2010		13
12/02/2009	-	9	15/02/2010		5
13/02/2009	-	4	16/02/2010		15
15/02/2009	-	20	24/02/2010		50
22/02/2009	25	8	25/02/2010		35
27/02/2009	-	10	28/02/2010		2
28/02/2009	-	2	03/03/2010		10
09/03/2009	-	9	07/03/2010		3
15/03/2009	-	10	11/03/201	19	-
24/03/2009	27	2	16/03/2010		4
04/04/2009	-	14	22/03/2010		30
08/04/2009	-	2	26/03/2010		42
Total	175	225	-	116	380

3.2.4 Plant growth measurements

The following indicators of plant growth were measured to describe growth per plant: leaf number, plant height, leaf area and dry matter. Five plants were randomly selected for the measurements. Observations started one week after emergence and continued on a weekly basis until termination of the growth indicators. Leaf number (fully unfolded with ligule visible), plant height (ground level to last fully unfolded leaf with last measurement made to the base of the tassel at silking) and leaf area were measured one week after emergence until flowering started 56 to 63 days after emergence (DAE). Leaf area (cm^2 $plant^{-1}$) was measured using a LI 3000 portable leaf area meter (Lambda Inst. Corp). Following the leaf area measurement, leaf samples together with stalks were oven dried at a temperature of 65^oC to a constant moisture content for dry matter determination. After drying, the total aboveground dry biomass was divided by the number of plants sampled and expressed in gram per plant. This measurement was also done on a weekly basis and continued until physiological maturity of the plants. According to Doorenbos and Kassam (1986) the growth stages for a medium growing season length maize genotype is 15-30 days for the initial phase, 45-75 days for the vegetative phase and 75-150 days for the reproductive phase, after planting. For ease of evaluating the effect of treatment factors on maize growth, our ultra-fast maize hybrid was grouped into growth phases *viz*., establishment phase (7-21 DAE), vegetative phase (28-49 DAE) and reproductive phase (56-105 DAE).

3.2.5 Calculation of growth rates

Leaf area index (LAI) was calculated as the ratio of total leaf area to ground area. Crop growth rate (CGR), is the dry matter accumulation rate per plant in unit time and was computed using Equation 2.1 in Chapter 2. Net assimilation rate (NAR) per plant, which is dry matter accumulation per unit of leaf area per unit time and was calculated using Equation 2.2 in Chapter 2.

3.2.6 Seed yield determination

Seed yield was determined by taking 10 randomly selected plants per treatment from central rows harvested. Seed yield was determined by calculating the seed mass per plant (g $plant^{-1}$). The seed mass of the sample plants were oven dried at a temperature of 65^oC for three days following a seed moisture content adjusted to 12.5%. Seed weight at the actual plant density (plants ha^{-1}) was used to calculate the seed mass per hectare (kg ha^{-1}).

The yield of the two seasons was combined after testing the homogeneity of variance and used for correlation analysis with growth parameters.

3.2.7 Statistical analysis

Data were subjected to analysis of variance using the general linear model SAS version 9.1 (SAS Inst., 2003). Data were combined over seasons after carrying out the homogeneity test of variances as suggested by Gomez & Gomez (1984). Treatment means were compared using the least significant difference (LSD) at a 5% level of significance.

3.3 Results and discussion

3.3.1 Summary of analysis of variance

A summary on the combined analysis of variance over seasons are presented in Table 3.6. These results showed that growth indicators: leaf number, plant height, leaf area and dry matter (DM) accumulation and growth rate indicators: LAI, CGR and NAR reacted differently to the main treatments *viz*. row spacing and plant density as well as their combined effect at different growth phases.

Analysis of variance revealed that leaf number was not significantly affected by either of the main effects or their interaction effect at any of the sampling dates. Since leaf count is a reliable indicator of maize development (Warrington & Kanemasu, 1983) this eliminated the fact the row spacing but more importantly plant density in this environment affected the development or rate of development of maize. However, in our case different combinations of row spacing and plant density did not significantly influence leaf count which suggests that leaf count is a genetic trait and less sensitive to spatial variation in this environment. Leaf number is, therefore omitted from further discussions. Plant height and leaf area showed significant differences as a result of the interaction effect of the main treatments from 35 DAE until the last day (65 DAE) of measurement. Dry matter accumulation was significantly affected by the row spacing and plant density interaction during the vegetative and early reproductive stage (42 - 77 DAE).

Crop growth rate indicators responded differently to the main treatments and treatment combinations. Leaf area index (LAI) and net assimilation rate (NAR) was only measured to flowering. The row spacing by plant density interaction significantly affected the LAI from 14 - 63 DAE. The NAR during the same period was significantly affected by the main treatments including plant density at 7 DAE. Crop growth rate (CGR) responded to plant density only for the period 14 – 105 DAE.

Table 3.6 Summary of analysis of variance indicating the effect of treatment factors on growth indicators and rates

Crop growth parameters	**Factors**	**Days after emergence**														
		7	14	21	28	35	42	49	56	63	70	77	84	91	98	105
Growth indicators																
Leaf number	RS	ns	ns	ns	ns	ns	ns	ns	ns	ns						
	PD	ns	ns	ns	ns	ns	ns	ns	ns	ns						
	RS x PD	ns	ns	ns	ns	ns	ns	ns	ns	ns						
Plant height	RS	ns	ns	ns	ns	*	*	*	*	*						
	PD	ns	ns	ns	ns	*	*	*	*	*						
	RS x PD	ns	ns	ns	ns	*	*	*	*	*						
Leaf area	RS	ns	ns	ns	*	*	*	*	*	*						
	PD	ns	ns	ns	*	*	*	*	*	*						
	RS x PD	ns	ns	ns	ns	*	*	*	*	*						
Dry matter accumulation	RS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	PD	ns	ns	ns	ns	ns	*	*	*	*	*	*	ns	ns	ns	ns
	RS x PD	ns	ns	ns	ns	ns	*	*	*	*	*	*	ns	ns	ns	ns
Growth rates																
Leaf area index	RS	ns	*	*	*	*	*	*	*	*						
	PD	ns	*	*	*	*	*	*	*	*						
	RS x PD	ns	*	*	*	*	*	*	*	*						
Crop growth rate	RS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	PD	ns	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	RS x PD	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Net assimilation rate	RS	ns	*	*	*	*	*	*	*	*						
	PD	*	*	*	*	*	*	*	*	*						
	RS x PD	ns	ns	ns	ns	ns	ns	ns	ns	ns						
Seed yield	RS															*
	PD															*
	RS x PD															*

*= significant at 5% probability level, ns=not significant, RS=row spacing, PD=plant density

Maize grain yield was measured at 105 DAE and significant differences were found as a result of the interaction effect of row spacing and plant density. From this summary and Table 3.6 it is clear that growth and growth rate indicators showed significant responses to either the main treatments or the interaction thereof. To simplify and clearly discuss the response of the selected parameters for the specified cultivar, the seasonal growth is divided into three growth stages. These stages will include the establishment (7-21 DAE), vegetative (28-49 DAE) and reproductive phase (56-105 DAE).

3.3.2 Establishment phase

3.3.2.1 Growth indicators

Data for growth indicators (leaf number, plant height, leaf area and DM) at establishment (7-21 DAE) are summarised in Table 3.7. Row spacing, plant density and their interaction did not result in significant differences of the selected growth indicators at establishment. Plants attained a mean leaf number of 4.4, plant height of 47.4 cm, leaf area 97.2 cm^2 and DM of 21.7 g per plant at 21 DAE. At the end of this growth phase plants reached 35.2% of the final leaf number, 24.1% of its plant height, 17.8% of its leaf area and 11.8% of the final DM accumulation. It is evident that although 35.2% of the leaf number was reached 3 weeks after emergence the plants only accumulated 11.8% of its final biomass. Plant density has been recognized as a major factor influencing the degree of competition between plants depending on the stages of growth with a profound impact on plant height, leaf area and DM (Hashemi *et al*., 2005). However, this competition varies depending on the proximity of plants to each other and the magnitude of the space available for individual plants. At an early growth phase plants are small with smaller leaves and root systems where a single plant owned sufficient feeding area with respect to its relative size. Thus, different combinations of row spacing and plant density at this stage could not exert a significant difference on crop growth indicators. This probably suggests that the establishment phase of crop growth is dependent on the type of crop, variety, seed quality, depth and method of planting, seedbed preparation, soil temperature, aeration and moisture. Therefore, at this phase interference and competition between plants were nearly minimal/negligible indicating that plant density comes to operation at latter stages of growth. Lauer & Rankin (2004) described the key factors influencing establishment of maize which include uniform seed depth, seed quality and optimum soil environment (soil temperature and water) for rapid germination and uniform emergence. The results of plant height concert with that of Mukhala (1998) who reported an average plant height of 50 cm at 25 DAE. The insignificant response of growth indicators to the treatments could be ascribed to the fact that plants were small and did therefore not exert a competitive effect on each other.

3.3.2.2 Growth rate indicators

Growth rate indicators: LAI, CGR and NAR as affected by row spacing and plant density during the establishment phase are presented in Table 3.8. A significant difference in LAI was detected due to the interaction effect of row spacing by plant density at 14 and 21 DAE. The greatest LAI (1.35) at 14 DAE was recorded at a row spacing of 0.45 m with a plant density of 150 000 plants ha^{-1}. Although this was the greatest LAI it did not differ significantly from the second (1.09) and third (1.03) greatest LAI recorded at 0.90 m by 150 000 plants ha^{-1} or 0.45 m by 125 000 plants ha^{-1}, respectively. With the exception of the second treatment combination a similar tendency was observed at 21 DAE. The smallest LAI was recorded for both measuring times at a row spacing of 0.45 m with a plant density of 50 000 plants ha^{-1}. A mean LAI of 1.24 was recorded at 21 DAE, which accounted for 27% of the final LAI at 63 DAE. Even at an early growth stage (14 DAE) row spacing and plant density significantly affected LAI indicating that LAI is directly correlated with the number of plants per unit area. Remison (1980) and Ottman & Welch (1989) also reported that plant density affected LAI because LAI is directed related to the number of plants per unit area.

Row spacing had a significant effect on NAR from 14 to 21 DAE. The highest NAR was obtained at a row spacing of 0.45 m followed by 0.90 m. Although the 0.45 m row spacing was responsible for the highest NAR it was not significantly higher than that of the 0.90 m row spacing at both 14 and 21 DAE. Plant density also resulted in significant differences in NAR from 7 to 21 DAE. The highest NAR was recorded at a plant density of 100 000 plants ha^{-1} followed by 75 000 and 50 000 plants ha^{-1} without a significant difference in the NAR of these plant densities at the respective sampling dates. The lowest NAR was obtained from the highest plant density (150 000 plants ha^{-1}). Row spacing above or below 0.45 m as well as plant density above or below 100 000 plants ha^{-1} exhibited a negative impact on the photosynthetic efficiency of leaves. Obviously leaves are the main organs of photosynthesis and their photosynthetic efficiency is affected by crop management practices such as planting pattern, row spacing and plant density. Combinations of variable row spacing and plant densities affected light distribution over the plot area and depended on the direction of skewness of space owned by individual plants (Figure 3.1). With a row spacing of 0.225 m for all plant density levels, the available space to a single plant skewed to north-south direction while for 0.90 m row spacing skewed to east-west. Crasta & Dixit

(1989) indicated that sowing maize in rows running in a north-south direction intercepted more solar radiation as compared to rows running in east-west direction. Akbar & Khan (2002) also reported that cultivating maize in a north-south direction gave the highest grain yield as compared to east-west row orientation and this might be attributed to better light interception in the former orientation. However, for efficient solar radiation interception a north-south row direction is necessary and this could be matched with a nearly square configuration. On the other hand, at a row spacing of 0.45 m for all plant density levels a relatively equidistance distribution of plants over the plot area was observed leading to better light interception that corresponded with increased photosynthetic efficiency of leaves. Similarly, crop growth rate compared to NAR showed the same tendency with regard to plant density only, at the respective sampling dates. Thus, the highest CGR was recorded at a plant density of 100 000 plants ha^{-1} followed by 75 000 plants ha^{-1}. The lowest CGR was calculated at the highest plant density.

In general, the establishment phase was characterized by a slow accumulation of growth indicators that relied mainly on seedbed preparation, depth of planting, soil moisture and temperature, germination capacity of seed and variety and not on the selected treatments or combinations thereof. Thus, during the establishment phase the accumulation of crop growth rate indicators were minimal. This suggests that during this phase and especially 14 DAE and earlier the seedlings differentiation and development with their smaller size experienced no/little interference and interaction between adjoining plants within its vicinity. It could also be ascribed to the fact that the seedlings were still utilising reserves of the seed planted. Therefore, the treatment factors did not have any significant effect on the growth indicators.

Table 3.7 Growth indicators as affected by row spacing and plant density during the establishment phase (7 – 21 DAE)

Treatments		**Indicators of growth**											
RS (m)	**PD (000 ha^{-1})**	**Leaf number**			**Plant height (cm)**			**Leaf area (cm^2)**			**Dry matter (g plant^{-1})**		
		Days after emergence(DAE)											
		7	14	21	7	14	21	7	14	21	7	14	21
0.225	50	3.3	3.6	4.5	18.3	24.3	51.0	15.1	45.9	129.0	1.6	9.8	26.6
	75	3.3	3.8	4.8	12.2	25.2	50.7	15.1	45.9	100.7	1.4	8.6	24.5
	100	3.0	3.6	4.1	18.7	23.3	40.0	14.5	45.2	98.3	1.0	7.8	23.2
	125	3.3	4.0	4.8	19.7	28.9	47.3	14.0	43.0	96.6	1.9	11.2	20.7
	150	3.6	3.8	4.8	20.7	27.3	52.7	13.2	42.7	76.2	1.4	7.9	17.4
0.45	50	3.2	3.6	4.1	15.7	23.3	44.0	15.2	47.6	115.0	1.1	8.4	24.6
	75	3.8	4.0	4.8	20.3	23.7	49.0	14.0	47.0	110.1	1.8	7.9	21.1
	100	3.8	4.0	4.5	15.4	26.3	44.7	13.3	46.4	107.7	1.6	6.7	18.9
	125	4.0	4.0	3.8	16.3	23.7	45.3	12.2	44.9	101.6	1.3	6.6	17.3
	150	3.1	3.8	4.1	17.3	23.8	49.3	11.2	44.0	83.9	1.5	6.1	16.9
0.90	50	3.3	3.3	4.5	18.3	27.0	47.0	13.8	49.9	99.6	1.2	8.6	25.8
	75	3.6	4.0	3.8	18.0	21.0	47.0	14.1	47.8	92.0	1.1	7.7	23.5
	100	4.0	4.0	4.1	15.2	24.0	51.7	13.0	47.8	86.1	1.1	6.9	20.4
	125	3.3	4.1	4.1	16.4	24.3	43.4	12.5	46.9	82.4	1.2	7.3	19.5
	150	3.4	3.8	4.5	17.0	25.4	47.3	12.5	45.4	78.8	1.5	7.1	17.1
	LSD$_{(T\leq0.05)}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	Mean	3.5	3.8	4.4	17.3	24.8	47.4	13.6	40.0	97.2	1.4	7.91	21.7
RS mean	0.225	3.3	3.8	4.6	17.9	25.8	48.3	14.4	44.5	100.0	1.5	9.1	22.5
	0.45	3.6	3.9	4.3	17.0	24.2	46.5	13.2	46.0	103.7	1.5	7.2	19.8
	0.90	3.5	3.8	4.2	16.9	24.3	47.3	13.0	47.6	87.8	1.2	7.5	21.3
	LSD$_{(T\leq0.05)}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
PD mean	50	3.2	3.6	4.4	17.3	24.4	45.6	14.7	47.8	114.5	1.3	9.0	25.7
	75	3.5	3.9	4.3	15.5	23.3	47.0	14.4	46.9	101.0	1.4	8.1	23.0
	100	3.6	4.1	4.4	16.5	25.1	46.7	13.6	46.4	97.4	1.3	7.1	20.8
	125	3.6	4.0	4.2	16.5	24.6	45.0	12.9	44.9	93.5	1.3	8.4	19.2
	150	3.3	3.8	4.5	18.4	25.3	49.9	12.0	44.0	79.6	1.5	7.0	17.2
	LSD$_{(T\leq0.05)}$	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	CV (%)	4.1	2.9	2.3	2.1	2.4	2.1	4.3	1.5	12.3	12.7	20.5	17.3

RS=row spacing, PD=plant density, ns= not significant

Table 3.8 Growth rate indicators as affected by row spacing and plant density during the establishment phase (7 – 21 DAE)

Treatments		**Growth rates**								
RS (m)	**PD (000 ha^{-1})**	**LAI**			**NAR (g m^{-2} d^{-1})**			**CGR (g m^{-2} d^{-1})**		
		Days after emergence (DAE)								
		7	14	21	7	14	21	7	14	21
0.225	50	0.07	0.35^{c}	0.77^{d}	12.3	20.1	29.8	1.2	15.2	24.3
	75	0.04	0.39^{c}	0.84^{d}	8.6	19.4	31.7	1.3	11.8	23.4
	100	0.03	0.40^{c}	0.86^{d}	7.1	18.4	39.7	1.5	9.7	19.4
	125	0.05	0.43^{c}	1.04^{cd}	5.3	15.9	35.1	2.2	8.1	17.7
	150	0.04	0.75^{bc}	1.22^{cd}	2.9	13.0	30.2	2.0	5.8	13.9
0.45	50	0.02	0.23^{c}	0.40^{d}	12.7	27.5	36.5	2.5	10.7	23.2
	75	0.03	0.39^{c}	0.83^{cd}	9.2	26.2	40.7	1.8	9.8	19.1
	100	0.05	0.58^{bc}	1.18^{cd}	7.9	25.5	40.2	1.8	7.8	17.3
	125	0.07	1.03^{ab}	2.42^{ab}	7.5	16.4	37.5	1.6	7.0	14.1
	150	0.07	1.35^{a}	2.97^{a}	6.8	11.9	31.5	0.8	5.2	11.6
0.90	50	0.05	0.27^{c}	0.55^{d}	12.4	31.8	36.0	2.4	14.0	24.4
	75	0.04	0.38^{c}	0.86^{d}	8.6	28.6	32.0	1.7	11.6	21.5
	100	0.07	0.63^{bc}	1.09^{cd}	8.1	26.3	27.5	1.2	8.5	20.4
	125	0.06	0.70^{bc}	1.77^{bc}	8.0	22.9	36.4	0.9	6.9	18.9
	150	0.08	1.09^{ab}	1.91^{bc}	7.6	17.2	32.4	0.8	5.4	12.3
	LSD$_{(T\leq0.05)}$	ns	0.55	0.90	ns	ns	ns	ns	ns	ns
	Mean	0.05	0.59	1.24	8.3	21.4	34.5	1.6	9.2	18.7
RS mean	0.225	0.05	0.46^{b}	0.94^{b}	7.1	17.2^{b}	36.4^{b}	1.6	8.1	19.5
	0.45	0.05	0.71^{a}	1.56^{a}	8.8	25.2^{a}	55.7^{a}	1.7	10.1	21.1
	0.90	0.06	0.61^{ab}	1.23^{ab}	8.8	21.4^{ab}	54.8^{a}	1.4	9.3	21.1
	LSD$_{(T\leq0.05)}$	ns	0.24	0.40	ns	5.3	11.5	ns	ns	ns
PD mean	50	0.05	0.28^{c}	0.57^{b}	8.0^{bc}	22.8^{ab}	49.8^{abc}	1.6	8.4^{bc}	18.9^{c}
	75	0.04	0.38^{bc}	0.84^{b}	9.0^{b}	24.5^{a}	54.5^{ab}	1.7	10.8^{ab}	22.3^{b}
	100	0.05	0.54^{b}	1.04^{b}	12.5^{a}	26.4^{a}	60.5^{a}	1.7	12.7^{a}	26.9^{a}
	125	0.06	0.72^{ab}	1.74^{a}	7.2^{bc}	17.8^{bc}	45.2^{bc}	1.6	7.3^{c}	16.1^{c}
	150	0.06	1.06^{a}	2.03^{a}	6.0^{c}	14.2^{c}	41.4^{c}	1.5	5.9^{c}	12.6^{d}
	LSD$_{(T\leq0.05)}$	ns	0.32	0.52	2.6	6.0	12.9	ns	3.2	3.2
	CV (%)	24.5	43.4	33.7	29.4	26.9	24.5	36.3	34.1	15.9

RS=row spacing, PD=plant density, ns= not significant

3.3.3 Vegetative phase

3.3.3.1 Growth indicators

Analysis of variance indicated that the interaction of row spacing by plant density resulted in significant differences in plant height and leaf area from 35 to 49 DAE. Dry matter response to the treatment combinations was only significant from 42 to 49 DAE. At 28 DAE both plant height and DM showed no response to either of the main treatments or the interaction thereof.

Vegetative growth was characterized by a rapid increase in plant height, leaf area and DM. This rapid increase of growth indicators can be contributed to an exponential increase in leaf area resulting in increased light interception and thus a high photosynthetic activity. The tallest plants were recorded at a row spacing of 0.225 m with a plant density of 125 000 plants ha^{-1} followed by the same row spacing at an increased plant density of 150 000 plants ha^{-1}. The shortest plants were measured at a row spacing of 0.90 m with a plant density of 50 000 plants ha^{-1}. Mean plant height at the end of this growth phase was 176.3 cm and accounted to 89.5% of the total plant height. Narrow row spacing coupled with higher plant densities resulted in taller plant heights whereas wider row spacing combined with lower plant density resulted in shorter plants. The tallest plant height at a high plant density coupled with narrow row spacing was likely due to the elongation of internodes ('etiolation' – as a result of insufficient radiation penetration, over shading and self-shading). When plants are placed in close proximity of each other as a result of increased plant density, the internodes lengthen and stems become elongated due to a phototropism reaction of plants in response to light stimulus (Mason *et al.,* 1974; Leopold & Kreidemann, 1975; Park *et al*., 1989; Azam *et al*., 2007). This was also confirmed by Ogunlella *et al.* (2005) and Amanullah *et al*. (2010) who indicated that plants were taller with increased plant density in reaction to an enhanced competition among plants for light.

Generally, leaf area per plant was reduced with increasing plant density within all row spacing variants. At 28 DAE the data revealed that plant density had a far greater effect on leaf area than row spacing. This is clearly evident when only main effects were inspected. The variation in leaf area was smaller between varying row widths (12 - 15%) compared to the 34% decrease in leaf area per plant from 50 000 to 150 000 plants ha^{-1}. With regard to the interaction effects the greatest leaf area per plant was recorded at a row spacing of 0.90 m with a plant density of 50 000 plants ha^{-1} followed by a plant density of 75 000 plants ha^{-1} at the same row spacing (35, 42 and 49 DAE). The smallest leaf area was throughout observed at a row spacing of 0.225 m by plant density of 150 000 plants ha^{-1}. In line with this, the greatest DM per plant was recorded at a row spacing of 0.90 m with a plant density of 50 000 plants^{-1}. The second greatest DM measurement was recorded again with a plant density of 50 000 plants ha^{-1} but with a row spacing of 0.225 m at both 42 and 49 DAE. Conversely the lowest DM per plant was recorded at the same row spacing but with a plant density of 150 000 plants ha^{-1}. At this growth phase plants reached a mean leaf area and DM per plant of 529.1 cm^2 and 149.5 g at 49 DAE, respectively. Thus, plants attained 97.1 and 81.6% of the total leaf area and DM at 49 DAE, respectively. These high values are justifiable, especially for leaf area, since this was approximately one week before flowering. Increased row widths associated with lower plant density had less density stress with respect to the demand of growth resources. On the other hand, narrow rows combined with high plant densities reduced leaf area and DM accumulation per plant by exerting a limitation on resource availability per plant.

Density stress in higher plant stands resulted in the obvious production of smaller leaves with a smaller leaf area which may attributes to the low red (R): far-red (FR) solar radiation ratios (Kasperbaur & Karlen, 1994). Thus, a low R/FR ratio during light periods reduces leaf size by inhibiting leaf growth at high plant densities. Maddonni *et al.* (2001) used two maize hybrids at three plant densities (30 000, 90 000 and 120 000 plants ha^{-1}) and reported that the hybrids smallest leaf area per plant was measured at the highest plant density and concert with the findings of Hay & Walker (1989), Bos *et al*. (2000) and Subedi *et al.* (2005). Therefore, at higher plant densities the expansion of leaf width and leaf length likely limited to a low assimilate availability for leaf growth and development. Moreover, at a high density a plant morphologically mimics itself according to the magnitude of space available. On the other hand, the highest DM accumulation at wider rows combined with low plant densities might be ascribed to reduced plant to plant competition for available water, nutrients and sunlight and the increased radiation interception in the absence mutual shading or reduced shading (Lee, 2006). In addition, at low plant densities all leaves are exposed to more efficient interception of solar radiation with no/little mutual shading. Conversely, a reduction in DM accumulation per plant with increasing plant densities is the result of intra and interplant competition for light, water, nutrition, and other potentially growth limiting environmental factors (Duncan, 2002). Similar results were reported by Sterner (1984), Shuting *et al.* (1993), Sangoi & Salvador (1996), Makinde & Alabi (2004) and Ibeawuchi *et al*. (2008) where DM per plant decreased with increased plant densities for maize plants. Conversely, the row spacing by plant density interaction did not cause significant differences in leaf number during the vegetative growth phase and once more it could be deduced that plant development was not impaired by the interaction treatments.

3.3.3.2 Growth rate indicators

Growth rate indicator responses to row spacing, plant density and the combination thereof during the vegetative phase, is presented in Table 3.10. Row spacing by plant density interaction significantly affected LAI. Van Averbeke (1991) indicated that LAI increased slowly during the establishment growth phase followed by an exponential growth rate at vegetative phase before the onset of flowering. This rapid increase of LAI as the growth period elapsed was due to an increased photosynthetic activity of leaves as a result of more interception of photosynthetically active radiation that contributed to the growth and development of leaves. It was observed that the greatest LAI was calculated at a row spacing of 0.45 m with a plant density of 150 000 plants ha^{-1} followed by a row spacing of 0.90 and 0.225 m with a plant density of 150 000 plants ha^{-1}. The smallest LAI was recorded at row spacing of 0.225 m with plant density of 50 000 plants ha^{-1}. At the end of this growth phase, 49 DAE, plants reached a mean LAI of 4.47 which accounted for 98.5% of the total LAI recorded.

Differences in LAI values were observed for all rows at various plant density levels. This distinct difference of LAI was proportional to plant density which illustrated that LAI values were proportionally increased with increasing plant density levels indicating that maize cultivated at higher plant densities had a greater LAI and vice versa. For all row spacings at plant density levels of 50 000 and 75 000 plants ha^{-1}, the LAI values were below 4 whereas at higher plant density levels (PD ≥ 125 000 plants ha^{-1}) plants attained LAI values above 5 at 49 DAE (near anthesis). Shuting *et al.* (1993) used four maize hybrids at plant densities of 45 000 and 75 000 plants ha^{-1} and obtained the highest LAI values at the highest plant density for the hybrids. Amanullah *et al.* (2008) also reported that an increase in plant density was accompanied with an increase in LAI of the maize plant. Bavec & Bavec (2002) pointed out that the LAI was influenced by a number of factors such as genotype, plant density, climate and soil fertility where plant density remained the most important factor with a profound effect on LAI. Thus, a greater LAI at high plant densities illustrates that more plants per unit area results in more soil surface coverage and better light interception within certain optimum limits of plant density. This result is also in agreement with findings of numerous investigators who reported a relationship between LAI and plant density indicating that the LAI increased as plant density increased (Begna, 1996; Mukhala, 1998; Stewart & Dwyer, 1999). This investigation clearly revealed that the combination of a 0.45 m row spacing with a plant density of 100 000 plants ha^{-1} presumably looks ideal when compared to other combinations because a reduction in row spacing to 0.225 m and an increasing plant density above 100 000 plants ha^{-1} resulted in mutual shading of leaves

Table 3.9 Growth indicators as affected by row spacing and plant density during the vegetative phase (28 – 49 DAE)

Treatments		**Indicators of growth**															
RS (m)	**PD (000 ha^{-1})**	**Leaf number**				**Plant height (cm)**				**Leaf area (cm^2)**				**Dry matter (g plant^{-1})**			
		Days after emergence (DAE)															
		28	35	42	49	28	35	42	49	28	35	42	49	28	35	42	49
0.225	50	6.1	7.8	12.1	12.1	77.0	108.3^{f}	156.3^{hij}	163.7^{hi}	231.2	360.6^{cd}	481.3^{d}	529.7^{ef}	78.6	115.3	151.6^{ab}	180.1^{ab}
	75	5.5	7.5	11.8	12.1	73.2	112.3^{ef}	166.7^{ef}	160.7^{ij}	214.8	322.4^{de}	427.8^{g}	514.3^{g}	67.9	99.3	146.2^{a-b}	161.8^{bc}
	100	5.3	7.1	10.1	12.8	63.3	130.3^{ab}	176.3^{cd}	175.3^{e}	193.6	299.1^{ef}	408.3^{ij}	503.2^{h}	65.0	97.4	131.7^{b-e}	141.2^{c-e}
	125	6.0	8.5	12.0	12.5	79.0	135.7^{a}	185.3^{a}	203.3^{a}	187.8	289.8^{e-g}	405.7^{j}	494.7^{i}	49.1	69.9	105.2^{fg}	129.5^{e}
	150	5.5	8.5	10.5	12.1	77.7	132.0^{ab}	183.7^{ab}	185.0^{cd}	167.3	229.6^{h}	373.7^{l}	430.0^{l}	46.1	68.0	98.8^{g}	122.6^{e}
0.45	50	5.3	7.1	10.1	12.1	63.0	108.3^{f}	153.7^{ij}	164.0^{hi}	215.5	372.3^{bc}	531.0^{b}	604.4^{c}	70.9	98.3	135.1^{b-d}	153.4^{cd}
	75	5.1	8.5	12.1	12.8	78.0	109.3^{ef}	155.7^{hij}	173.7^{ef}	207.2	352.3^{cd}	482.9^{d}	589.2^{d}	54.5	91.3	123.7^{c-g}	152.3^{cd}
	100	5.8	7.8	11.1	12.5	75.5	110.7^{ef}	158.5^{ghij}	187.7^{c}	194.8	325.8^{c-e}	459.2^{e}	534.3^{f}	52.4	85.6	120.6^{c-g}	144.4^{c-e}
	125	5.3	7.8	11.1	12.8	69.2	130.0^{b}	183.0^{ab}	195.0^{b}	184.8	277.5^{e-h}	441.7^{f}	511.5^{g}	49.7	83.0	110.5^{d-g}	142.7^{c-e}
	150	5.3	7.5	10.8	12.8	69.3	114.0^{de}	163.3^{fg}	188.3^{bc}	160.8	272.4^{f-g}	411.79^{i}	467.8^{j}	44.4	79.0	107.0^{e-g}	133.8^{de}
0.90	50	5.0	7.1	11.1	12.1	65.7	107.3^{f}	152.3^{k}	155.0^{j}	228.0	430.9^{a}	564.3^{a}	645.1^{a}	82.9	112.4	165.1^{a}	194.9^{a}
	75	5.1	7.1	10.1	12.5	64.3	109.7^{ef}	155.3^{hij}	165.3^{ghi}	192.4	417.0^{ab}	532.0^{b}	619.3^{b}	68.0	95.5	129.4^{b-f}	163.2^{bc}
	100	5.6	9.0	12.5	12.8	75.8	110.7^{ef}	158.7^{ghi}	172.0^{fgh}	156.7	300.8^{ef}	504.8^{c}	545.7^{e}	52.5	85.7	126.7^{b-f}	152.7^{cd}
	125	5.3	7.1	9.8	12.1	66.3	122.0^{c}	171.7^{de}	178.0^{de}	145.8	248.5^{gh}	417.7^{h}	512.8^{g}	49.9	79.1	118.4^{d-g}	145.1^{c-e}
	150	5.5	7.0	9.5	12.5	71.0	119.3^{cd}	158.7^{ghi}	177.0^{e}	117.9	247.8^{gh}	393.2^{k}	434.1^{k}	46.9	75.1	99.5^{g}	125.1^{e}
	LSD$_{(T\leq0.05)}$	Ns	ns	ns	ns	ns	5.4	6.2	7.1	ns	48.3	23.9	13.6	ns	ns	25.8	22.5
	Mean	5.4	7.7	10.9	12.4	71.2	117.3	165.2	176.3	186.6	316.5	455.5	529.1	58.6	88.9	124.6	149.5
RS mean	0.225	5.7	7.9	11.3	12.3	74.0	123.1^{a}	173.5^{a}	182.4^{a}	168.2^{b}	286.6^{b}	448.5^{c}	528.4^{b}	61.4	87.4	119.4	145.3
	0.45	5.3	7.7	11.1	12.6	71.0	114.5^{b}	162.8^{b}	175.2^{b}	198.9^{a}	337.2^{a}	465.3^{a}	541.5^{a}	54.4	90.0	129.5	147.6
	0.90	5.3	7.7	10.6	12.4	68.6	114.0^{b}	159.3^{c}	171.2^{c}	192.6^{a}	325.7^{a}	453.2^{bc}	528.2^{b}	60.0	89.6	125.0	155.7
	LSD$_{(T\leq0.05)}$	Ns	ns	ns	ns	ns	2.4	2.8	3.2	12.4	21.6	11.8	5.8	ns	ns	ns	ns
PD mean	50	5.5	7.4	11.1	12.3	68.8	117.3^{b}	159.3^{e}	171.5^{bc}	222.1^{a}	387.9^{a}	509.5^{a}	611.1^{a}	77.5	108.7	150.6^{a}	176.1^{a}
	75	5.2	7.5	11.0	12.4	71.3	116.2^{b}	163.8^{d}	173.8^{bc}	207.6^{a}	364.1^{a}	489.6^{b}	584.8^{b}	63.5	95.4	133.1^{b}	159.1^{b}
	100	5.6	7.9	11.4	12.7	72.8	116.3^{b}	166.3^{c}	176.9^{ab}	181.7^{b}	299.1^{b}	446.6^{c}	495.1^{c}	56.6	89.6	126.3^{b}	146.1^{c}
	125	5.5	7.7	11.0	12.5	72.8	118.0^{b}	166.8^{b}	176.5^{ab}	172.8^{b}	279.4^{bc}	434.9^{d}	492.4^{c}	49.6	77.3	111.4^{c}	139.1^{cd}
	150	5.6	7.7	10.7	12.5	74.7	124.0^{a}	168.9^{a}	177.9^{a}	148.7^{c}	251.9^{c}	397.9^{e}	480.1^{d}	45.8	74.0	101.8^{c}	1277.2^{d}
	LSD$_{(T\leq0.05)}$	Ns	ns	ns	ns	ns	2.7	3.2	3.5	22.2	27.9	12.3	6.6	ns	ns	14.9	13.0
	CV (%)	8.6	2.1	1.4	2.5	2.2	2.2	2.1	1.9	5.9	7.1	2.5	4.3	23.8	16.4	9.7	7.0

RS=row spacing, PD=Plant density, ns= not significant

due to a higher LAI where photosynthetic efficiency of leaves was reduced. These results were also supported and correlated with the yield response in section 3.3.4.2. Increasing row spacing from 0.45 m to 0.90 m and decreasing plant density below 100 000 plants ha^{-1} appeared to cause underutilization of resources.

Significant differences in NAR were detected due to the main effect of row spacing and plant density (Table 3.10). The highest NAR was observed at a row spacing of 0.45 m but it did not differ significantly from that of 0.90 m, with the exception of sampling at 49 DAE. The effect of row spacing became more prominent as growth progressed and reached a maximum at the end of the vegetative growth phase (49 DAE) when the lowest NAR occurred at a row spacing of 0.225 m. Reduction in the row spacing from 0.45 to 0.225 m lowered photosynthetic efficiency of plants due to increased LAI which resulted in mutual shading of leaves. On the other hand, widening of row spacing from 0.45 to 0.90 m likely resulted in an underutilization of resources such as water, sunlight and nutrients effect as a result of the wider rows. Similarly, plant density impacted significantly on NAR. The highest NAR was observed at a plant density of 100 000 plants ha^{-1} followed by 75 000 plants ha^{-1}. The lowest NAR was recorded at a plant density of 150 000 plants ha^{-1}. Increasing plant density above a certain threshold negatively impacted on NAR due to the mutual shading of leaves as result of increased LAI as well as interplant competition. Amanullah *et al.* (2008) indicated that the NAR declined with increasing plant density due to less light interception in dense stands resulting from increased LAI. Ahmad *et al*. (2010) in the study of agro-physiological traits of three maize hybrids at three plant densities (40 816, 57 142 and 95 238 plants ha^{-1}) recorded the lowest NAR at the highest plant density for all hybrids and concluded that the lowest NAR at the highest plant density was ascribed to proportionally less DM accumulation on an individual plant basis. Mohsan (1999), Ma *et al*. (2007) and Ullah *et al.* (2010) also confirmed that increasing plant density above a certain threshold (varies between different environments) negatively impacted on NAR of maize. In contrast, plant density below a certain optimum lowered the photosynthetic efficiency of plants which might probably be attributed to limitation of resources (nutrients and water) as a result of weed competition in lower plant stands.

Crop growth rate (CGR) response was only affected significantly by plant density (Table 3.10). Crop growth rate (CGR) is the DM accumulation per unit of land area per unit of time (Wilson, 1981). The highest CGR was recorded at a plant density of 100 000 plants ha^{-1} followed by 75 000 plants ha^{-1}. The lowest CGR was observed at plant density of 150 000 plants ha^{-1} which could be attributed to water stress because the irrigation scheduling was calculated for 100 000 plants ha^{-1} (Van Averbeke, 1991). It was obvious that the use of plant densities above 100 000 plants ha^{-1}, which seem to be the optimum plant density of this trial, impacted more negatively on CGR than plant densities at less than the optimum. This observed CGR reduction with increasing plant density might be attributed to a lower DM production on a per plant basis. Amanullah *et al. (*2009) reported that plant density above a certain optimum/peak aggravated intra and interplant competition and reduced leaf area resulting in less interception of solar radiation with a corresponding decline in CGR. On the other hand, a decline in CGR with lower plant densities was likely associated with fewer plants per unit area to provide complete soil coverage to decrease/minimize evaporation from the soil surface. Valadabadi & Farahani (2009) reported that a reduction of the maize CGR at a low plant density was due to little plasticity in leaf area per plant. They also added that maize plants have a small capacity to develop new reproductive structures such as tillers in response to available resources per plant. This result is in line with findings of Amanullah *et al.* (2010) who reported that the CGR declined through an increase or decrease in plant density from a specific optimum plant density due to inter and intra plant competition for water, nutrients and solar radiation. The data therefore clearly indicated that the optimum plant density for an optimum LAI in the event of improved light capturing and efficient utilization of soil water and nutrients is likely at a plant density of a 100 000 plants ha^{-1}.

Table 3.10 Growth rate indicators as affected by row spacing and plant density during the vegetative phase (28 – 49 DAE)

Treatments		**Growth rate indicators**											
RS (m)	**PD (000 ha^{-1})**	**LAI**				**NAR (g m^{-2} d^{-1})**				**CGR (g m^{-2} d^{-1})**			
		Days after emergence (DAE)											
		28	35	42	49	28	35	42	49	28	35	42	49
0.225	50	0.92^{e}	1.28^{e}	2.01^{f}	2.45^{h}	40.8	34.5	36.7	7.8	69.2	86.7	145.1	77.9
	75	1.27^{de}	2.06^{c-e}	2.76^{ef}	3.65^{ef}	28.8	35.2	28.5	7.5	64.0	76.9	117.1	66.2
	100	1.35^{de}	2.09^{c-e}	3.15^{d-f}	4.16^{de}	22.4	31.1	26.8	6.0	53.1	64.3	108.5	60.7
	125	2.09^{b-e}	3.50^{a-c}	4.76^{a-c}	5.41^{a-c}	21.2	25.7	18.5	5.2	50.1	54.0	91.1	55.9
	150	2.54^{a-d}	3.47^{a-c}	4.31^{b-d}	5.69^{ab}	17.7	23.1	17.2	4.5	45.0	43.7	66.6	53.8
0.45	50	1.52^{de}	1.96^{de}	2.13^{f}	2.57^{h}	38.4	31.4	26.0	9.5	67.4	92.8	157.3	107.3
	75	1.22^{de}	2.06^{c-e}	2.89^{ef}	3.59^{e-g}	33.1	27.7	17.7	8.7	56.5	74.3	133.1	86.8
	100	1.75^{c-e}	2.80^{b-e}	3.88^{c-e}	4.69^{cd}	29.5	23.4	14.2	7.5	48.7	53.6	124.6	71.5
	125	3.11^{a-c}	4.41^{ab}	5.21^{ab}	5.83^{ab}	29.0	20.8	12.8	7.0	46.1	42.7	71.2	66.4
	150	3.95^{a}	4.68^{a}	5.68^{a}	6.31^{a}	27.8	20.5	11.1	5.8	42.9	34.7	63.2	63.9
0.90	50	1.21^{de}	1.84^{de}	2.44^{f}	2.65^{gh}	40.4	39.5	22.1	12.2	69.2	97.9	109.5	69.6
	75	1.59^{de}	2.07^{c-e}	2.51^{f}	2.76^{f-h}	36.8	36.8	21.5	9.1	60.1	72.4	91.5	57.9
	100	1.79^{c-e}	3.12^{a-d}	4.81^{a-c}	5.17^{bc}	35.8	31.5	20.1	9.0	53.1	58.2	88.8	49.1
	125	2.38^{b-e}	3.92^{ab}	5.39^{ab}	5.77^{ab}	35.2	29.2	18.4	7.7	48.1	41.1	74.7	42.7
	150	3.51^{ab}	4.43^{a}	5.65^{a}	6.28^{a}	31.7	24.2	17.2	6.1	42.2	31.0	65.5	40.7
	LSD$_{(T\leq0.05)}$	1.52	1.61	1.28	0.99	ns	ns	ns	ns	ns	ns	ns	ns
	Mean	2.01	2.91	3.84	4.47	31.2	28.9	20.6	7.6	54.4	61.6	100.5	64.7
RS mean	0.225	1.75^{b}	2.62^{b}	3.42^{b}	4.92^{b}	26.2^{b}	24.8^{b}	13.0^{b}	6.2^{c}	54.6	59.6	81.3	51.9
	045	2.19^{a}	3.05^{a}	4.16^{a}	4.57^{a}	36.0^{a}	32.2^{a}	25.5^{a}	13.0^{a}	55.8	65.1	109.9	79.2
	0.90	2.09^{ab}	3.07^{a}	3.93^{ab}	4.52^{ab}	31.5^{ab}	30.0^{ab}	19.8^{ab}	7.7^{b}	56.3	60.1	105.7	69.0
	LSD$_{(T\leq0.05)}$	0.57	0.40	0.57	0.22	7.1	4.5	7.7	1.2	ns	ns	ns	ns
PD mean	50	1.21^{b}	1.69^{c}	2.19^{c}	2.55^{d}	29.1^{bc}	28.0^{bc}	18.5^{ab}	7.2^{bc}	48.2^{cd}	57.0^{c}	99.2^{ab}	62.5^{bc}
	75	1.36^{b}	2.06^{bc}	2.72^{c}	3.33^{c}	32.4^{ab}	31.8^{ab}	20.7^{ab}	8.1^{b}	60.4^{b}	71.7^{b}	108.9^{a}	73.5^{b}
	100	1.63^{b}	2.67^{b}	3.95^{b}	4.67^{b}	39.8^{a}	35.5^{a}	25.2^{a}	9.8^{a}	69.2^{a}	87.3^{a}	128.4^{a}	86.9^{a}
	125	2.53^{a}	3.94^{a}	5.22^{a}	5.76^{a}	28.4^{bc}	24.8^{cd}	15.4^{b}	6.4^{cd}	51.6^{c}	66.7^{cd}	77.0^{bc}	54.7^{c}
	150	3.33^{a}	4.19^{a}	5.11^{a}	6.00^{a}	24.0^{c}	22.7^{d}	13.7^{b}	5.4^{d}	44.3^{d}	48.9^{d}	65.1^{d}	51.3^{c}
	LSD$_{(T\leq0.05)}$	0.87	0.93	0.74	0.52	7.9	5.1	8.6	1.5	5.1	12.9	30.2	13.2
	CV (%)	35.2	25.9	15.6	10.4	24.5	16.9	43.7	19.1	8.9	20.5	30.1	19.2

RS=row spacing, PD=Plant density, ns= not significant

3.3.3.3 Correlation between growth indicators and dry matter production

The relationship between growth indicators (plant height, leaf area and DM per plant) on a per plant basis and DM (g m^{-2}) for the vegetative phase is presented in Figure 3.2. Comparison of growth indicators and DM were made on a relative basis. Plant height and leaf area were positively correlated with DM production. The positive correlation of leaf area with DM accumulation suggests that the photosynthetic capacity of the plants depend on the amount of solar radiation intercepted. Waldren (1983) indicated that the DM accumulation in maize is a function of leaf area because the production is directly related with the amount of solar radiation intercepted by the leaf surface. Sadek *et al*. (2006) in their correlation analysis for five inbred lines of white maize and Carpici & Celik's (2010) correlations of yield and yield components for forage maize reported that plant height and leaf area were positively correlated with DM accumulation. Conversely, DM production per unit area was negatively correlated with DM accumulation per plant. Thus, DM accumulation per plant corresponded with a subsequent reduction in DM production per unit area presumably due to an increased land area occupied by a single plant. The estimated multiple linear regression equation $Y= -0.63x_1$ (PH)$+0.44x_2$ (LA) - $0.07x_3$ (DM) + 0.83 with a coefficient of determination ($R^2=0.77$) was significant ($P \leq 0.05$) indicating that the combined effect of plant height, leaf area and DM per plant contributed significantly to DM production per unit area.

The relationship between growth rate indicators and DM production per unit area are shown in Figure 3.3. All growth rate indicators: LAI, CGR and NAR were positively correlated with DM accumulation illustrating that increasing LAI, NAR and CGR led to an increase in DM per unit area. Dry matter production by a crop is proportional to the amount of radiation intercepted by the leaf canopy (Biscoe & Gallagher, 1977). Thus, the amount of light intercepted by a crop during its growing season is a function of its LAI suggesting that an increasing LAI is proportional to an increase in DM accumulation. The same result was reported by Rasheed *et al.* (2003) that the more the LAI, the higher the DM accumulation potential of the crop and vice versa. This was further supported by an increasing photosynthetic efficiency of plants (NAR) which is positively correlated with DM accumulation. Inostroza *et al.* (2011) in the evaluation of seedling vigour among 80 recombinant lines of barely reported that NAR was positively correlation with DM accumulation. Though positively, CGR was poorly correlated with DM accumulation. Thus, DM accumulation was linearly slowly increased with increasing CGR. The multiple linear regression equation: $Y=0.67x_1$ (LAI) $-0.21x_2$ (CGR) $-0{,}09x_3$ (NAR) +0.43 with coefficient of determination (R^2=0.95) also showed that the combined effects of growth rate indicators were responsible for a significant contribution to DM accumulation per unit area.

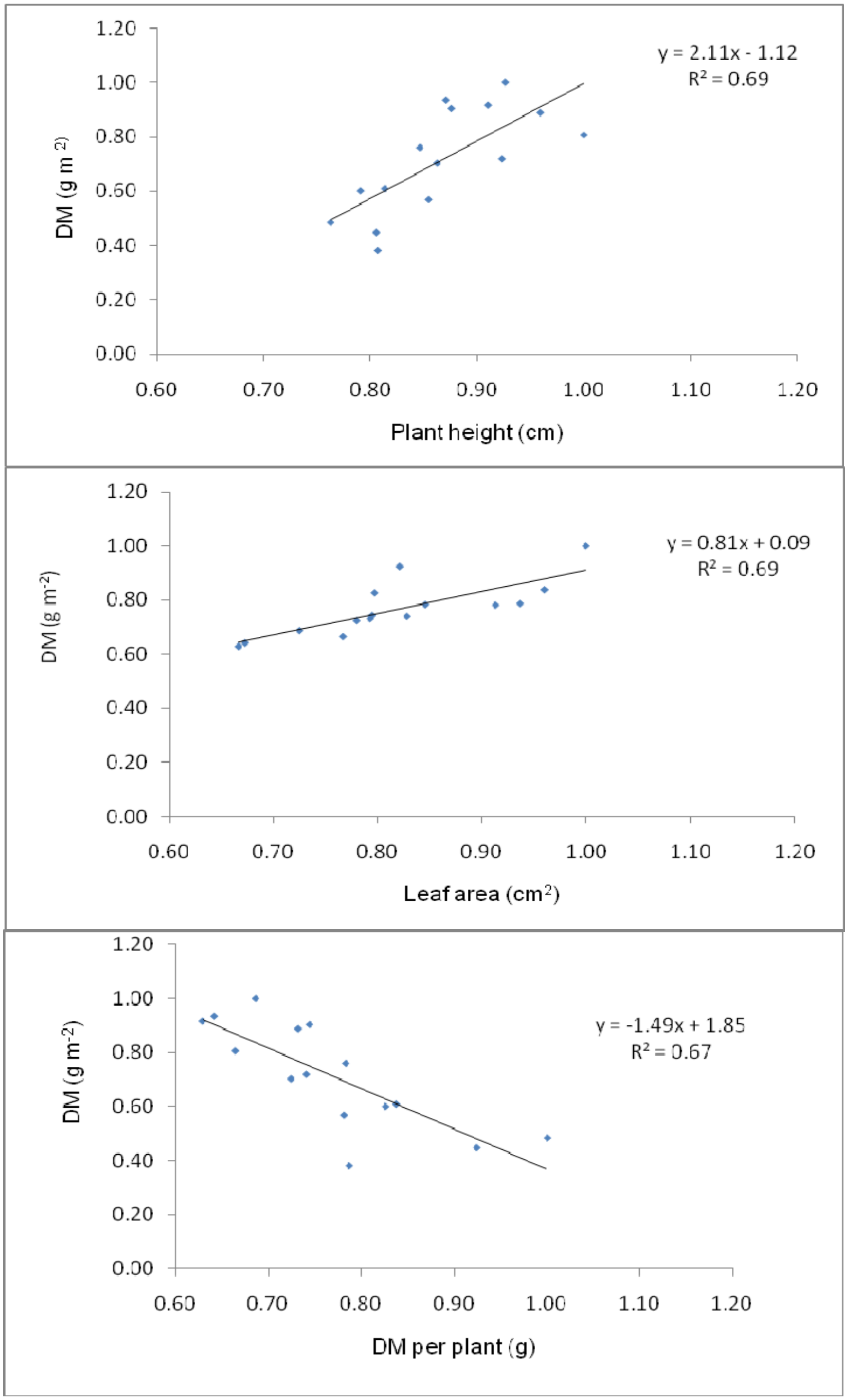

Figure 3.2 Relations between growth indicators (per plant basis) and DM (g m^{-2}) at the vegetative phase

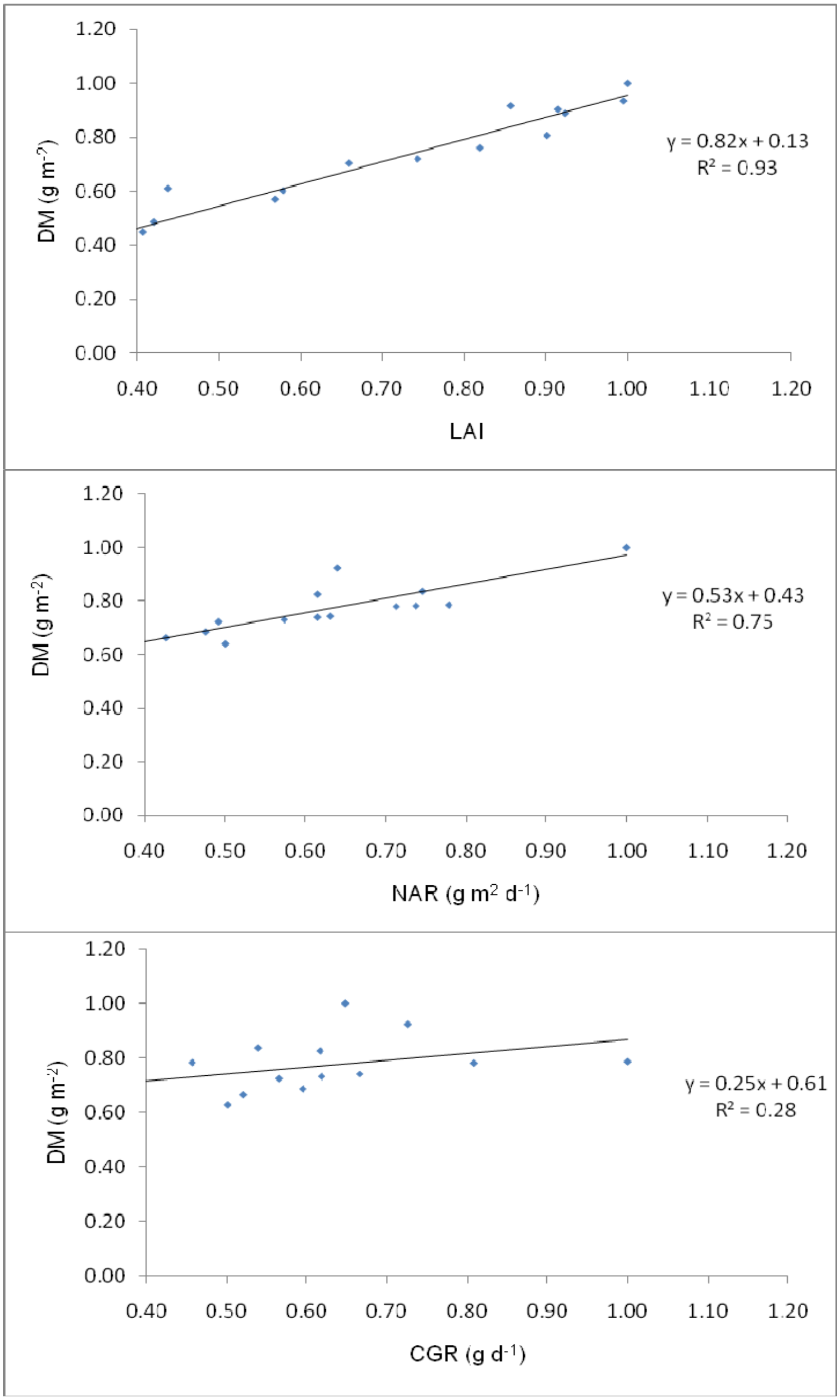

Figure 3.3 Relations between growth rate indicators and DM (g m^{-2}) at the vegetative phase.

3.3.4 Reproductive phase

3.3.4.1 Growth indicators

The response of growth indicators to row spacing and plant density are summarised in Table 3.11. Both plant height and leaf area showed a significant response to the interaction effect of row spacing by plant density. Maximum plant height was reached at 56 and 63 DAE with the tallest plants (± 224 cm) at a combination of 0.225 m row spacing and a plant density of 125 000 plants ha^{-1}. Leaf area was the greatest for both sampling dates at a combination of 0.90 m row spacing by 50 000 plants ha^{-1}. Comparing plant height and leaf area it is obvious that different treatment configurations resulted in different maximum plant parameter measurements. Modarres *et al*. (1998) tested four genotypes of maize at two plant densities (65 000 and 90 000 plants ha^{-1}) and recorded the tallest plants at the highest plant density while leaf area was the greatest at the lowest plant density. These findings concert with that of Ibeawuchi *et al*. (2008), Gizawy (2009) and more specifically Moaveni *et al*. (2011) who studied physiological parameters' response to four plant densities (70 000, 90 000, 110 000 and 130 000 plants ha^{-1}) and recorded the highest plant height at the highest plant density and greatest leaf area at the lowest plant density. The current results, as well as similar findings of previous researchers confirm that plants tend to etiolate with increasing plant density as a result of greater competition for light under high plant density. Therefore the ultra-fast maize hybrid that was bred to be smaller than conventional cultivars shows the same morphological reaction as its ancestors.

Row spacing by plant density interaction resulted in a significant difference in DM accumulation from 56 to 77 DAE (Table 3.11). The greatest DM per plant was recorded at a row spacing of 0.90 m with a plant density of 50 000 plants ha^{-1}. The lowest DM per plant was recorded at a row spacing of 0.225 m with a plant density of 150 000 plants ha^{-1}. This result indicated that DM production decreased as plant density increased within all row spacing levels. Bahadur *et al.* (1999) tested a maize genotype at five plant densities (35 000, 50 000, 60 000, 80 000 and 95 000 plants ha^{-1}) and recorded the highest DM per plant at the lowest plant density. Amanullah *et al*. (2010) also confirmed that increasing plant density negatively impacted on DM accumulation per plant. A reduction in DM per plant with increasing plant density was likely due to less penetration of light through the canopy structure. However, neither the row spacing by plant density interaction nor any main effect resulted in significant differences of DM accumulation from 84 to 105 DAE. The non-significant effect on the latter sampling dates (84 to 105 DAE) is attributed to ceasing of the vegetative growth followed by grain filling where metabolic activity is low and do not contribute to growth (Brown, 1984). It is worthwhile to mention that most of the plant interference and competition exerted due to treatment factors occurred during vegetative growth phase. Therefore, similar treatments or treatment combinations also resulted in the highest plant height, leaf area and DM accumulation which are indicative of a carryover effect of treatments during the vegetative phase. Basically, during the reproductive phase, the accumulation of growth indicators cease following the onset of flowering presumably due to remobilization of soluble solutes from vegetative parts (source) to strong sink (the ear) with progression of grain filling. Aging may be detrimental to DM production, because after the transition from the vegetative to the reproductive growth phase, the formation of new leaves ceases. Moreover, as leaves get older, their photosynthetic capacity decreases due to loss of chlorophyll, as well as the loss of stem and leaf weight due to a transfer of soluble solutes to the ear. Goldsworthy and Tayler (1970) also reported a reduction in DM accumulation per plant after flowering/fertilization and ascribed it to the remobilization of soluble solutes to a strong sink (the ear).

3.3.4.2 Growth rate indicators and seed yield

Growth rate indicators and seed yield as affected by row spacing and plant density are summarised in Table 3.12. Row spacing by plant density interaction had a significant effect on LAI. The greatest LAI was recorded at a row spacing of 0.45 m with a plant density of 150 000 plants ha^{-1} followed by a row spacing of 0.90 m with a plant density of 150 000 plants ha^{-1}. As expected LAI also showed a tendency to increase with an increase in plant density at all row spacing treatments. Plants exhibited the smallest LAI at a row spacing of 0.225 m with a plant density of 50 000 plants ha^{-1}. Bruns & Abbas (2003) tested two maize hybrids at five plant densities (43 000, 48 400, 54 300, 64 200 and 76 500 plants ha^{-1}) and reported the greatest LAI of the hybrids at the highest plant density. During this growth phase (56 and 63 DAE) the mean LAI was 4.56 which is nearly similar to the LAI value (4.47) measured at the end of the vegetative growth phase (49 DAE). When LAI values at 49 DAE of the vegetative phase is compared with that at 63 DAE of the reproductive phase, the differences between the two phases were minimal/negligible indicating a carryover effect of treatments from the vegetative phase. Thus, leaf growth reached its peak near anthesis and its response to treatment factors ceased at the reproductive phase. This might probably be attributed to remobilization of assimilates into a developing ear (grain filling) which limited the assimilate partitioning to leaves for additional growth and development. This illustrated that leaf growth and development reached its peak near flowering. It was also observed that row spacing and plant density combinations had a profound effect on LAI of plants throughout the growing period. For all row spacings at plant densities of 50 000 and 75 000 plants ha^{-1}, the LAI values were below 4 whereas at higher plant densities (PD ≥ 125 000 plants ha^{-1}) plants attained LAI values above 5 at anthesis to silking.

Only the main effects, row spacing and plant density, resulted in significant differences in NAR (Table 3.12). The highest NAR was recorded at a row spacing of 0.45 m followed by 0.90 m. It has to be noted that there was no significant difference in the NAR of these two row widths. Regarding plant density, the highest NAR value was observed at a plant density of 100 000 plants ha^{-1} followed by 75 000 plants ha^{-1}. The lowest NAR value was calculated at a plant density of 150 000 plants ha^{-1}. This was the result for both sampling dates (56 and 63 DAE) and the decreasing tendency in NAR that commenced at the end of the establishment phase continued but to a smaller degree compared to the vegetative phase. The photosynthetic efficiency of leaves (NAR) due to main effects of row spacing and plant density peaked at the establishment phase (21 DAE) and then declined as growing period advanced. Thus, the NAR was highest at establishment followed by the vegetative phase with the lowest NAR during the reproductive phase. Brown (1984) indicated that NAR is high when plants are small and leaves are few without shading each other at an early growth stage. Sharifi & Pirzad (2011) recorded the highest NAR at an early growth stage (28 DAE) using three maize hybrids at three plant densities (80 000, 100 000 and 120 000 plants ha^{-1}). They also pointed out that NAR decreased considerably it peaked through advancement of the growing season towards maturity. This suggests that NAR is at its highest when plants are small and all leaves are exposed to full sunlight during the early stages of growth. As plants grow, more and more leaves are being formed resulting in partial or full shading of leaves that leads to a reduction in NAR as the growing season progresses.

Similarly, CGR response was limited to the main effect of plant density only. The highest CGR was recorded at a plant density of 100 000 followed by 75 000 plants ha^{-1}. The lowest CGR was observed at a plant density of 150 000 plants ha^{-1}. Generally CGR increased from establishment to the vegetative phase and then tended to decline to the reproductive phase. The reduction of CGR after peaking at the vegetative phase (42 DAE) was likely the result of cessation of the vegetative growth, loss of leaves, low metabolic activity and senescence of leaves (Brown, 1984, Gardner et al., 1985). However, row spacing by plant density interaction had no significant effect on CGR. In summary only LAI showed significant differences as a result of the interaction effect of row spacing and plant density considering the growth rate indicators.

Seed yield also responded in a similar manner as LAI (Table 3.12). The greatest seed yield was measured at a row spacing of 0.45 m with a plant density of 100 000 plants ha^{-1} followed by 0.90 m at the same plant density. The former yield did not differ significantly from that of 75 000 plants ha^{-1} at 0.45 m row spacing or 75 000 and 100 00 plants ha^{-1} at 0.90 m row spacing. Balanced growth and development of plants require optimum spatial arrangement of row spacing and plant density. Hence, deviation from optimum row spacing and plant density had a negative impact on seed yield. This finding also indicated, although not significant, that increasing row spacing from 0.45 to 0.90 m at an optimum plant density (10 000 plants ha^{-1}) caused a yield loss of 11.54% while reducing the row spacing to 0.225 m resulted in a yield loss of 19.39%. Similarly, increasing plant density from 100 000 to 125 000 plants ha^{-1} at an optimum row spacing (0.45 m) led to a yield reduction of 23.50% while decreasing to 75 000 plants ha^{-1} resulted in a 12.88% yield loss. Seed yield reduction associated with wider rows with low plant density might be attributed to less number of plants per unit area. On the other hand, seed loss with narrow rows and high plant density was the result of barren and lodged plants. Seed yield will be dealt with in Chapter 4 and will only be used for correlation with selected crop growth parameters.

3.3.4.3 Correlation between selected parameters and grain yield

The relationship between growth indicators and grain yield during the reproductive phase is presented in Figure 3.4. During this growing period, different plant parts participate in different interrelated metabolic functions which express their either positive or negative correlation with grain yield. Plant height was negatively correlated with grain yield while leaf area and DM were positively correlated. The negative correlation between plant height and grain yield suggest that the two traits are not closely associated. Khazaei *et al*. (2010) in a correlation study of agronomic traits of sweet corn under different levels of plant density indicated that plant height was not correlated with grain yield. On the other hand, Olakojo & Olaoye (2011) reported a weak correlation between plant height and grain yield. The contradictory reports on the correlation between plant height and grain yield could be attributed to genotype and environmental differences. In general the correlation of all growth indicators with grain yield was poor; indicating that their contribution towards grain yield was small. The multiple linear regression equation $Y= -1.31x_1$ (PH) $+0.08x_2$ (LA)-$0.32x_3$ (DM) +2.10 with coefficient of determination ($R^2=0.24$) was not significant ($P \geq 0.05$), which proved that the combined effect of plant height (PH), leaf area (LA) and DM did not contribute significantly to grain yield.

Table 3.11 Growth indicators as affected by row spacing and plant density at reproductive phase

Treatments		**Growth indicators**													
RS (m)	**PD (000 ha^{-1})**	**Leaf number**		**Plant height (cm)**		**Leaf area (cm^{2})**		**Dry matter (g plant^{-1})**							
		DAE													
		56	63	56	63	56	63	56	63	70	77	84	91	98	105
0.225	50	12.6	12.2	190.3^{g}	189.7^{ef}	583.7^{bc}	570.7^{de}	235.3^{ab}	273.5^{a}	293.0^{ab}	301.4^{ab}	337.0	279.7	245.1	222.9
	75	12.0	11.9	191.3^{g}	190.0^{ef}	502.2^{f}	561.8^{c}	230.8^{a-c}	253.0^{a-c}	271.7^{bc}	283.0^{a-c}	274.6	256.3	225.1	207.9
	100	12.3	12.1	194.0^{efg}	192.7^{e}	485.8^{h}	530.0^{h}	220.2^{a-c}	245.8^{a-d}	258.9^{b-d}	237.7^{b-f}	217.5	203.5	191.0	172.6
	125	12.3	12.2	224.7^{a}	224.3^{a}	473.9^{j}	501.2^{j}	180.4^{bc}	192.7^{ef}	196.5^{fg}	220.2^{c-g}	183.1	179.2	172.7	132.6
	150	12.0	12.3	218.0^{ab}	217.0^{b}	452.4^{k}	470.6^{l}	167.5^{c}	181.6^{f}	177.5^{g}	170.4^{g}	167.1	159.3	145.3	117.3
0.45	50	12.3	12.0	174.3^{hi}	189.3^{f}	584.0^{b}	638.5^{b}	236.8^{ab}	257.0^{ab}	269.6^{bc}	279.5^{a-c}	276.3	253.7	240.8	223.6
	75	12.8	12.4	188.7^{g}	191.3^{ef}	580.4^{bc}	595.3^{d}	219.7^{a-c}	240.4^{a-e}	247.5^{b-e}	252.2^{b-e}	247.2	225.2	220.8	200.2
	100	12.5	12.2	192.0^{fg}	192.7^{e}	570.4^{d}	540.5^{g}	216.0^{a-c}	239.5^{a-e}	240.5^{c-f}	225.5^{c-g}	216.3	214.0	200.4	192.6
	125	12.6	12.4	200.0^{cde}	200.3^{d}	497.7^{g}	527.3^{hi}	203.3^{a-c}	215.1^{b-f}	214.1^{d-g}	211.9^{d-g}	208.5	194.0	178.4	169.3
	150	12.3	12.1	206.3^{bc}	210.0^{c}	495.1^{g}	526.6^{hi}	178.0^{bc}	196.1^{d-f}	183.2^{g}	173.6^{fg}	162.9	149.4	140.1	131.2
0.90	50	12.3	12.1	169.3^{i}	172.0^{i}	600.1^{a}	644.7^{a}	257.1^{a}	283.3^{a}	327.7^{a}	327.8^{a}	315.0	303.9	284.9	276.0
	75	12.0	12.2	179.0^{h}	180.7^{g}	579.6^{c}	556.6^{f}	215.6^{a-c}	249.2^{a-c}	268.7^{bc}	264.0^{a-d}	252.6	244.6	212.2	196.5
	100	12.5	12.3	194.0^{efg}	192.7^{e}	481.7^{j}	525.6^{d}	178.1^{bc}	238.4^{a-e}	261.0^{b-d}	245.2^{b-e}	229.6	222.4	204.1	191.4
	125	12.0	12.3	201.3^{cd}	202.3^{d}	474.8^{j}	502.4^{j}	172.4^{bc}	206.1^{c-f}	208.0^{e-g}	202.8^{d-g}	202.1	198.4	185.3	176.0
	150	11.3	12.3	209.3^{b}	210.3^{c}	446.2^{l}	483.2^{k}	168.4^{c}	184.4^{f}	192.3^{fg}	191.4^{e-g}	185.0	176.5	176.1	136.6
	LSD$_{(T\leq0.05)}$	ns	ns	7.1	3.3	22.0	28.0	66.1	50.6	49.4	65.9	Ns	ns	ns	ns
	Mean	12.3	12.2	195.5	197.0	520.5	545.0	205.3	230.4	240.7	245.5	231.6	217.3	201.5	183.1
RS mean	0.225	12.2	12.1	201.8^{a}	204.9^{a}	499.6^{c}	536.9^{bc}	194.0	229.9	231.0	227.9	222.2	207.3	195.8	170.7
	0.45	12.5	12.2	194.6^{b}	195.2^{b}	548.7^{a}	566.9^{a}	211.2	229.6	251.6	246.3	236.9	229.2	212.5	195.3
	0.90	12.0	12.2	187.5^{c}	188.1^{c}	513.3^{b}	541.3^{b}	210.7	231.7	239.5	243.2	235.9	215.6	196.1	183.4
	LSD$_{(T\leq0.05)}$	ns	ns	3.2	1.5	10.8	12.6	ns	ns	ns	ns	Ns	ns	ns	ns
PD mean	50	12.4	12.1	192.2^{c}	192.8^{d}	589.3^{a}	644.3^{a}	243.1^{a}	271.3^{a}	296.8^{a}	302.9^{a}	309.4	279.1	256.9	240.8
	75	12.3	12.2	197.2^{b}	196.8^{c}	518.8^{b}	594.1^{b}	222.0^{ab}	247.5^{ab}	262.6^{b}	266.4^{ab}	258.1	242.0	219.4	201.5
	100	12.4	12.2	195.2^{bc}	197.7^{bc}	512.2^{c}	537.7^{c}	204.8^{bc}	241.2^{b}	253.4^{b}	236.1^{bc}	221.1	213.3	198.5	185.5
	125	12.3	12.3	195.3^{bc}	198.6^{b}	482.1^{d}	504.5^{d}	185.4^{bc}	204.6^{c}	206.2^{c}	211.6^{cd}	197.9	190.5	178.8	159.3
	150	11.9	12.2	203.2^{a}	203.1^{a}	464.6^{e}	503.9^{d}	171.3^{c}	187.4^{c}	184.3^{c}	178.5^{d}	171.7	161.7	153.8	128.3
	LSD$_{(T\leq0.05)}$	ns	ns	3.5	1.7	13.9	13.3	38.2	29.3	28.5	38.1	Ns	ns	ns	ns
	CV (%)	2.5	2.6	3.2	2.8	6.4	4.2	15.0	10.2	9.6	12.9	12.4	9.5	9.4	9.8

RS=row spacing, PD=plant density, ns= not significant

Table 3.12 Growth rate indicators and seed yield as affected by row spacing and plant density at reproductive phase

Treatments		**Growth rate indicators**												**Seed yield (kg ha^{-1})**
RS (m)	**PD (000 ha^{-1})**	**LAI**		**NAR (g m^{2} d^{-1})**		**CGR (g d^{-1})**								
		DAE												
		56	63	56	63	56	63	70	77	84	91	98	105	
0.225	50	2.57^{e}	2.73^{d}	6.4	3.8	60.4	41.4	30.7	26.6	23.9	16.9	10.4	7.8	7143.4^{d}
	75	3.74^{c-e}	3.58^{cd}	5.2	2.8	53.2	38.9	25.0	20.5	16.5	12.5	9.7	7.2	8769.7^{bc}
	100	4.58^{bc}	4.52^{bc}	4.5	2.4	30.3	25.0	19.5	18.1	14.4	10.2	6.8	5.7	8987.9^{bc}
	125	5.50^{ab}	5.32^{ab}	4.1	2.0	26.7	22.5	15.6	12.9	10.2	9.3	5.0	4.7	8529.3^{bc}
	150	5.39^{ab}	5.22^{ab}	2.7	1.1	21.8	18.4	12.7	11.4	7.8	10.9	4.9	3.7	7949.5^{cd}
0.45	50	2.81^{de}	2.77^{d}	8.8	4.4	57.4	44.8	38.5	33.8	22.6	14.5	12.9	7.1	9547.5^{b}
	75	3.97^{cd}	3.90^{cd}	7.4	4.2	40.6	34.5	29.8	22.9	14.9	8.7	4.9	3.9	9713.1^{ab}
	100	4.75^{bc}	4.67^{bc}	6.8	3.2	32.8	33.1	22.3	13.2	12.7	8.3	3.8	3.6	11149.5^{a}
	125	5.67^{ab}	5.44^{ab}	6.2	2.8	23.5	23.1	13.8	12.7	10.4	8.3	3.1	2.6	8529.3^{bc}
	150	6.42^{a}	6.32^{a}	5.2	2.5	16.8	19.6	10.2	8.9	7.7	4.6	1.8	1.2	7951.5^{cd}
0.90	50	2.69^{e}	2.94^{d}	9.0	5.7	48.7	41.2	33.8	30.4	20.8	7.1	5.6	4.4	9139.4^{bc}
	75	3.14^{de}	3.61^{cd}	8.4	5.2	43.3	35.2	18.1	17.4	14.5	6.8	4.7	3.3	9709.1^{ab}
	100	5.52^{ab}	5.30^{ab}	7.0	4.5	42.2	29.9	15.5	12.8	8.5	5.9	4.7	3.2	9862.6^{ab}
	125	5.67^{ab}	5.52^{ab}	5.8	3.2	27.7	26.7	15.1	10.4	7.1	5.2	3.4	2.8	8947.5^{bc}
	150	6.32^{a}	6.28^{a}	3.4	2.7	21.2	20.1	11.4	7.9	5.9	3.6	1.6	1.4	8353.5^{bcd}
	$\text{LSD}_{(T\leq0.05)}$	1.22	1.29	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	1647.1
	Mean	4.58	4.54	6.1	3.4	36.4	30.3	20.8	17.3	13.2	8.8	5.5	4.2	8952.2
RS mean	0.225	4.36^{b}	4.27^{b}	4.5^{b}	2.4^{b}	34.2	27.9	18.8	15.8	11.4	5.7	4.0	3.0	8276.0^{b}
	0.45	4.70^{a}	4.73^{a}	7.0^{a}	4.2^{a}	38.5	31.0	25.2	23.9	15.2	11.9	7.4	5.8	9378.2^{a}
	0.90	4.69^{a}	4.62^{a}	6.7^{a}	3.4^{ab}	36.6	30.6	22.9	18.3	14.6	9.6	6.1	4.3	9202.4^{a}
	$\text{LSD}_{(T\leq0.05)}$	0.24	0.37	1.4	1.8	ns	ns	ns	ns	ns	ns	ns	ns	543.5
PD mean	50	2.69^{d}	2.81^{d}	6.0^{bc}	3.1^{abc}	35.2^{bc}	29.3^{b}	20.6^{bc}	17.5^{bc}	13.5^{b}	8.7^{bc}	4.8^{c}	3.9^{bc}	8610.1^{bc}
	75	3.61^{c}	3.70^{c}	6.8^{ab}	4.1^{ab}	44.3^{ab}	36.1^{a}	24.7^{b}	22.3^{b}	16.1^{b}	10.0^{b}	6.9^{b}	5.1^{ab}	9397.3^{ab}
	100	4.95^{b}	4.83^{b}	8.0^{a}	5.0^{a}	52.5^{a}	40.6^{a}	33.8^{a}	30.7^{a}	22.1^{a}	13.7^{a}	10.4^{a}	6.9^{a}	10000.0^{a}
	125	5.61^{ab}	5.42^{ab}	5.1^{c}	2.5^{bc}	25.7^{cd}	23.8^{bc}	16.5^{cd}	14.3^{c}	9.5^{c}	7.2^{bc}	3.8^{cd}	3.2^{bc}	8668.7^{bc}
	150	6.04^{a}	5.94^{a}	3.7^{d}	2.0^{c}	19.6^{d}	18.9^{c}	12.3^{d}	11.7^{c}	7.3^{c}	5.7^{c}	2.5^{d}	1.9^{c}	8084.9^{c}
	$\text{LSD}_{(T\leq0.05)}$	0.70	0.74	1.4	2.0	10.4	5.8	4.3	6.5	3.8	3.1	2.0	2.2	701.6
	CV (%)	12.5	13.2	22.80	25.67	28.1	18.6	19.3	32.2	26.3	32.8	33.8	25.5	8.3

RS=row spacing, PD=plant density, ns= not significant

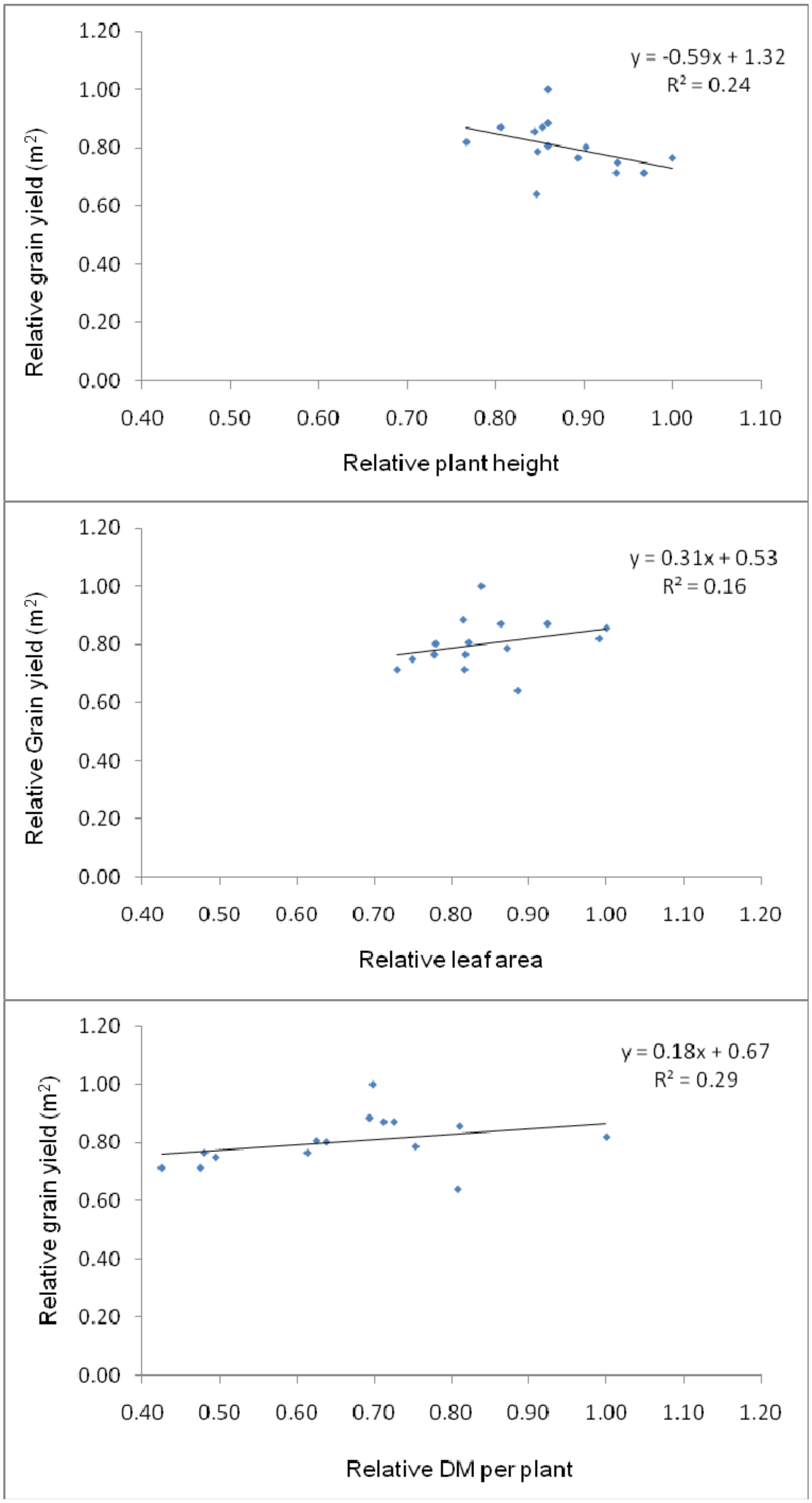

Figure 3.4 Relations between growth indicator and grain yield at the reproductive phase.

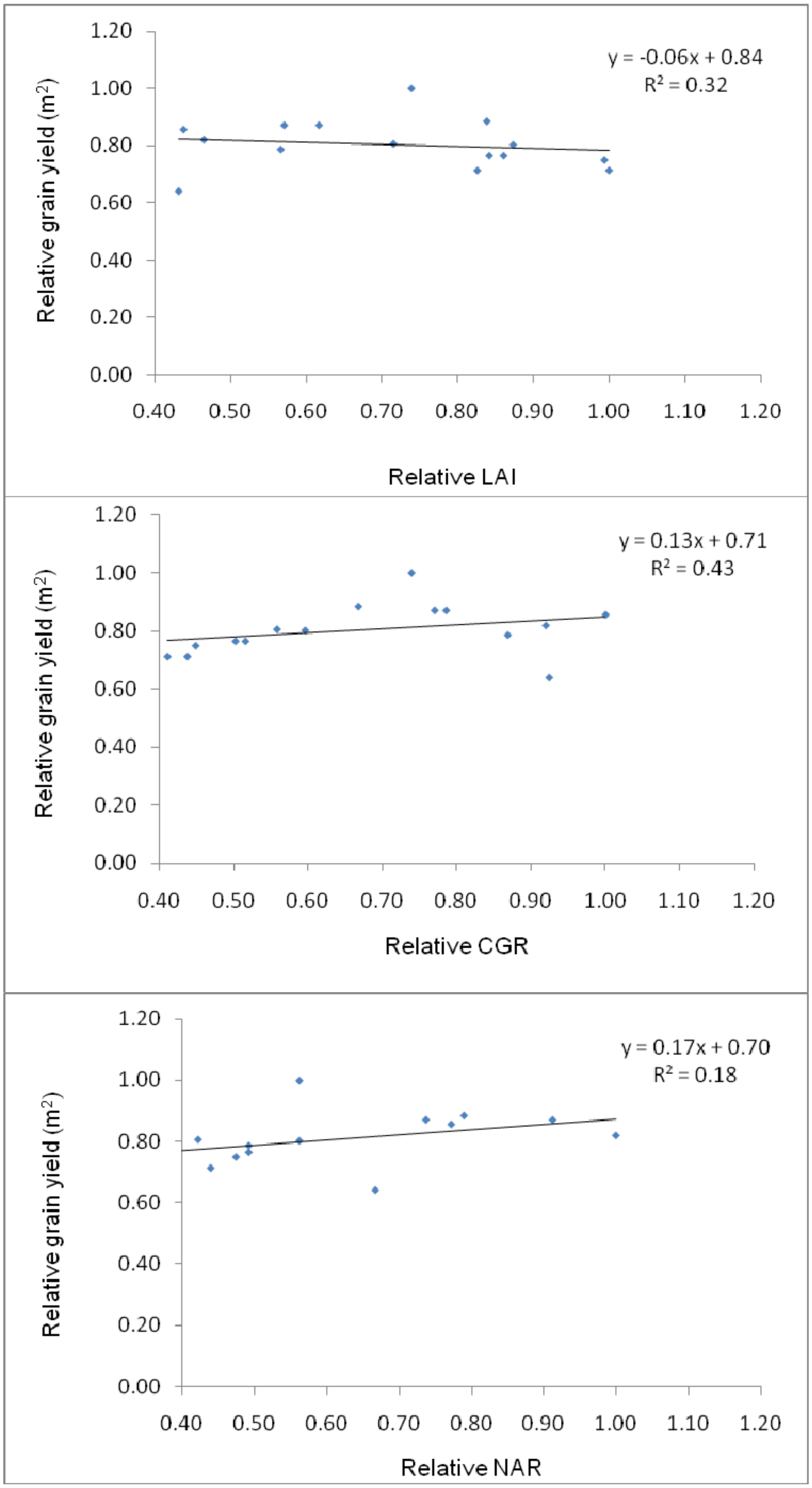

Figure 3.5 Relations between growth rate indicators and grain yield at the reproductive phase.

The relationship between crop growth rate indicators and grain yield is shown in Figure 3.5. All crop growth rate indicators exhibited greater but still poor correlations to grain yield during this phase. Wannows *et al*. (2010) in genetic variances, heritability and correlation of agronomic traits of yellow maize reported a weak correlation between LAI and grain yield. This correlation between LAI and grain yield contradicted the finding of Haghighi & Yamahmodi (2011) who reported a strong positive correlation between LAI and grain yield in the evaluation of physiological characteristic of yield and its components of maize. The variable results with respect to correlation between LAI and grain yield was likely due to crop variety differences in DM partitioning of reproductive organs (the ear). In line with this, NAR and CGR were also positively, but poorly correlated with grain yield. However, Kumar & Singh (2001) in the growth analysis of maize during long and short crop seasons reported a weakly negative correlation between NAR and grain yield. Regarding the combined effect of growth rate indicators, the multiple linear regression $Y= 0.61x_1$ (LAI) + $0.17x_2$ (CGR) + $0.78x_3$ (NAR) + 2.85 with $R^2=0.32$ was once more not significant ($P \leq 0.05$) which indicated that the combined effect of LAI, CGR and NAR on yield was minimal.

3.4 Summary and Conclusion

Growth indicators reacted differently to row spacing by plant density combinations during various growth phases. During the establishment phase, treatment effects on growth indicators were not significant because the small plants did not compete with each other. Only LAI was significantly affected due to the interaction effect of row spacing by plant density at 14 and 21 DAE. Significantly the greatest LAI was recorded at a row spacing of 0.45 m with a plant density of 150 000 plants ha^{-1}. Row spacing significantly affected NAR with the highest NAR was recorded at a row spacing of 0.45 m. Plant density significantly affected NAR and CGR where both indicators were highest at a plant density of 100 000 plants ha^{-1}.

During the vegetative phase, treatment interactions significantly affected plant height and leaf area from 35 to 49 DAE and significant differences were detected for DM from 42 to 49 DAE. The tallest plants were recorded at a row spacing of 0.225 m and plant density of 125 000 plants ha^{-1}. Leaf area per plant was greatest at a row spacing of 0.90 m and plant density of 50 000 plants ha^{-1} at 35, 42 and 49 DAE. In line with this, the greatest DM per plant was recorded at the row spacing of 0.90 m and the plant density of 50 000 plants $^{-1}$. Only LAI was significantly affected by the interaction of row spacing and plant density with the greatest LAI at the row spacing of 0.45 m and the plant density of 150 000 plants ha^{-1}. Row spacing resulted in a significant difference in NAR with the highest at a row spacing of

0.45m. Similarly, plant density impacted significantly on NAR and CGR where the highest NAR and CGR were observed at a plant density of 100 000 plants ha^{-1}. During the reproductive phase, plants reached their full height and maximum leaf area. In line with this, row spacing by plant density interaction significantly affected grain yield with the highest grain yield recorded at the row spacing of 0.45 m with the plant density of 100 000 plants ha^{-1} closely followed by 0.90 m with the same plant density. Therefore, it can be concluded that a row spacing of 0.45 or 0.90 m and plant density of 100 000 plants ha^{-1} was the optimum combination for the ultra-fast maize hybrid and the growing condition under consideration.

CHAPTER 4

YIELD COMPONENT AND YIELD RESPONSE OF MAIZE TO ROW SPACING AND PLANT DENSITY

4.1 Introduction

Maize grain yield is affected by spatial arrangement of row spacing and plant density due to its monoecious floral organization, low tillering ability and of short flowering period (Vega *et al*., 2001). The distribution pattern of plants in variable spatial arrangements has significant on yield because it affects the proximity of plants within and between rows. This on grain yield is primarily related to competition between plants for resources such as sunlight, soil water and nutrients (Duncan, 2002; Nafziger, 2006). A number of studies have been conducted on plant competition to determine the optimum plant density for maize (Olson & Sander, 2003). Increasing plant density delays crop maturity and decreases seed weight, seeds per ear and seeds per row (Sangoi *et al*., 2002; Ogunlella *et al*., 2005). On the other hand, total biomass is increased with increasing plant density, but harvest index decreased at a high plant density (Amano & Salazer, 1989). Hassan (2000) also reported that plant and ear height increased with increasing plant density, while leaf area per plant and ear length decreased with increasing of plant density.

Among agronomic practices, row spacing has a special significance since it affects plant density, root development, plant growth and seed setting (Davi *et al*., 1995). Planting maize in a narrow row spacing results in more equidistant spacing of plants, which theoretically minimizes competition among plants for water, nutrients and sunlight. Several researchers reported that the effect of row spacing on maize dry matter (DM) and yield (Pinter *et al*., 1994; Widdicombe & Thelen, 2002). Maize DM yield is influenced by numerous interactions including the environment (temperature, photoperiod and light intensity), agronomic management (row spacing, plant density, sowing date, fertilizer and harvest stage), and genetic factors (Graybill *et al*., 1991). Roth (1996) indicated that a 9% DM yield increase was recorded for forage maize grown at 0.38 m row spacing as compared with 0.76 m row spacing. Similarly, Cox *et al*. (1998) also recorded a maize DM yield increase of 4% as row width decreased from 0.76 to 0.38 m.

Plant density, the number of plants per unit area, is one of the most important yield determinants of maize. Plant density affects grain yield by influencing post-flowering source/sink ratio and kernel number per plant (Borras *et al*., 2003). These traits decrease with increasing plant densities (Westgate *et al*., 1997; Andrade *et al*., 2002). Inevitably crop growth rate depends on the amount of intercepted photosynthetic ally active radiation (IPAR) which is directly related to the plant density. Plant density has a profound impact on dry matter production. Generally, higher plant densities would enable plants to capture more incident photsynthetically active radiation (IPAR) initially, but crowding increases after canopy closure (Borras *et al*., 2003).

Maize breeders were successful in developing modern ultra-fast maize hybrids with highly improved grain yield per land area through improvement in tolerance to abiotic and biotic stresses without significantly altering the yield potential per plant. The development of ultra-fast maize hybrids demanded the use of high plant densities, because (i) the hybrids are characteristically early maturing with less number of leaves and a smaller leaf area as compared to longer season hybrids and (ii) their low yield potential per plant. Sangoi *et al*. (2002) indicated that the optimum plant density depends on several factors such as water availability, soil fertility, spatial arrangement and hybrid maturity. Many investigators also indicated that agronomic practices such as row spacing and plant density affected the crop environment, which influenced the yield and yield components of maize. Thus, optimum spatial arrangement of row spacing and plant density need to be maintained for modern ultra-fast maize hybrids in order to exploit natural resources, such as nutrients, sunlight and soil water to ensure satisfactory yields. The objective of this study was to evaluate the response of the yield components and yield for the selected ultra-fast maize hybrid to varying row spacing and plant density configurations.

4.2 Materials and Methods

4.2.1 Treatments and experimental design

Field experiments were conducted for two consecutive cropping seasons (2008/09 to 2009/10) at the Kenilworth Experimental Station of the Department of Soil, Crop and Climate Sciences, University of the Free State (UFS), Bloemfontein. In this study three row spacings/widths (0.225, 0.45 and 0.90 m) and five plant densities (50 000, 75 000, 100 000, 125 000 and 150 000 plant ha^{-1}) were used. The total land area used was 3240 m^2 and each plot was 3.6 m wide and 8 m long. The treatments were arranged in a factorial combination and laid out in a randomized complete block design (RCBD) with three replications. Regarding the experimental site, agro-meteorological data, soil physical and chemical properties, particle distribution and bulk density of the profile, summary of treatment combinations, agronomic practices and statistical analysis used are described in Chapter 3 section 3.2.1, 3.2.2, 3.2.3 and 3.2.7, respectively.

4.2.2 Measurements

4.2.2.1 Yield components

Data recorded on yield components included number of ears per plot, ear length, ear diameter, number of rows per ear, number of seeds per row, seeds per ear, thousand seed weight, plant lodging, barren plants and prolificacy (ears per plant). The number of ears was determined by counting ears per plot of the harvestable area. Ear length and diameter was measured for five randomly selected plants from the base to the tip and at approximately the middle of the ear at harvesting, respectively. Number of rows per ear and number of seeds per row was counted for five randomly selected plants per plot. Seeds per ear were determined multiplying the number of rows by the number of seeds per row. Thousand seed weight (TSW) was measured by counting a thousand seeds with a seed counter and weighing it. Plant lodging and barrenness were assessed before harvesting by counting the number of plants lodged and those that exhibited barrenness per plot and are expressing as a percentage of the final stand. Barrenness is the failure of plants to produce viable ears (Sangoi, 1996) and plants were considered barren when they did not present a visible ear or when they produced a rudimentary female inflorescence with less than 10 seeds. Similarly, plants were considered lodged when broken below the ears and/or leaning more than 45^{o} from the vertical (Joseph & Rankin, 2004). Prolificacy is the property of producing more than one ear per plant and was estimated by dividing the number of ears by the number of plants per plot.

4.2.2.2 Yield

Grain was manually harvested from a plot area of 1.8 m x 7 m = 12.6 m^{2} and converted to kg ha^{-1} after adjusting the moisture content to 12.5%. Biomass yield was calculated as the sum of stover weighed and the total grain yield. Harvest index (HI) is the ratio of grain yield to the total biomass yield which was estimated by dividing grain yield by total biomass.

4.3 Results and discussion

4.3.1 Summary of analysis of variance

A summary on the combined analysis of variance over seasons showing the effect of treatment factors on yield and yield components are presented in Table 4.1.

Table 4.1 Summary of analysis of variance indicating the effect of treatment factors on yield and yield components

Crop parameters	Treatment factors		
	RS	**PD**	**RS x PD**
Barren plants (%)	*	*	*
Plant lodging (%)	*	*	*
Number of ears per plot (m^2)	*	*	*
Prolificacy	ns	*	ns
Ear length	*	*	*
Ear diameter	*	*	ns
Number of rows per ear	ns	ns	ns
Number of seeds per row	*	*	*
Number of seeds per ear	*	*	*
Thousand seed weight	*	*	*
Total biomass	*	*	*
Grain yield	*	*	*
Harvest index	*	*	*

* = Significant at 5% probability level, ns = not significant, RS = row spacing, PD = plant density

With the exception of ear diameter, prolificacy and number of rows per ear, the combination of row spacing by plant density significantly affected all parameters. Ear diameter was significantly affected by both main effects only. Prolificacy was only significantly affected by plant densities less than 75 000 plants ha^{-1} and concerted with literature (DeLeon & Coors, 2002). The number of rows per ear was the least sensitive variable and was not significantly affected by either row spacing or plant density. The results indicated that row spacing, plant density and interaction of row spacing by plant density had a profound effect on yield and yield components of maize. Based on this, the effects of the treatment factors on yield and yield components are dealt with in detail. The percentage of barren plants and plant lodging on treatment basis were also determined and are summarized in Table 4.2. This assessment of barren plants and plant lodging was done because of their assumed negative impact on final grain yield.

4.3.2 Barren plants and plant lodging

4.3.2.1 Barren plants

Data for the number of barren plants as affected by row spacing and plant density are presented in Table 4.2. Development of barren plants tended to increase with increasing plant density across all row spacings. The highest number of barren plants occurred at the row spacing of 0.225 m and the plant density of 150 000 plants ha^{-1} followed by the same row spacing at the plant density of 125 000 of plants ha^{-1}. For all row spacings at plant densities of 50 000 and 75 000 plants ha^{-1}, the number of barren plants was negligible. Barrenness is one of the major factors limiting optimum conversion of light energy to grain in maize cultivated at high plant densities, especially beyond a critical maximum density (Sangoi, 1996; Tollenaar *et al*., 1997). The physiological alteration associated with barrenness in narrow row spacings coupled with high plant density is a delay in ear differentiation and growth of ear premordia (Jacobs & Pearson, 1991). Moreover, the formation of barren plants in supra-optimal densities is attributed to the limitation of assimilate supply that can cause seed and ear abortion (Zinselmeier *et al.*, 1995). In dense plant stands, many seeds may not develop which is associated with poor pollination resulting from a delayed silking period compared to tassel emergence, increasing barren plants with adverse effects on final crop yield (Hashemi-Dezfouli & Herbert, 1992; Otegui, 1997; Sangoi *et al*., 2002). The current results concert with findings of Subedi *et al.* (2005) where high plant density stress as a result of overcrowding initiated barrenness.

4.3.2.2 Plant lodging

The number of plants lodged as affected by row spacing and plant density are shown in Table 4.2. A variable number of lodged plants were recorded in response to row spacing, plant density and their interactions. The number of plants lodged as a result of row spacing, averaged over plant density, ranged between 0.2 and 2.8% where the highest number of plants lodged at the row spacing of 0.225 m followed by 0.90 m. Plant lodging increased with plant density within all row spacings (0 - 14.6%), even more so where the plant density was increased beyond a critical level (PD >125 000 plants ha^{-1}, Table 4.2) (Karlen & Camp, 1985b).

The interaction effect of a 0.225 m row spacing by 150 000 plants ha^{-1} aggravated plant lodging (40.1%). At high plant densities (PD ≥ 125 000 plants ha^{-1}) plant lodging might be the result of weak stems and shallow root development due to overcrowding of plants per unit area. The tendency of plant lodging at increased plant density is also associated with a disorganized light profile in dense plant densities according to Sangoi & Salvador (1996). Rajcan & Swanton (2001) suggested that when plants grow in a dense canopy, they tend to receive a different quality of light radiation, enriched with far red (FR) and impoverished in red (R) radiation where this high FR/R ratio triggers many morphological changes in plant architecture, stimulating stem elongation, favouring apical dominance and reducing stem diameter. Such changes make maize stalks more susceptible to stem breakage and root lodging before seeds attain physiological maturity.

Table 4.2 Effect of row spacing and plant density on barren plants and plant lodging

RS (m)	PD (x 000 ha^{-1})	Barren plants (%)	Plant lodging (%)
0.225	50	0.0^{k}	0.0^{g}
	75	2.6^{h}	0.0^{g}
	100	10.6^{c}	6.2^{c}
	125	16.7^{b}	7.9^{b}
	150	19.8^{a}	40.1^{a}
0.45	50	0.0^{k}	0.0^{g}
	75	0.6^{j}	0.0^{g}
	100	1.3^{j}	0.0^{g}
	125	3.9^{g}	0.4^{g}
	150	4.8^{f}	0.8^{f}
0.90	50	0.0^{k}	0.0^{g}
	75	0.4^{jk}	0.0^{g}
	100	6.3^{e}	0.4^{g}
	125	6.5^{e}	2.2^{e}
	150	7.9^{d}	2.8^{d}
	LSD$_{(T \leq 0.05)}$	0.43	0.36
RS mean	0.225	9.9^{a}	2.8^{a}
	0.45	2.1^{c}	0.2^{c}
	0.90	4.2^{b}	1.1^{b}
	LSD$_{(T \leq 0.05)}$	0.19	0.16
PD mean	50	0.0^{e}	0.0^{d}
	75	1.2^{d}	0.0^{d}
	100	6.1^{c}	2.2^{c}
	125	9.0^{b}	3.5^{b}
	150	10.8^{a}	14.6^{a}
	LSD$_{(T \leq 0.05)}$	0.24	0.2
	CV (%)	4.9	5.5

RS = row spacing, PD = plant density

4.3.3 Yield components

4.3.3.1 Number of ears per plot

Analysis of variance indicated that row spacing by plant density significantly affected the number of ears per plot (Table 4.3). Number of ears per plot increased as plant density increased within all row spacings. Variation in row spacing had little effect (± 9%) on number of ears per plot. Thus, number of ears per plot showed greater differences due to the effect of plant density than row spacing. The highest number of ears per plot (127 ears plot^{-1}) was observed at the row spacing of 0.225 m and the plant density of 150 000 plants ha^{-1} followed by a row spacing of 0.225 m with a plant density of 125 000 plants ha^{-1} (115.3 ears plot^{-1}). The lowest number of ears per plot (54.8 ears plot^{-1}) was produced at a row spacing of 0.225 m with a plant density of 50 000 plants ha^{-1}. Number of ears per plot showed a direct relation with plant density indicating that the highest plant density produced the highest number ears per plot at all row spacings and vice versa. The ratio of plant density per hectare to number of ears per plot increased nearly linearly with an increase in plant density over all row spacings. Thus, from 50 000 to 150 000 plants ha^{-1} the ratio increased from 846:1 to 1303:1, respectively. This means that fewer ears per plant were produced with an increase in plant density. Therefore, individual plants were less productive or led to barrenness. Arif *et al*. (2010) reported the highest number of ears per unit area was obtained from the highest plant density. It has to be noted that the range of plants used have to be considered. This result is also in concert with that of Azam *et al.* (2007) where high density plants produced the highest number ears per unit area.

4.3.3.2 Prolificacy

Prolificacy is the character of plants to produce more than one ear per plant and it was described by Mock & Pearce (1975) as one of the important traits exhibiting superior stand and yield performance. Prolificacy is a genetic trait that seems to be polygenically controlled and influenced by the environment and cultural practices such as plant density and correlated factors in an environment where maize plants are grown. Analysis of variance revealed that plant density significantly affected prolificacy (Table 4.3). The highest number of ears per plant (1.5) was obtained from a plant density of 50 000 plants ha^{-1} with a nearly linear decrease to 150 000 plants ha^{-1} (0.9). At lower plant densities, plants showed the tendency of producing even two ears per plant. Increasing plant density inhibited the prolific character of plants as evidenced by most of the single-eared plants at plant densities of a 100 000 plants ha^{-1} and more, and is in agreement with findings of Otegui (1995). Similar results were reported by Kesornkeaw *et al*. (2009) where increasing plant density reduced the prolificacy of plants. However, this contradicts the findings of Cox (1996), Gonzalo *et al.* (2006) and Azam *et al*. (2007) who reported that prolificacy did not respond to variation in plant densities. According to Hallauer & Troyer (1972) genotypes that produce two ears per plant in a favourable environment may produce only a single ear per plant or even develop a barren plant in an unfavourable environment. These variable reports on number of ears per plant by different investigators can probably be attributed to varietal differences of maize and the prevailing environmental conditions. Row spacing and its interaction with plant density did not show significant differences on prolificacy of plants in this study.

Table 4.3 Effect of row spacing and plant density on yield components of maize

RS (m)	PD (x 000 ha^{-1})	Number of ears plot^{-1}	Prolificacy	Ear length (cm)	Ear diameter (cm)	Number of seeds row^{-1}	Seeds ear^{-1}	TSW (g)
0.225	50	54.8^{i}	1.5	16.88^{ab}	5.10	39.1^{abc}	619.3^{ab}	238.4^{def}
	75	80.5^{fg}	1.2	15.53^{c}	4.98	36.9^{bcd}	610.0^{ab}	237.4^{def}
	100	95.8^{cdef}	1.1	13.76^{de}	4.85	33.1^{e}	528.1^{c}	229.8^{efg}
	125	115.3^{ab}	1.1	12.77^{fgh}	4.80	32.5^{ef}	508.3^{c}	219.8^{efg}
	150	127.5^{a}	1.1	11.67^{g}	4.78	27.9^{g}	462.3^{d}	208.6^{g}
0.45	50	60.3^{hi}	1.5	17.04^{a}	5.13	39.5^{a}	621.7^{a}	306.9^{a}
	75	76.1^{gh}	1.5	15.77^{bc}	5.11	38.6^{abcd}	608.3^{ab}	277.7^{bc}
	100	94.8^{def}	1.1	14.86^{cd}	4.98	36.7^{cd}	595.3^{ab}	270.0^{bc}
	125	107.8^{bcd}	1.0	13.69^{de}	4.82	33.5^{e}	517.7^{c}	259.2^{cd}
	150	112.5^{abc}	0.8	12.04^{fg}	4.73	30.4^{fg}	495.6^{cd}	242.6^{def}
0.90	50	62.8^{hi}	1.6	17.40^{a}	5.13	39.6^{a}	625.6^{a}	292.3^{ab}
	75	70.5^{ghi}	1.1	15.83^{bc}	4.99	39.4^{ab}	620.5^{a}	274.3^{bc}
	100	87.3^{efg}	1.1	14.87^{cd}	4.95	37.3^{abcd}	602.9^{ab}	244.3^{de}
	125	102.1^{bcde}	1.0	14.78^{cd}	4.89	36.2^{d}	576.0^{b}	234.8^{def}
	150	107.1^{bcd}	0.9	12.99^{ef}	4.82	32.1^{ef}	515.5^{c}	217.4^{fg}
	LSD$_{(T\leq0.05)}$	16.9	Ns	1.17	ns	2.59	43.95	25.2
RS mean	0.225	94.7^{a}	1.2	14.12^{b}	4.90^{b}	33.9^{c}	545.6^{b}	226.8^{c}
	0.45	90.3^{ab}	1.2	14.68^{b}	4.95^{a}	35.7^{b}	567.7^{ab}	271.3^{a}
	0.90	85.9^{b}	1.1	15.17^{a}	4.96^{a}	36.8^{a}	588.1^{a}	252.6^{b}
	LSD$_{(T\leq0.05)}$	6.5	Ns	0.52	0.06	1.16	23.54	11.3
PD mean	50	59.3^{d}	1.5^{a}	17.0^{a}	5.12^{a}	39.3^{a}	622.2^{a}	279.2^{a}
	75	75.7^{c}	1.3^{ab}	15.71^{b}	5.02^{b}	38.3^{a}	612.9^{a}	263.2^{b}
	100	92.6^{b}	1.1^{bc}	14.49^{c}	4.92^{b}	35.7^{b}	575.1^{b}	248.0^{c}
	125	107.4^{ab}	1.0^{bc}	13.74^{d}	4.83^{cd}	34.0^{c}	534.0^{c}	237.9^{c}
	150	116.4^{a}	0.9^{c}	12.23^{e}	4.77^{d}	30.1^{d}	491.1^{d}	222.9^{d}
	LSD$_{(T\leq0.05)}$	9.8	0.17	0.67	0.08	1.49	30.39	14.5
	CV(%)	16.2	18.4	6.9	2.6	7.5	8.0	8.7

ns = not significant, RS = row spacing, PD = plant density

4.3.3.3 *Ear length*

Analysis of variance indicated that row spacing by plant density interaction resulted in significant differences in ear length (Table 4.3). Ear length decreased with increasing plant density within all row spacings while it increased with widening row spacing from 0.225 to 0.90 m within all plant density levels. The longest ear (17.40 cm) was measured at the row spacing of 0.90 m with the plant density of 50 000 plants ha^{-1} followed by the row spacing of 0.45 m at the same plant density (17.04 cm). The shortest ear length (11.67 cm) was measured from the row spacing of 0.225 m with plant density of 150 000 plants ha^{-1}. Reduction of ear length with increasing plant density might be attributed to a limitation of assimilates as a result of low photosynthetic activity of leaves at higher plant densities due to a lower availability of growth influencing factors. Thus, the amount of assimilates translocated to the developing ear after fertilization, though not measured, could have a negative impact on growth and development of the ear. Saha *et al.* (1994) indicated that ear length was always the longest at low plant densities and tended to decline with increasing plant densities. Dense populations resulted in low photosynthetic efficiency of leaves due to the shading of ears which led to the formation of small ears (Saha *et al*., 1994). Overwhelming evidence by Al-Rudha & Al-Younis (1978), Kamel *et al.* (1983), Tokatlidis *et al*. (2005), Abouziena *et al.* (2008) and Sharif *et al*. (2009) concurred and proved that ear length decreased with increasing plant density.

4.3.3.4 Ear diameter

Analysis of variance indicated that the main treatment of row spacing significantly affected ear diameter (Table 4.3). Ear diameter decreased proportionally as row spacing narrowed from 0.90 to 0.225 m. The thickest ear diameter (4.96 cm) was measured at a row spacing of 0.90 m followed by 0.45 m (4.95 cm) and both were significantly thicker than the ear diameter of the 0.225 m row spacing (4.90 cm). Rate of development is commonly affected by competition among plants and it is related to the interaction between plants of same species growing in close proximity to each other in a field (Nafziger, 2006). One of the more obvious determinants of interplant competition is the proximity of adjoining plants across row spacings. As row spacing narrowed in the current, interplant competition for resources increased and promoted a decrease of ear diameter due to the limitation of dry matter partitioning to the ear. Similarly, significant differences were detected due to the effect of plant density on ear diameter. In general ear diameter decreased as plant density increased. The thickest ear diameter (5.12 cm) was recorded at a plant density of 50 000 plants ha^{-1} followed by a significantly thinner ear diameter of 5.02 cm at a plant density of 75 000 plants ha^{-1}. The smallest ear diameter (4.77 cm) was recorded at a plant density of 150 000 plants ha^{-1}. Increasing plant density had a negative impact on ear diameter primarily due to increased intraplant competition for growth resources as earlier mentioned. As a result of this increased competition and interference among plants, the amount of assimilate partitioned to developing reproductive parts (the ear) would be limited resulting in formation of small sized ears. Similar results were reported by Ogunlella *et al*. (1988) and Konuskam (2000) where low plant densities resulted in greater ear diameter and with increasing plant density the ear diameter growth was impaired and smaller sized ears were obtained. It also has to be noted that the difference in ear diameter as a result of row spacing was 0.6 mm compared to the 3.5 mm of plant density. This once more confirms the consistency in results where all yield components were more responsive to plant density than row spacing.

4.3.3.5 Number of seeds per row

Analysis of variance indicated that the effect of row spacing by plant density interaction resulted in significant differences in the number of seeds per row (Table 4.3). In general, number of seeds per row decreased with increasing plant density within all row spacings. Similarly, the number of seeds per row tended to increase as row spacing widened from 0.225 to 0.90 m. All row spacings at the lowest plant density produced the highest number of seeds per row and vice versa. The greatest number of seeds per row (39.6) was recorded at the row spacing of 0.90 m and the plant density of 50 000 plants ha^{-1} followed by a row spacing of 0.45 m with a plant density of 50 000 plants ha^{-1} (39.5). The least number of seeds per row (27.9) was recorded at a row spacing of 0.225 m with a plant density of 150 000 plants ha^{-1}. Varying combinations of row spacing by plant density resulted in varying number of seeds per row, which might be attributed to variable size of ears as a result of increased competition for assimilates. As result of this increased competition, insufficient amounts of assimilates could be partitioned to the developing ear during grain filling. These results are supported by the findings of Zhang *et al*. (2006) and Shakarami & Rafiee (2009) who reported that the highest number of seeds per row of the maize ear was recorded at lower plant densities as compared to that of higher plant densities.

4.3.3.6 Number of seeds per ear

Significant differences were detected due to the effect of row spacing by plant density interaction on the number of seeds per ear (Table 4.3). Seed number is the yield component accounting for most of the differences in grain yield. Number of seeds per ear decreased within all row spacings as plant density increased. Conversely, number of seeds per ear increased as row spacing increased from 0.225 to 0.90 m within plant densities. The greatest number of seeds per ear (625.6) was recorded at a row spacing of 0.90 m with a plant density of 50 000 plants ha^{-1} and was closely followed by a row spacing of 0.45 m at the same plant density (621.7). The least number of seeds per ear (462.3) was recorded at a row spacing of 0.225 m with a plant density of 150 000 plants ha^{-1}. The interaction of all row spacings by plant densities of 50 000 and 75 000 plants ha^{-1} had a negligible effect on the number of seeds per ear illustrating the absence of competition between plants. Therefore, all row spacings at the lowest plant density produced the greater number of seeds per ear without any significant difference. However, interaction of nearly all row spacings at plant densities of 100 000, 125 000 and 150 000 plants ha^{-1} modified the number of seeds per ear which was an indication of the existence of plant interference and competition for growth resources. Increasing plant density led to a reduction in number of seeds per ear presumably due to increased interplant competition and shading of lower leaves by upper leaves so that light could not penetrate throughout and distribute to all leaves for efficient photosynthetic activity. Shakarami & Rafiee (2009), using three plant densities *viz*: 70 000, 100 000 and 130 000 plants ha^{-1}, reported the least number of seeds per plant at the highest plant density. Zinselmeier *et al*. (2000) reported that high plant densities increased ear leaf shading, which reduced carbon exchange rates and resulted in a reduction of number of seeds per ear. The same results were also reported by Karim *et al*. (1983), Tianu *et al*. (1983), Sharma & Adamu (1984), Singh & Srivastava (1991) and Roy & Biswas (1992) concert with the findings of this study.

4.3.3.7 Thousand seed weight (TSW)

Analysis of variance revealed that the effect of row spacing by plant density resulted in significant differences on TSW (Table 4.3). It was noticed that TSW tended to decrease as plant density increased within all row spacings. The greatest TSW (306.9 g) was recorded at a row spacing of 0.45 m with 50 000 plants ha^{-1} followed by 0.90 m at a plant density of 50 000 plants ha^{-1} (292.3 g). The smallest TSW (208.6 g) was recorded at the row spacing of 0.225 m and the plant density of 150 000 plants ha^{-1}. Row spacing 0.45 m exhibited superiority in TSW at all levels of plant density which was followed by a row width of 0.90 m. A row spacing of 0.225 m showed the smallest TSW performance at all plant density levels. Reduction of row spacing accompanied with increasing plant density negatively impacted on TSW most likely due to the intra and interplant competition. This increased competition for resources became severe, which in turn affected grain filling. High plant densities place high demands upon available soil water and likely caused a more rapid decline in the water potential of both the soil and plant leading to deficient supplies thus restricting metabolic processes involved in seed filling (Slatyer, 1969). This insufficient supply of water could have been the result of both interplant competition and irrigation scheduling. It has to be noted that irrigation was calibrated to a yield potential of 10 t ha^{-1} and a reference plant density of 100 000 plants ha^{-1}. The average yield (9938 kg ha^{-1}) was in line with the yield potential set for these trials, but plant density exceeded the plant population density of 100 000 plants ha^{-1} by 25 and 50%. Therefore, inter plant competition resulted in the reduction of TSW, but other yield components were not excluded as previously highlighted. Zamir *et al*. (2010) reported that a reduction of TSW with increasing plant density was due to unfavourable growing conditions, such as less aeration, light penetration at high plant densities. Arif *et al*. (2010) indicated that TSW decreased with increasing plant density and reported the greatest TSW at the lowest plant density. This finding is also similar to that reported by Poneleteit & Egli (1979), Zamir *et al*. (1999), Sangoi *et al*. (2002), Bruns & Abbas (2003) and Maddonni *et al*. (2006) who also indicated that an increase in plant density decreased the effective grain filling period and resulted in the production of smaller seeds.

4.3.4 Yield

4.3.4.1 Biomass

Combined analysis of variance over seasons revealed that row spacing by plant density interaction resulted in significant differences in biomass (Table 4.4). With the exception of row spacing by plant density combinations of 0.45 m by 100 000 (21675 kg ha^{-1}) and 125 000 plants ha^{-1} (21264 kg ha^{-1}), the greatest biomass production was found at a row spacing of 0.225 m by plant densities 75 000 to 150 000 plants ha^{-1}. The single greatest biomass (22667 kg^{-1}) was recorded at a row spacing by plant density of 0.225 m by 100 000 plants ha^{-1}. For all row spacings biomass exhibited a curvilinear relation with plant density being at a 100 000 plants ha^{-1}. After attaining its peak for all rows at a plant density of 100 000 plants ha^{-1}, biomass tended to decline with further increase in plant density (Figure 4.1). This clearly indicated that plant densities beyond this optimum level (100 000 plants ha^{-1}) led to depletion of available resources and limited dry matter accumulation.

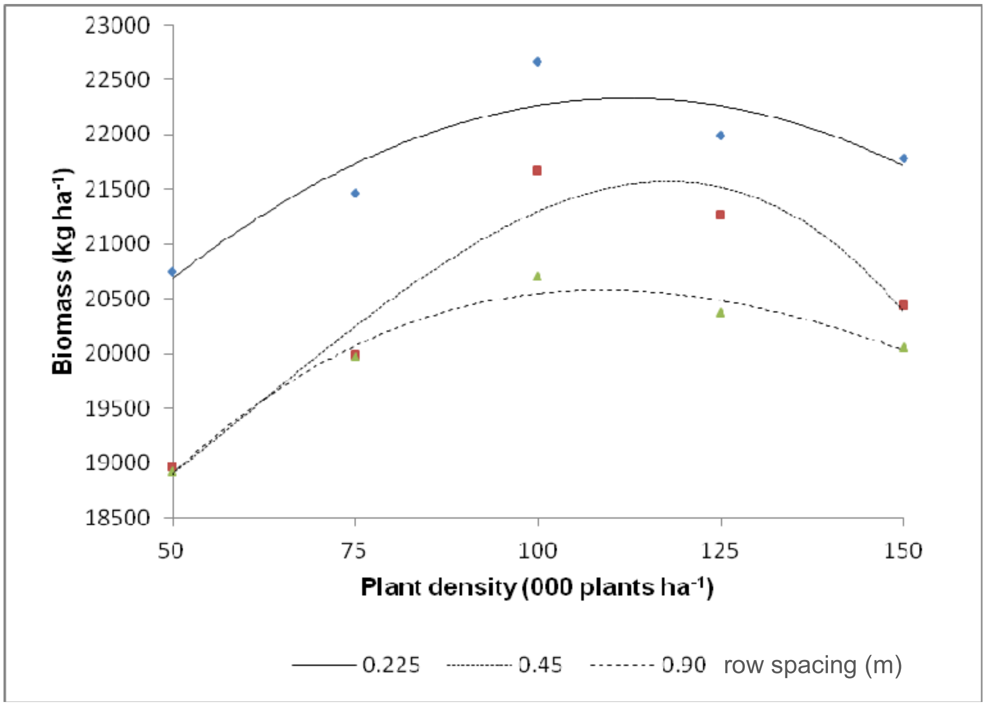

Figure 4.1 Biomass as affected by row spacing and plant density.

Biomass is a function of numerous interacting environmental and genetic factors and its production is directly related to potential growth and development factors such as solar radiation, water supply, availability of mineral nutrients and crop management practices. Depletion of these sustaining factors will figure forth in low biological yield on an individual plant basis (Donald, 1963; Daughty *et al.*, 1983). Hashemi *et al*. (2005) found similar decreasing trends in biomass with increasing plant densities and reported that the greatest biomass yield was obtained at a plant density of 100 000 plants ha^{-1}. According to Van Averbeke and Marais (1992) the above-ground biomass production of maize did not decrease at plant densities in excess of the critical density but levelled off. Their results also indicated that the above-ground biomass levelled off at plant densities of 80 000 to 100 000 plants ha^{-1} with full irrigation. On the other hand, reduction of biomass for plant densities below 100 000 plants ha^{-1} might be ascribed to a lesser number of plants per unit area and underutilization of available resources.

A reduction in row spacing from 0.90 to 0.45 m at an optimum plant density (100 000 plants ha^{-1}) resulted in a gain of 4.7% biomass whereas as further reduction from 0.45 to 0.225 m showed a further gain of 9.5%. Unfortunately this was not significant. From a view point of total biomass, the row spacing of 0.225 m performed superior at all plant density levels. This illustrated that subjecting plants to reduced row spacing increased the ability of plants for capturing resources which was reflected as evident in their increased biomass production. Bullock *et al*. (1998) proved that narrow row spacings made more efficient use of available light and shaded the soil surface to a greater degree during the early part of the growing season while the soil is still moist and therefore, narrow row spacings are more effective in producing biomass. This does not necessary mean a higher yielding ability, which will be dealt with in the following section. It is thus difficult from the above to conclude which treatment combination (0.45 m x 100 000 or 0.90 m x 100 000 plants ha^{-1}) were to be the most obvious choice for maize production.

4.3.4.2 Grain yield

Combined analysis of variance over seasons revealed significant differences due to the effect of row spacing by plant density interaction on grain yield (Table 4.4). The highest grain yield (12554 kg ha^{-1}) was recorded at the row spacing of 0.45 m with the plant density at 100 000 plants ha^{-1} followed by a row spacing of 0.90 m at the same plant density (11350 kg ha^{-1}). These did not differ significantly but was significantly higher than the lowest grain yield (7250 kg ha^{-1}) recorded at the row spacing of 0.225 m with a plant density of 50 000 plants ha^{-1}. Grain yield followed a curvilinear response to plant density levels across all row spacings with the maximum yield between 75 000 and 100 000 plants ha^{-1} (Figure 4.2). Thus, grain yield was increased for all row spacings with increasing plant densities up to 100 000 plants ha^{-1} followed by a decline with further increases in plant density above this optimum plant density. These results are in concert with literature where a 100 000 plants ha^{-1} resulted in the highest yields and as soon as plant densities were raised above this point a decline in yield occurred (Shakarami & Rafiee, 2009; Gozubenli, 2010). Since the interaction of row spacing by plant density significantly influenced yield, it is difficult to refer to a specific row spacing/width to be the preferred. Biomass data clearly showed that row spacings of either 0.45 or 0.90 m resulted in maximum yields. A row spacing of 0.225 m is definitely not preferred for grain production (Figure 4.2), but could be considered when biomass (e.g. silage) is the main aim of production (Figure 4.1). Therefore, row spacings of 0.45 and 0.90 m will be dealt with in more detail.

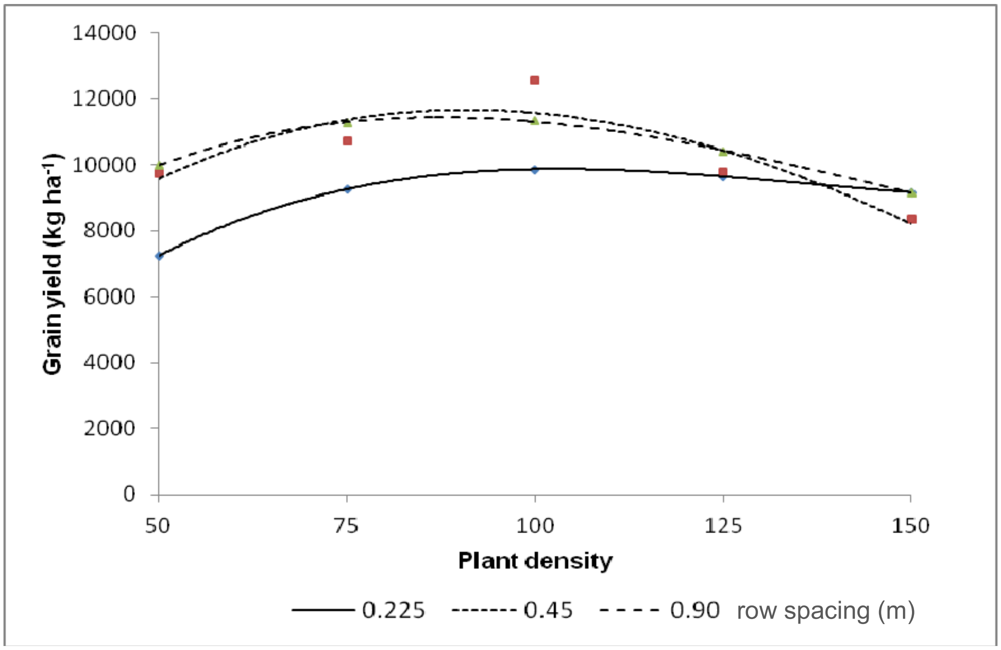

Figure 4.2 Mean grain yield as affected by row spacing and plant densities.

From the above discussion it is clear that 0.45 m by 100 000 plants ha^{-1} would be optimal for producing maize. Unfortunately yield only cannot be considered, but practical applications and risks also have to be considered. From a practical viewpoint the majority of irrigated maize is planted in 0.90 m rows at varying plant densities. Very few if any maize is planted at 0.45 m, but some producers do plant at 0.76 m to accommodate high plant densities. Regarding risk, data showed that although the yield ability of 0.90 m by 100 000 plants ha^{-1} was slightly less (9.6% - non-significant) compared to that of 0.45 m by 100 000 plants ha^{-1}, the loss in yield when plant densities were 25% less or more than the optimum of 100 000 plants ha^{-1} was far greater at the 0.45 m row spacing than that of the 0.90 m row spacing. The mentioned reduction in yield between 0.45 and 0.90 m row spacings also concerted with findings of Barbieri *et al.* (2000).

Crop yield is a function of a number of factors and processes such as amount of light intercepted by the canopy, metabolic efficiency of plants and the translocation efficiency of photosynthates from leaves to economic parts. These processes are affected by spatial arrangement of row spacing and plant density. Differences in plant densities in of this study caused a profound impact on maize grain yield by affecting yield and yield components. Plant density exerts a strong influence on maize growth and yield as a result of the competitive ability of plants at variable densities (Singh & Chaudhary, 2008). Plant density also affects grain yield of maize by influencing the agronomic traits, such as number of seeds per ear, seed weight, number of ears per plant, spikelet differentiation, spikelet fertilization and seed dry weight (Sangoi, 2000). Balanced growth and development of plants need an optimum plant density because optimum density enable plants' efficient utilization of available nutrients, soil water and better light interception coupled with other growth factors. Narrow row spacing coupled with increasing plant density above an optimum level intensifies competition for solar radiation, soil nutrients and soil moisture.

One of the main causes of yield reduction at high plant densities is an increased formation of barren plants. Lemcoff & Loomis (1994) indicated that severe competition among plants in higher density resulted in a limitation of nitrogen and carbon supply with consequent emergence of barren plants and a decrease in the number of seeds per plant and seed size. The emergence of barren plants at high plant densities could result in a delay in ear differentiation and growth of ear premordia (Jacobs & Pearson, 1991). Moreover, Naeem (1998), Mohsan (1999), Maddoni *et al*. (2001) and Ma *et al.* (2007) reported that increasing plant density above a certain optimum increased plant sterility and initiated the formation of barren plants. On the other hand, plant density lower than optimum exhibited lower grain yield per unit area which might attributed to a lower number of plants per unit area. Reduction of plant density below an optimum resulted in a negative impact on grain yield primarily due to underutilization of resources. The same impact was reported by Hashemi-Dezfouli & Herbert (1992) and Echarte *et al*. (2000) that plant density below the optimum led to decreased use efficiency of available resources. However, this finding is in contrast to results of Maddonni *et al.* (2006) who indicated that maize grain yield was stable in response to changes in plant densities. The specific range op plant density has to be considered when comparing different findings.

An optimum plant density exists for all crop species and it varies with cultivar and prevailing environmental factors. Thus, alteration of plant density above or below an optimum plant density results in a negative impact on grain yield presumably due to severe competition or underutilization of resources, respectively. The differences in maize yield in response to variable row spacing and plant density levels necessitates for careful adjustment of their combinations for modern ultra-fast maize hybrids to prevailing environmental conditions and input levels. The results of this study suggested that the optimum row spacing and plant density level for an ultra-fast maize hybrid was 0.45 to 0.9 m row spacing with a plant density of 100 000 plants ha^{-1} under irrigation. This specific treatment combination enables maize leaves to capture enough/sufficient sunlight and other resources, which subsequently was converted into more vegetative growth resulting in higher grain yield due to a high metabolic efficiency of the maize hybrid under consideration.

Table 4.4 Effect of row spacing and plant density on yield of maize

RS (m)	**PD (x 000 ha^{-1})**	**Biomass (kg ha^{-1})**	**Grain yield (kg ha^{-1})**	**Harvest index**
0.225	50	20748^{abc}	7250^{g}	0.35^{f}
	75	21463^{ab}	9260^{defg}	0.43^{ed}
	100	22667^{a}	9859^{bcde}	0.44^{cd}
	125	21990^{ab}	9644^{cde}	0.43^{ed}
	150	21780^{ab}	9159^{ef}	0.42^{cde}
0.45	50	18963^{ef}	9738^{bcde}	0.51^{b}
	75	19994^{bcd}	10707^{b}	0.53^{ab}
	100	21675^{ab}	12554^{a}	0.58^{a}
	125	21264^{ab}	9775^{bcde}	0.46^{bc}
	150	20444^{bcd}	8363^{ef}	0.41^{de}
0.90	50	18925^{f}	9991^{bc}	0.53^{cd}
	75	19966^{de}	11264^{bcd}	0.53^{ab}
	100	20702^{abc}	11350^{ab}	0.54^{ab}
	125	20379^{bcd}	10406^{bcd}	0.51^{abcd}
	150	20054^{bcd}	9155^{fg}	0.46^{bc}
	$LSD_{(T \leq 0.05)}$	2056	1234	0.06
RS mean	0.225	21655^{a}	9024^{b}	0.41^{b}
	0.45	20468^{bc}	10685^{a}	0.52^{a}
	0.90	20005^{c}	10355^{a}	0.51^{ab}
	$LSD_{(T \leq 0.05)}$	919	548	0.02
PD mean	50	19545^{c}	9629^{c}	0.46
	75	20474^{bc}	10544^{b}	0.50^{a}
	100	21681^{a}	11321^{a}	0.51^{a}
	125	21078^{a}	9942^{bc}	0.46^{ab}
	150	20760^{b}	8256_{d}	0.45^{ab}
	$LSD_{(T \leq 0.05)}$	1187	708	0.03
	CV (%)	9.1	10.81	11.05

RS = row spacing, PD = plant density

4.3.3.3 Harvest index (HI)

Analysis of variance over seasons revealed that row spacing by plant density interaction resulted in significant differences in HI (Table 4.4). Generally, HI showed an increasing tendency within all row spacings with an increase in plant density up to 100 000 plants ha^{-1}. The HI declined with a further increase in plant density at 125 000 plant ha^{-1} but this was not significant. The highest HI (0.58) was recorded at a row spacing of 0.45 m with a plant density of 100 000 plants ha^{-1} followed by a row spacing of 0.90 m at a plant density of 100 000 plants ha^{-1} (0.54). The lowest HI (0.34) was observed at a row spacing of 0.225 m with a plant density of 150 000 plants ha^{-1}.

Harvest index is the physiological efficiency and ability of a crop for converting the total dry matter into economic yield (Sinclair, 1998). Hence, harvest index reflects the proportion of assimilate distribution between economic and total biomass yield (Donald & Hamblin, 1976). The HI values were closely associated with the amount of grain yield on per treatment basis. Sharif *et al.* (2009) by using three maize hybrids at three plant densities (80 000, 100 000 and 120 000 plants ha^{-1}) demonstrated that the highest HI value was 0.34 at a plant density of 100 000 plants ha^{-1}. The difference in HI between the results of Sharif *et al.* (2009) and this study may be attributed to variability in cultivar, environmental factors and crop management practices.

4.4 Summary and Conclusion

Row spacing, plant density and its interaction influenced yield and yield components of maize significantly. Prolificacy of plants decreased with an increase in plant density while emergence of barren plants was favoured by narrow row spacings coupled with high plant densities. The highest number of seeds per row, seeds per ear and the longest ear length were recorded at a row spacing of 0.90 m with a plant density of 50 000 plants ha^{-1}. The highest biomass was observed at a row spacing of 0.225 m with a plant density of 100 000 plants ha^{-1} while grain yield and HI were at their highest at a row spacing of 0.45 m with a plant density of 100 000 plants ha^{-1}. These results proved that the optimum row spacing and plant density level for the ultra-fast maize hybrid under consideration is a row spacing between 0.45 and 0.90 m at a plant density of 100 000 plants ha^{-1}.

CHAPTER 5

PHENOLOICAL RESPONSE OF MAIZE TO ROW SPACING AND PLANT DENSITY

5.1 Introduction

The entire maize development period includes all days from sowing date through emergence, elongation, booting, tasseling, silking, forming seed and maturing. This entire maize development period varies with sowing date, temperature, moisture and crop management such as row spacing and plant density (Liangzhi *et al.,* 1992). Phenological development determines the period of establishment, vegetative and reproductive growth of the maize plant. Spatial arrangements of row spacing and plant density are considered as the most important factors affecting maize phenology, such as days to tasseling, silking and maturity (Hassan & Khaliq, 2008).

In general phenology deals with the qualitative and quantitative aspects and description of a plant's life cycle from seed to seed. A qualitative aspect of phenology includes morphological development and the partitioning of the life cycle into distinct stages of development, such as seedling emergence, flowering and physiological maturity. On the other hand, a quantitative aspect of development encompasses rate of development and the duration of the life cycle. Phenological records of the dates on which seasonal phenomena occur possibly provide important events and information on how climate affects ecosystems over time. Thus, phenological development of most plants is strongly related to the accumulation of heat or temperature units of maximum or base temperatures. Here base and maximum temperatures refer to a threshold temperature below or above which the occurrence of growth is very little or negligible. These lower and upper threshold temperatures vary with plant species. For instance, the rate of development of maize from planting to anthesis is a function of temperature rather than photosynthesis. Both photosynthesis and development are very slow at temperatures of 10°C and both reach their maximum rates at 30-33°C (Duncan & Hesketh, 1968; Brouwer *et al.,* 1970).

Plant density influences synchrony of flowering and hence grain yield (Hall *et al*., 1982). Increasing plant density results in interplant competition that affects vegetative and reproductive growth of crop plants as a result of a higher plant density water deficits may occur and accelerate reproductive growth in many plants (Tetio-Kagho & Gardner, 1988b). Vega *et al.* (2000) found that there is a direct effect of increasing plant density to enhance interplant variability in several phenotypic traits (eg. biomass, plant height, ear height, leaf area, antheis-silking interval and kernel number). Increasing plant density beyond optimum levels under specific conditions initiates the emergence of ear barrenness resulting in ears without kernels. Daynard & Muldoon (1983) reported that a reduction in the number of kernels per ear resulted from fewer flower initials being formed prior to flowering, poor pollination due to asynchrony of the tasseling and silk, and abortion of kernels after fertilization. They suggested that competition for water, light and nutrients are considered to be determinant factors on optimum plant densities in the maize growing environment.

High plant densities affect the interval for pollen shedding and silk emergence. The time from planting to silking increased from 84 to 95 days as plant density increased from 50 000 to 200 000 plants ha^{-1}. It was also reported that the time gap between pollen shedding and silking increased with an increase in plant density from almost zero to nine days. This in combination with the fact that plants not shedding pollen and not silking were observed only at the higher plant densities (150 000 to 200 000 plants ha^{-1}) and contributed to increased ear barrenness (Tokatlids & Koutroubas, 2004). Therefore, plant density is one of the most important factors affecting crop phenology (days to tasseling, silking and maturity). A good understanding of the phenology of a crop is essential in physiological and agronomic studies of the crop, because seasonal dry matter accumulation is a function of the duration of the life cycle of annual crops like maize. Hence, this study was initiated with the objective of evaluating the effect of row spacing and plant density on the phenological development of an ultra-fast maize hybrid under irrigation.

5.2 Materials and methods

5.2.1 Data collection

Regarding the experimental site, soil physical and chemical properties, agrometeorological data, summary of treatment combinations, agronomic practices and statistical analysis used are described in Chapter 3 in section 3.2.1, 3.2.2, 3.2.3 and 3.2.7, respectively. The phenological indicators recorded were growing degree days, days to anthesis, days to silking, anthesis-silking intervals and days to physiological maturity. Growing season was recorded when 50% of plants shed pollen per plot. From this observation and temperature data the heat units required to reach that growth stage using the base temperature for maize being 10^{o}C (Cross & Zuber, 1972) was calculated according to the formula Gilomere & Rogers (1958) as:

$$GDD = \sum \frac{[(Tmax+Tmin)]}{2} - Tbase \qquad 5.1$$

Where:

T_{max} = Daily maximum air temperature
T_{min} = Daily minimum air temperature
T_{base} = Base temperature

Days to anthesis (AD) and silking (SD) were measured as number of days after planting to when 50% plants in the plot shed pollen and extruded silks, respectively. Anthesis-silking intervals were calculated as: ASI = SD – AD. Physiological maturity is the completion of the reproductive period at the point which no further increase in dry matter weight takes place. It was recorded when 50% of plants per plot exhibit complete loss of green colour from ear sheaths (Ritchie & Hanway, 1992).

5.3 Results and discussion

5.3.1 Summary of analysis of variance

A summary on the combined analysis of variance over seasons showing the effect of treatment factors on crop phenological parameters and heat units are depicted in Table 5.1. Inspection of the result indicated with the exception of days to physiological maturity that all other indicators were significantly affected by either row spacing or plant density as main tereatments.

Table 5.1 Summary of analysis of variance indicating the effect of treatment factors on phenological parameters

Phenological parameters	**Treatment factors**		
	RS	**PD**	**RS x PD**
Days to anthesis	*	*	ns
Days to silking	*	*	ns
Anthesis-silking interval	*	*	ns
Days to physiological maturity	*	*	*
Heat units	*	*	ns

* = Significant at 5% probability level, ns = not significant
RS = row spacing, PD = plant density

5.3.2 Days to anthesis

Analysis of variance indicated that row spacing resulted in significant differences in days to anthesis (Table 5.1). Anthesis is the period during which a flower is fully open and functional. For maize, it is time when the anthers are ready for pollen shed. Anthesis is also a signal for the onset of the reproductive growth phase. Increasing row spacing from 0.225 to 0.90 m prolonged days to anthesis from 56.8 to 58.1 days after planting (Table 5.2). Thus, plants cultivated with narrow rows reached anthesis slightly earlier than plants cultivated in wider rows. This illustrated that narrow row spacing enforced earlier tasseling which, might be attributed to intense competition among the plants for resources, such as light interception.

Significant differences were also detected due to the effect of plant density on days to anthesis (Table 5.2). In general days to anthesis were shortened as plant density increased. Plants reached anthesis earlier at high plant densities (PD > 125 000 plants ha^{-1}) than at low plant densities (50 000 plants ha^{-1}). A difference of 2.4 days was recorded between the highest and lowest plant densities.

Basically, as the number of plants in a planting pattern increases the distance between plants decrease and competition among individual plants increases (Duncan, 1984). In this case higher plant density increased intraplant competition for growth influencing factors. During the occurrence of such density stress conditions, the available growth factors, such as soil water and nutrients, become depleted and limit the growth and development of plants. Plants therefore cease vegetative growth and initiate reproductive growth in an attempt to complete their life cycle. On the other hand, at low plant densities intra-plant competition is minimal where all plants have equal access to growth resources without severe limitations. Rengel & Graham (1995) also at high plant densities maize reached anthesis earlier as a result of stress imposed by a too dense stand. These results all concert with the findings of Azam *et al*. (2007), who reported that at low plant densities days to anthesis were prolonged as compared to high plant densities. Conversely, Gozubenli & Konuskan (2010) reported that plant densities ranged from 60 000 to 102 000 plants ha^{-1} did not show significant differences on days to anthesis in popcorn. Aforementioned results are all in contrast with the findings of Hashemi-Dezfouli & Herbert (1992), Sangoi *et al*. (2002), Tokatlidis *et al*. (2005) and Nasser & Eli-Gizay (2009) who reported that increasing plant density delayed anthesis of the maize plant. These contradictions have to be considered with the background of genetic material as well as environmental conditions.

5.3.3 Days to silking

Analysis of variance indicated that row spacing resulted in significant differences on days to silking (Table 5.1). Time taken to extrude 50% of silks per plot as affected by row spacing, ranged from 61.0 to 61.7 days after planting for 0.225 to 0.9 m, respectively. The longest period to silking (61.7 days) was recorded at a row spacing of 0.90 m followed by 0.45 m with 61.3 days to silking (Table 5.2). The shortest period to silking (61.1 days) was recorded at a row spacing of 0.225 m. Days to silking followed the same trend as that of anthesis (section 5.3.2) where wider rows prolonged the number of days to silking while narrow row spacing shortened it.

Plant density significantly affected days to silking (Table 5.2). The longest period to silking was observed at a plant density of 50 000 (62.2 days) and 75 000 (61.6 days) plants ha^{-1}. Once more the highest plant density (150 000 plants ha^{-}1) recorded the shortest period (60.7 days) to silking. Dense planting might have enhanced the rate of plant development and this could be ascribed to the depletion of resources due to more competition and interference within plants or poor light interception. This result is consistent with findings of Azam *et al*. (2007) who reported that low plant densities prolonged days to silking. Similarly to days to antheis, these results contradict the results reported by other researchers. Hashemi-Dzefouli & Herbert (1992) reported that the time for 50% silking was delayed by up to five days as plant density increased to 70 000 plants ha^{-1} and under the higher plant densities (120 000 plants ha^{-1}) about 10% of the plant did not show any silk 7 days after anthesis. Edmeades *et al*. (1993) pointed out two reasons that caused a delay of silking in higher plant densities. The first reason was due to hierarchical pattern in reproductive development in which tassel growth dominates ear growth (apical dominance) and the second was an assimilate shortage in which case insufficient translocation of assimilates to the ear at high plant densities occurs. Sato *et al*. (1978), Sangoi *et al.* (2002), Tokatlidis *et al*. (2005) and Nasser & Eli-Gizay (2009) also reported that increasing plant density relatively delayed silking date of maize plants.

5.3.4 Anthesis-silking interval

Analysis of variance revealed that row spacing significantly affected anthesis-silking interval (Table 5.1). Anthesis-silking interval (ASI) as affected by row spacing ranged from 3.5 to 4.1 days. The longest anthesisi-silking interval of 4.1 days was recorded at row spacing of 0.225 m followed by 0.45 m with an anthesis-silking interval of 3.8 days. The shortest anthesis-silking interval (3.5 days) was observed at a row spacing of 0.90 m (Table 5.2).

Analysis of variance revealed significant differences in the anthesis-silking interval on account of plant density (Table 5.2). The gap between anthesis and silking was delayed with increasing plant density levels. The longest anthesis-silking interval recorded (4.4 days) was at the plant density of 150 000 plants ha^{-1} which was followed by 125 000 plants ha^{-1} with an anthesis-silking interval of 3.9 days. The anthesis-silking interval of 50 000 (3.2 days) and 75 000 plants ha^{-1} (3.7 days) were both significantly less than that of plant densities more or equal to 100 000 plants ha^{-1}. This clearly indicated that plants cultivated at high plant densities increased the anthesis-silking interval. Increased anthesis-silking intervals at high plant densities can be attributed to a lack of balanced development between the male (tassel) and female (ear) inflorescence. At high plant densities plants develop a larger tassel that may enforce apical dominance over ear development resulting in delayed silk development or the total absence thereof with corresponding barren plants. Tokatlidis & Koutroubas (2004) reported that plant density affected the required time interval for pollen shedding and silk emergence. They investigated increasing plant densities from 150 000 to 200 000 plants ha^{-1}. The time gap between anthesis and silking increased leading to the occurrence of plants neither setting anther nor silking, contributing to barrenness. This result conforms to findings of Ipsilantis & Vafias (2005) who reported an increased anthesis-silking interval with increasing plant densities.

5.3.5 Days to physiological maturity

Analysis of variance over seasons showed that row spacing by plant density interaction had significant effects on days to physiological maturity of plants (Table 5.1 and 5.2). In general, plants took 110 to 128 days after planting to lose 50% of its green colour from the ear sheaths. The largest number of days to physiological maturity (128 days) was recorded at the row spacing of 0.90 m with a plant density of 50 000 plants ha^{-1}. The least number of days to physiological maturity (110 days) was observed at the row spacing of 0.225 m with the plant density of 150 000 plants ha^{-1}. Therefore, a difference of 18 days (± 2.5 weeks) was recorded between the highest longest and least number of days to physiological maturity. Generally, plant densities of 75 000 plants ha^{-1} and less at all row spacings resulted in a longer growing season. This result clearly showed that a combination of narrow row spacing with high plant density aggravated inter and intraplant competition for growth influencing factors, such as water, light and mineral nutrients. Such stress caused by greater than optimal plant densities triggered plants to mature earlier. Tollenaar & Daynard (1982) and Tollenaar (1992) also reported that high plant densities (PD ≥ 100 000 plant ha^{-1}) promoted leaf senescence and then shortened the vegetative growth phase of maize plant due to assimilate starvation. Borras *et al. (*2003) also reported that the period to physiological maturity shortened when light quality and quantity at the lowermost leaf strata was reduced with increased plant density. Investigators reported variable observations with respect to the impact of plant density on days to physiological maturity of maize. Kgasago (2006) reported that variations in plant density did not cause significant differences in days to physiological maturity. Contradicting to the above Hashemi-Dzefouli & Herbert (1992), Sangoi *et al.* (2002), Tokatlidis & Koutroubas (2004), Ogunlella *et al.* (2005) and Moriri *et al*. (2010) all reported that an increase in plant density delayed the maturity date of maize plant. The supporting as well as contradictory findings might be attributed to variation in maize cultivars, soil fertility, planting time, climatic factors, management practices and the environment where maize was grown.

Table 5.2 Effect of row spacing and plant density on days to anthesis, silking, anthesis-silking interval (ASI), physiological maturity and heat units

RS (m)	**PD (x 000 ha^{-1})**	**Days to anthesis**	**Days to silking**	**ASI**	**Days to physiological maturity**	**Heat units**
0.225	50	58.8	62.0	3.2	123.0^{b}	756.6
	75	56.6	61.6	5.0	123.0^{b}	750.1
	100	56.1	60.8	4.7	111.3^{e}	737.9
	125	56.5	60.5	4.0	110.0^{e}	735.1
	150	56.4	60.5	4.1	110.0^{e}	739.6
0.45	50	58.5	62.1	3.6	123.0^{b}	756.3
	75	58.2	61.8	3.6	119.0^{c}	753.1
	100	57.0	61.0	4.0	115.3^{d}	747.3
	125	57.2	60.8	3.6	115.3^{d}	753.7
	150	56.5	60.8	4.3	112.0d^{e}	741.9
0.90	50	59.7	62.8	2.8	128.0^{a}	762.4
	75	57.3	61.6	4.3	125.0^{b}	763.5
	100	58.3	61.8	3.5	122.7^{b}	754.2
	125	58.0	61.8	3.8	119.0^{c}	758.5
	150	57.0	61.8	4.0	115.3^{cd}	748.7
	$\text{LSD}_{(T\leq0.05)}$	ns	ns	ns	2.6	ns
RS mean	0.225	56.8^{b}	61.0^{b}	4.1^{a}	115.5^{b}	743.9^{b}
	0.45	57.4^{ab}	61.3^{ab}	3.8^{ab}	116.9^{b}	750.5^{ab}
	0.90	58.1^{a}	61.7^{a}	3.5^{b}	122.0^{a}	757.5^{a}
	$\text{LSD}_{(T\leq0.05)}$	0.6	0.6	0.4	1.2	8.7
PD mean	50	59.0^{a}	62.2^{a}	3.2^{c}	124.7^{a}	758.4^{a}
	75	57.4^{ab}	61.6^{ab}	3.7^{bc}	122.3^{b}	755.8^{ab}
	100	57.2^{abc}	61.2^{abc}	3.9^{ab}	116.4^{c}	749.8^{abc}
	125	57.1^{bc}	61.0^{bc}	3.9^{ab}	114.8^{c}	747.0^{bc}
	150	56.6^{c}	60.6^{c}	4.4^{a}	112.4^{d}	741.9^{c}
	$\text{LSD}_{(T\leq0.05)}$	0.8	0.8	0.7	1.5	11.3
	CV (%)	2.18	2.37	35.32	1.33	2.26

* = Significant at 5% probability level, RS = row spacing, PD = plant density, ns = not significant

5.3.6 Heat units

Analysis of variance revealed that row spacing resulted in significant differences in the maize heat unit (growing degree days) requirement (Table 5.1). The amount of heat units required by plants increased as row spacing widened from 0.225 to 0.90 m (Figure 5.1 and Table 5.2). The heat unit requirement of plants as affected by row spacing ranged from 743.9 to 764.5. More heat units were required at the row spacing of 0.90 m (757.5) than 0.45 m (750.5). The lowest heat unit requirement was at the row spacing of 0.225 m (743.9).

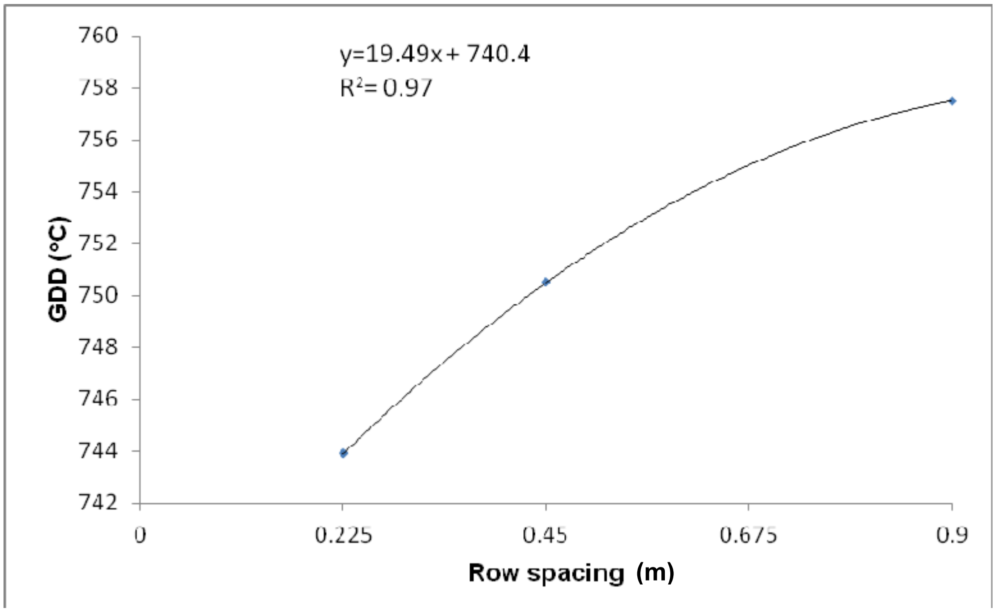

Figure 5.1 Heat unit (GDD) requirement of maize as affected by row spacing

Growth and development of maize from planting to physiological maturity are strongly dependent on temperature. The amount of heat units required by plants was associated with length of growing period of the vegetative phase. The longer the vegetative growth the more heat units are required. Thus, wider row spacing relatively prolonged the length of growing season where plants required more heat units and vice versa.

Significant differences were observed due to the effect of plant density on heat unit of plants (Table 5.2). With increasing plant density from 50 000 to 150 000 plants ha^{-1}, the heat unit requirement of 50% of the plants per plot to shed pollen tended to decline (Figure 5.2). The greatest heat units were required by plants to shed 50% of pollen per plot at plant density of 50 000 and followed by 75 000 plants ha^{-1}. The lowest heat units were required at plant density of 150 000 plants ha^{-1}. This illustrated that the heat unit requirement of plants decreased with increasing plant density. Reduction of heat unit requirement with increasing plant density was mainly due to the shorter vegetative growth period at higher plant density and vice versa.

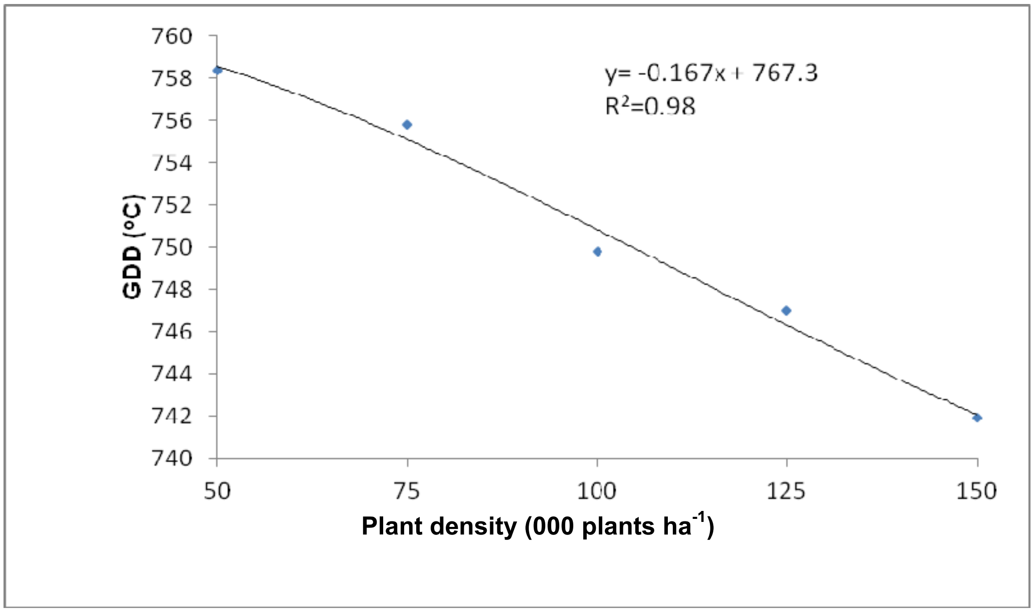

Figure 5.2 Heat unit (GDD) requirement of maize as affected by plant density

5.3.7 Correlation between phenological parameters and grain yield

The correlation of phenological indicators with grain yield, irrespective of row spacing and plant density, is presented in Table 5.3. The association of days to anthesis, silking, anthesis-silking interval and days to physiological maturity with grain yield was not significant ($P \leq 0.05$). This suggests that the effect of phenological indicators on grain yield should take into account their association with other yield components, such as thousand seed weight, number of seeds per row and ear. Gissa (2008) recorded a weak negative correlation of days to anthesis ($r = -0.05$) and anthesis-silking interval ($r = -0.27$) with grain yield and grain protein content of maize inbred lines. Noor *et al.* (2010) and Yusuf (2010) also reported a weak and non-significant correlation of days to anthesis ($r = 0.09$), silking ($r = 0.03$) and anthesis-silking interval ($r = -0.06$) with maize grain yield, supporting the current findings. The most recent report that supports the above is that of Iqbal *et al*. (2011) who reported non-significant negative correlations of days to silking and physiological maturity with grain yield by using four white flint maize inbred lines, with r values that ranged between -0.07 to -0.53 and -0.05 to -0.43 for days to silking and physiological maturity, respectively. On the other hand, Beck *et al.* (1997) indicated that phenological traits correlated strongly with grain yield under stress conditions, such as high plant density and low soil fertility as compared to non-stressed conditions. The inconsistent correlation that may occur of phenological traits with grain yield might be attributed to differences in cultivar and environment.

Table 5.3 Correlation of phenological parameters with grain yield

Parameter	Grain yield
Days to antheis	0.03^{ns}
Days to silking	0.02^{ns}
Athesis silking interval	0.04^{ns}
Days to physiological maturity	0.04^{ns}

ns= not significant

5.4 Summary and Conclusion

Row spacing, plant density and their interactions resulted in modifications of some of the phenolgical indicators of the maize. Days to anthesis and silking were relatively prolonged at wider row spacings as compared to narrow rows while ASI shortened with wider rows. Similarly, plants required more heat units with wide row spacings than narrow row spacings to reach 50% pollen shedding per plot. At low plant densities, plants took relatively more days to anthesis and silking whereas anthesis-silking intervals was relatively longer at the highest plant density. In line with this, heat unit requirement by plants was the greatest at low plant densities to shed 50% pollen per plot. Regarding days to physiological maturity, plants took relatively more days to attain their physiological maturity for all rows at lowest plant density. A clear understanding of the phenology of a crop is essential in physiological and agronomic studies of the crop, because seasonal dry matter accumulation is a function of the duration of the life cycle of annual crops like maize. With increased plant density beyond the optimum, the emergence of ear barrenness was initiated. This had a negative impact on expected grain yield that caused a decrease in number of kernels per ear due to formation of few flowers, poor pollination and abortion of kernels after fertilization. On the other hand, wide row spacing coupled with low plant density prolonged the vegetative growth phase which is undesirable with respect to resource utilization. Grain yield recorded in Chapter 4 indicated that row spacing of 0.45 m combined with a plant density of 100 000 plants ha^{-1} gave the highest grain yield. It was proved that balanced phenological development occurred at the row spacing of 0.45 m and the plant density of 100 000 plants ha^{-1}. Therefore, the combination of a 0.45 m row spacing with the plant density of 100 000 plants ha^{-1} is considered the optimum combination for the ultra-fast maize hybrid under consideration.

CHAPTER 6

EFFECT OF ROW SPACING AND PLANT DENSITY ON WATER USE AND WATER USE EFFICIENCY OF MAIZE

6.1 Introduction

Successful maize production requires an understanding of various management practices as well as environmental conditions that affect crop performance (Eckert, 1995). Thus, crop management practices such as tillage, crop rotation, row spacing and plant density can affect the water use efficiency (WUE) of crops (Angus & Van Herwarden, 2001). Selection of appropriate cultivars, planting dates, water supply and cultural practices have shown to affect maize yield potential and stability (Norwood, 2001). Any cropping system that improves WUE is a means of increasing crop production in the face of finite water supplies (Richards *et al*., 2002). Development of agronomic systems that are based on efficiency, rather than production, will increase the sustainability of production systems (Hatfield *et al.*, 2001). In line with this, WUE continues to be the interest of most plant and soil scientists. Angus & Van Herwarden (2001) and Passioura (2006) also indicated that efficient crop water use can be used to assess whether yield was limited by water supply or some other factor. To increase WUE, more of the initial water resource should be routed into transpiration by reducing unproductive water losses (evaporation of soil water, drainage and runoff). Therefore, WUE by higher plants is of vital importance in agricultural ecosystems (dry land and irrigation) in terms of the development of water conserving agriculture (Udayakumar *et al*., 1998).

Irrigated agriculture plays a vital role in stabilizing grain production and strengthening food security. The main emphasis of enhancing WUE in irrigated cropping is to increase crop yield per unit of water applied and the reallocation of water to other priority areas. Irrigation scheduling can be an effective technique of attaining high WUE crops by increasing yield or reducing water use. Water requirements of a crop vary with genotype and environmental conditions. Basically total dry matter or production of economic yield is related water use by crops (Taylor *et al*., 1983; Jensen *et al*., 1990; Khan *et al*., 2001). The term WUE originates in the economic concept of productivity, which measures the amount of any given resource that must be expended to produce an output unit (Eck, 1986; Howell *et al*., 1998). Water use efficiency describes a plant’s photosynthetic production rate relative to the rate at which it transpires water to the atmosphere and thus measures the performance of a plant (Bacon, 2004). In simple terms, increasing WUE means lowering the water needs to achieve a higher unit of production. Therefore, in agricultural systems, optimum water management should be established to maximize the WUE, which is associated with economic yield produced with corresponding total amount of water consumed (Kafkafi, 1997). This led to the concept of WUE which was defined as crop total biomass or grain yield per unit of water used, which is also a useful factor to determine the seasonal water requirement of a crop (Brown, 1999).

Optimizing plant density is crucial in semi-arid dry land areas where crop growth is constrained by precipitation and a high evaporative demand. High plant densities may deplete most of the available water before the crop reaches maturity, while low densities may leave water unutilized in the soil (Bayu *et al*., 2004). However, optimum plant density varies considerably worldwide, depending on the environment, production system, water supply and cultivar selected (Ozer, 2003). Plant density has been observed to have a large impact on growth, development and grain yield by affecting water use of the crop (Momoh & Zhou, 2001). It was also reported that among several natural resources, water is often the most limiting dry land factor in crop growth, development and final yield (Francis, 1989). Thus, severe crop water stress will usually result in growth reduction at any stage of development. Crops differ with respect to their sensitivity to crop water stress at different growth stages. Crop water sensitivity is invariably linked with plant density indicating that the more plants per unit area, the higher the expected yield to a certain limit (Bertoria *et al.,* 1998). Thus, for each production system, there is a plant density that can maximize the utilization of available resources, such as water, allowing the expression of maximum potential attainable yield. In line with this, maize is known to be more sensitive to variations in plant density as compared to other members of the grass family where its growth and development is influenced by these variations (Casal, 1985; Almeida & Sangoi, 1996). On the other hand, limited research studies in water use of modern high yielding and ultra-fast maize hybrids at variable plant densities have been reported on. One of the strategies of producing an acceptable yield is manipulation of crop management practices targeted with an efficient utilization of a limited resource like water (Zwart & Bastiaanssen, 2004). Hence, this study was conducted to evaluate the effect of row spacing and plant density on water use of an ultra-fast maize hybrid under irrigation in the central part of South Africa.

6.2 Materials and methods

6.2.1 Experimental conditions

A field trial was conducted for two consecutive seasons (2008/09 to 2009/10) at the Kenilworth Experimental Station of the Department of Soil, Crop and Climate Sciences, University of the Free State (UFS), north-west of Bloemfontein. Regarding the experimental site, agro-meteorological data, soil physical and chemical properties, particle distribution and bulk density of the profile, summary of treatment combinations and agronomic practices used are described in Chapter 3 section 3.2.1, 3.2.2 and 3.2.3, respectively.

6.2.2 Field trial layout

Due to financial constraints and therefore the inability to acquire enough neutron access tubes at the time of the experiment, the trial was non-replicated, but repeated for two seasons on the same plots. For the non-replicated trial, utilization of a two factor split plot arrangement is natural, convenient and efficient to run for such an experiment (Cox, 1958; Sokal & Rohlf, 1981; Box & Jones, 1992). Therefore, the irrigation trial was laid out in a split plot arrangement of two factors. In this arrangement row spacing referred to as the main plot factor while plant density as subplot factor. The treatment combination with the theoretical and actual plant densities are summarized in Chapter 3 (Table 3.4).

6.2.3 Irrigation

6.2.3.1 Method of irrigation

The trial was irrigated with a single tower centre pivot irrigation system. All emitters were equipped with pressure regulators and calibrated before the onset of the experiment. The coefficient of uniformity was 90% and the application rate capacity was measured as 12 mm day^{-1}, which is sufficient for the peak water use of maize for a target yield of 10 t ha^{-1} and with a reference plant density of 100 000 plants ha^{-1}. The crop was irrigated weekly and irrigation amounts were determined by measuring soil water with a neutron soil water meter.

6.2.3.2 Irrigation scheduling and soil water measurement

Twenty neutron soil water access tubes were installed prior to planting in the center of each plot to a depth of 1.8 m. Soil water content was measured at 0.3 m intervals to a depth of 1.8 m using a calibrated neutron probe. Irrigation was conducted at weekly intervals from planting to crop physiological maturity based on a predetermined refill point (PRP) from previous studies of the site (Van Rensburg, 1988). The PRP was calculated as the drained upper limit (DUL) of plant available water (PAW) with a value of 421 mm 1.8 m^{-1}. Thirty mm was subtracted from 421 mm to allow rain storage if rain would occur immediately after irrigation. The profile soil water content was kept at the PRP of 391 mm 1.8 m^{-1} by replenishing it weekly with an amount equal to the deficit i.e. Deficit = PRP – total soil water content. The volumetric water contents were converted into depth of water in mm per 1.8 m soil depth. The irrigated amounts and rainfall recorded are summarized in Chapter 3 (Table 3.5).

6.2.3.3 Change in soil water content

The change in soil water content (ΔW - mm) was calculated as the difference between the total root zone water contents of two consecutive measurements.

6.2.3.4 Precipitation

Precipitation (P - mm) was recorded from rain gauges placed on four corners of the experiment and the recorded values were averaged and taken into account. Detail of the rainfall recorded is summarized in Chapter 3 (Table 3.5).

6.2.3.5 Drainage and runoff

The water holding capacity of the root zone is expressed by the DUL value of 421 mm. In this study deep percolation (DP) is the internal drainage beyond the root zone and was considered negligible, because the highest measured soil water content was 416 mm, which was below the DUL. Moreover, the rainfall characteristics during the growing seasons were highly influenced by the amount, intensity and duration. Rainfall during the growing season was poorly distributed. The highest rainfall intensity (< 25 mm hr^{-1}) was lower than the infiltration of the soil (33 mm ha-1-Chimungu, 2009) thus it was assumed that runoff was negligible.

6.2.3.6 Evapotranspiration

In field research, water use of a crop has commonly been defined as the evapotranspiration (ET) component of water balance. Therefore, water use of maize is the seasonal ET, which is the quantity of water used in transpiration and that evaporated from the soil from planting to crop physiological maturity and was determined by solving the ET components of the water balance by using Equation 2.5 in Chapter 2.

6.2.3.7 Leaf area Index

Leaf area index was measured using a LI 3000 portable leaf area meter (Lambda Inst. Corp) on randomly selected plants (3) where three leaves per plant from the bottom, middle and top with the main ear as a reference at silking (63 DAE). Here the LAI is used for correlation with seasonal ET; otherwise LAI was dealt with in detail in Chapter 3 as an indicator.

6.2.3.8 Biomass and grain yield

Grain was manually harvested from a plot area of 1.8 m x 7 m = 12.6 m^2 and converted to kg ha^{-1} after adjusting the moisture content to 12.5%. Biomass yield was estimated as the sum of stover weighed and the grain yield.

6.2.3.9 Water use efficiency calculations

Water use efficiency was calculated as the ratio of total biomass and of grain yield (kg ha^{-1}) to seasonal ET estimated by using Equations 2.3 in Chapter 2.

6.2.3.10 Crop water requirement

Crop water requirement refers to the amount of water needed to meet water loss through ET and determined using the formula (FAO, 2006, 2010):

$$ET_{crop} = (KC \times ETo)\ GD \qquad (6.1)$$

Where: KC = Crop factor
ETo = Reference ET
GD = Growing day

Crop factor (KC) was estimated as the ratio of actual ET (ETcrop) to potential ET (ETo). In estimating KC the mean values of ETcrop and ETo of two cropping seasons (2009 & 2010) were used.

6.2.4 Statistical analysis

A two way interaction effect of row spacing x plant density analysis was adopted (Abeysekara & Abeysiriwardena, 2001) using the general linear model SAS version 9.1 (SAS Inst., 2003). Treatment means were compared using the least significant difference (LSD) at a 5% level of probability.

6.3 Results

A summary on the combined analysis of variance over seasons showing the effect of treatment factors on soil water balance indicators, biomass, grain yield, seasonal ET, mean daily ET and WUE of biomass and grain yield are presented in Tables 6.1 and 6.2. The results showed that row spacing and its interaction with plant density did not result in significant differences of any of the water components: soil water content, soil water change, seasonal ET and mean daily ET throughout the growing season. In contrast, plant density resulted in significant differences in seasonal and mean daily ET at 105 DAE. The greatest amount of water use (428 mm) was recorded at a plant density of 125 000 plants ha^{-1} followed by 100 000 plants ha^{-1} (427 mm). The lowest amount of water (393 mm) was consumed at a plant density of 50 000 plants ha^{-1}. Similarly, the highest mean daily ET of 5.6 mm day^{-1} was recorded at a plant density of 125 000 plants ha^{-1} followed by 100 000 plants ha^{-1} with a mean daily ET of 5.4 mm day^{-1}. The lowest mean daily ET of 5.0 mm day^{-1} was measured at a plant density of 50 000 plants ha^{-1}.

Significant differences were detected due to effect of row spacing by plant density interaction on biomass, grain yield and WUE (biomass and grain yield) of maize. **T**he greatest biomass (22659 kg ha^{-1}) was recorded at a row spacing of 0.225 m with a plant density of 100 000 plants ha^{-1} followed by the same row spacing and a plant density of 125 000 plants ha^{-1} (22473 kg ha^{-1}). The lowest biomass (16884 kg ha^{-1}) was recorded at a row spacing of 0.90 m with a plant density of 50 000 plants ha^{-1}. The highest grain yield (12429 kg ha^{-1}) was obtained from a row spacing of 0.45 m with a plant density of 100 000 plants ha^{-1} followed by a row spacing of 0.90 m at the same plant density (11948 kg ha^{-1}). The lowest grain yield (7774 kg ha^{-1}) was recorded at a row spacing of 0.225 m and a plant density of 50 000 plants ha^{-1}. Regarding WUE, the highest biomass WUE (52.7 kg ha^{-1} mm^{-1}) was recorded at a row spacing of 0.45 m with a plant density of 125 000 plants ha^{-1} followed by a 0.90 m row spacing with a plant density of 100 000 plants ha^{-1} (52.6 kg ha^{-1} mm^{-1}). The lowest biomass WUE (42.4 kg ha^{-1} mm^{-1}) was recorded at a row spacing of 0.225 m with a plant density of 150 000 plants ha^{-1}. The highest grain yield WUE (28.7 kg ha^{-1} mm^{-1}) was recorded at a row spacing of 0.45 m and a plant density of 100 000 plants ha^{-1} followed by row spacing of 0.90 m and a plant density of 100 000 plants ha^{-1} (26.3 kg^{-1} ha^{-1} mm^{-1}). The lowest grain yield WUE (18.6 kg ha^{-1} mm^{-1}) was obtained from a row spacing of 0.225 m with plant density of 150 000 plants ha^{-1}. It is clear from the summary of result that the water components were not influenced by the row spacing by plant density interaction. However, only plant density significantly affected the seasonal and mean daily ET. Based on this, the effect of the treatment factors on the seasonal ET, mean daily ET and WUE will be dealt with in detail in the following section. Since the effect of the treatments on biomass and grain yield were dealt with in detail in Chapter 4 the emphasis will be on the water components and yield in relation WUE.

Table 6.1 Summary of analysis of variance indicating the effect of treatment factors on water components, yield and WUE

Water parameters	Factors	Days after emergence														
		7	14	21	28	35	42	49	56	63	70	77	84	91	98	105
Water components																
Soil water content (mm)	RS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	PD	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	RS x PD	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Soil water change (ΔW) (mm)	RS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	PD	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	RS x PD	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Seasonal ET (water use) (mm)	RS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	PD	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
	RS x PD	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Mean daily ET (mm day^{-1})	RS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
	PD	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*
	RS x PD	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Biomass yield (kg ha^{-1})	RS															*
	PD															*
	RS X PD															*
Grain yield (kg ha^{-1})	RS															*
	PD															*
	RS x PD															*
Water use efficiency (kg ha^{-1} mm^{-1})																
Biomass	RS															*
	PD															*
	RS x PD															*
Grain yield	RS															*
	PD															*
	RS x PD															*

*= Significant at 5% probability level, ns=not significant, RS=row spacing, PD=plant density.

Soil water content: Is the quantity of water present in soil at 1.8 m depth during measurement

Soil water change: It is the difference in soil for two consecutive measurements.

Daily ET: Consumptive use during given sampling interval divided by interval between sampling days used less water during growing season.

Table 6.2 Effect of row spacing and plant density on water components and crop yield

RS (m)	PD (x 1000 ha^{-1})	Seasonal ET (mm)	Mean daily ET (mm day^{-1})	Biomass (kg ha^{-1})	Grain yield (kg ha^{-1})	Biomass WUE (kg ha^{-1} mm^{-1})	Grain yield WUE (kg ha^{-1} mm^{-1})
0.225	50	392	5.1	17494^{de}	7774^{e}	44.6^{de}	19.8^{cde}
	75	430	5.1	19479^{de}	9695^{bcd}	45.3^{cde}	22.5^{bcd}
	100	435	5.4	22759^{a}	9984^{bcd}	52.3^{ab}	22.7^{bcd}
	125	458	5.7	22473^{ab}	9381^{bcde}	51.3^{abc}	21.4^{cde}
	150	410	4.9	17398^{ef}	7665^{cde}	42.4^{e}	18.6^{e}
0.45	50	395	4.9	18079^{ef}	10360^{bcd}	45.7^{cde}	26.2^{ab}
	75	417	5.2	21221^{bc}	10722^{abc}	$49.1^{a\text{-}d}$	25.7^{abc}
	100	432	5.2	21983^{ab}	12429^{a}	$50.8^{a\text{-}d}$	28.7^{a}
	125	419	5.5	22116^{cde}	9738^{bcd}	52.7^{a}	23.2^{b}
	150	424	4.8	20348^{cde}	8769^{de}	47.9^{bc}	20.6^{de}
0.90	50	393	4.9	16884^{f}	8942^{bcd}	42.9^{de}	25.8^{abc}
	75	419	5.0	20036^{def}	10806^{ab}	47.8^{bc}	25.7^{abc}
	100	415	5.5	21906^{def}	11948^{ab}	52.6^{a}	26.3^{ab}
	125	425	5.1	20749^{cde}	9897^{bcd}	$48.8^{a\text{-}d}$	23.2^{b}
	150	406	5.1	20279^{cde}	9167^{bcd}	49.9^{bc}	22.5^{bcd}
	LSD$_{(T\leq0.05)}$	ns	ns	3777	1917	10.0	4.6
RS mean	0.225	421	5.2	18869^{b}	9139^{b}	44.8^{b}	21.7^{b}
	0.45	418	5.1	22544^{a}	10423^{a}	53.9^{a}	24.9^{a}
	0.90	412	5.1	21329^{ab}	10194^{a}	51.8^{ab}	24.7^{ab}
	LSD$_{(T\leq0.05)}$	ns	ns	2656	857	4.4	2.0
PD mean	50	393^{c}	5.0^{c}	18479^{b}	9462^{bc}	46.9^{c}	24.0^{b}
	75	422^{b}	5.1^{bc}	20873^{ab}	10408^{ab}	49.4^{ab}	24.6^{ab}
	100	427^{a}	5.4^{a}	21462^{a}	11121^{a}	50.2^{ab}	26.0^{a}
	125	428^{a}	5.6^{a}	20988^{ab}	9672^{bc}	50.5^{a}	22.6^{cd}
	150	413^{ab}	5.1^{c}	19735^{b}	8934^{c}	47.7^{bc}	21.6^{d}
	LSD$_{(T\leq0.05)}$	20	0.2	2057	1107	5.7	2.7
	CV (%)	4.8	4.6	10.5	9.0	10.0	8.7

RS = row spacing, PD = plant density, ns = not significant

6.4 Discussion

6.4.1 Water

Water use of maize is the seasonal ET, which is the sum of water used for transpiration and that evaporated from the soil from planting to crop physiological maturity. Since seasonal ET and water use are equivalent terms, water use will be used in this discussion. The results indicated that the main effects of row spacing and its interaction with plant density did not have a significant effect on water use. However, plant density affected water use significantly.

In general, crop water use exhibited a curvilinear relationship with plant density being the highest at the optimum plant density followed with a subsequent decline as plant density increased beyond this critical level (Figure 6.1a). Three distinct phases were observed in the relation between water use and plant density. In the first phase, water use rapidly increased from a plant density of 50 000 to 100 000 plants ha^{-1}. It was obvious that both evaporation and transpiration occurred to a large extent due to a lower number of plants per unit area where mutual shading and soil surface coverage were nearly minimum / negligible. Therefore, increasing the number of plants per unit area was accompanied with a progressive advancement in water use until a maximum of 100 000 to 125 000 plants ha^{-1} was reached. This suggests that plant density levels below 100 000 plants ha^{-1} were below the optimum with a smaller LAI which necessitates the addition of more plants to optimize water use. Otherwise, the available soil water is liable to non-productive losses such as drainage and evaporation. Indeed, the simplest way of increasing LAI is by manipulating plant density, because of their direct relationship. Tetio-Kagho & Gardner (1988b) reported that increasing LAI with manipulation of plant density consequently increases water consumption by crops to a certain critical optimum under irrigation and this critical optimum varies with maize cultivar. Amanullah *et al.* (2008) also reported that an increase in plant density is coupled with a corresponding proportional increase in LAI with subsequent maximization of water use.

At the second phase, water use reached the plateau in plant densities between 100 000 to 125 000 plants ha^{-1}. At this plateau increasing plant density from 100 000 to 125 000 plants ha^{-1} (25 000 plants ha^{-1}) surprisingly did not show visible change in water use. The curvilinear correlation between water use and LAI best explains the dependency of water use on LAI indicating that water use is directly related to the number of plants per unit area. According this result the highest water use of 428 mm occurred nearly at a LAI of 6 to 7.5 (Figure 6.1c). Several researches reported different mean water uses for maize under irrigation like, Morey *et al*. (1980) 375 mm, Hammond (1981) 435 mm and Hook (1985) 430 mm for early maturing maize cultivars whereas Mayaki *et al*. (1976) 625 mm, Retta & Hanks (1980) 550 mm, Mukhala (1998) 718 mm and Ali (2003) 559 mm for late maturing ones. The similarities and differences in water use of these studies' results and the aforementioned could be attributed to maize genotype, length of growing period as well as climatic differences.

Water use increased with an increased LAI up to 7.5 and then declined for LAI values above this. This suggested that the LAI values either below 6 or above 7.5 are negatively associated with water use. This LAI range is a reflection of plant densities between 100 000 and 125 000 plants ha^{-1} where a higher seasonal water use occurred. Adelana & Milbourn (1972) and Duncan (1975) reported mean LAI values of 5 and 5.3 for early maturing maize cultivars under irrigation for a maximum yield with efficient water use. They also indicated a decline in water use when the LAI exceeded 7.5. Barriere & Traineau (1986) reported that the optimum mean LAI was 6 for silage maize, whereas Howell *et al*. (1996) observed a LAI of 5 for a full hybrid maize under irrigation. Van Averbeke & Marais (1992) concluded that plant density and LAI with respect to water use is dependent on the production targeted (biomass or grain yield). For biomass production they recommended a plant density of 110 000 plants ha^{-1} and a LAI of 8 while for grain yield a plant density of 90 000 plants ha^{-1} and a LAI of 7. This indicates that the optimum LAI for optimum water use is in between 6 and 7 which correspond to a plant density of a 100 000 to 125 000 plants ha^{-1}. In this study the optimum grain yield was recorded at the row spacing of 0.45 and 0.90 m and the plant density of 100 000 plants ha^{-1}, which indicates that the optimum LAI was within the limits of 6 to 7 and was achieved at a plant density of 100 000 to 125 000 plants ha^{-1}.

At the third phase, water use declined rapidly with an increase in plant density from 125 000 to 150 000 plants ha^{-1} (Figure 6.1a). Thus, the addition of more plants per unit area reduced water use. This declining tendency in water use at higher plant densities was likely due to a much greater LAI which resulted in mutual shading of plants with proportional minimization of both transpiration and evaporation. At this declining point the LAI exceeded 7.5. Although the soil water content and soil water change (ΔW) were not statistically significant (Table 6.1), the highest soil water content (419 mm) and ΔW (+30.4 mm) were recorded at the highest plant density during the season. From this it is clear that soil water content was greater than water use indicating that excess water was stored in the soil profile. This probably suggests that an overcrowding plant density impaired transpiration due to a higher LAI which resulted in full coverage of the soil surface and mutual shading of adjoining plants as a result of the close proximity of plants. Hence, the excess water that may have built up in the soil profile is non-productive with respect to crop demand and probably can cause nutrient leaching from root zone.

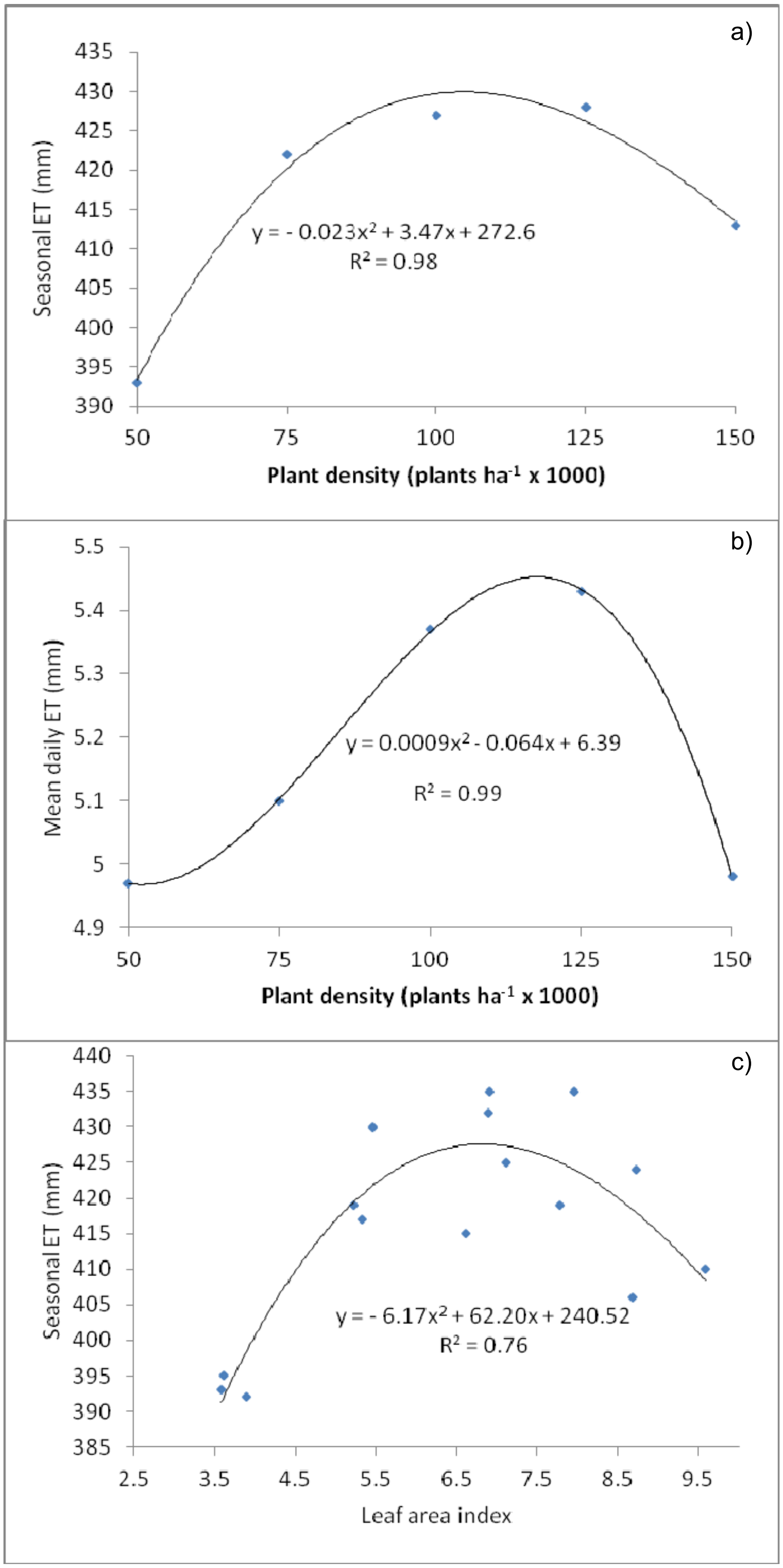

Figure 6.1 Water use (a) and daily ET (b) as affected plant density and their correlation with LAI (c)

The other negative impact of increasing plant density above the optimum is that the lower leaves becomes unproductive as a result of shading from upper leaves. Hence, optimum plant density should match with the availability of soil water in order to maximize the grain yield. Deviation from the optimum plant density could lead to loss of soil available water (Holt & Timmons, 1968; Karlen & Camp, 1985b; Bayu *et al,* 2004). Therefore, the optimum LAI according to these results was between 100 000 and 125 000 plants ha^{-1}. Mean daily ET in response to plant density followed a similar trend at the mentioned three phases and confirmed the phenomenon. However, an appropriate recommendation has to be based on the efficiency of water use with respect to the purpose of production either biomass (e.g. silage) or grain yield.

6.4.2 Water use efficiency

Water use efficiency refers to different processes and ratios. Here WUE refers to the ratio of yield either biomass or grain to water use (seasonal ET) during crop growth. Spatial arrangement of row spacing by plant density resulted in an influence on WUE of maize. In this case WUE will be dealt with in terms of biomass and grain yield. A basic principle that should be implemented to manage the soil water balance is ensuring minimum unproductive water loss in order to increase the amount of water that can be transpired. In this regard spatial arrangement of row spacing by plant density plays a prominent role in WUE. Indeed, row variations coupled with varying plant density influences WUE by affecting the magnitude of land surface coverage (LAI), light distribution, relative directional skewness (north-south or east-west) and land surface area occupied by a single plant.

In an attempt to explain and understand row spacing by plant density effect on WUE, the biomass WUE is grouped into three *viz.* WUE values above 50 kg ha^{-1} mm^{-1} (*high)*, 46 to 50 (*moderate)* and WUE values below 46 kg ha^{-1} mm^{-1} (*low)* (Figure 6.2 and Table 6.3). A relatively high WUE was recorded for spatial arrangements of 0.45 x 125 000, 0.90 x 100 000, 0.225 x 100 000, 0.225 x 125 000 and 0.45 m x 100 000 plants ha^{-1} with biomass WUE ranging from 50.8 to 52.7 kg ha^{-1} mm^{-1} with the highest at a row spacing of 0.45 m with a plant density of 125 000 plants ha^{-1} (Table 6.2). The approximate amount of water used by these spatial arrangements of row spacing and plant density ranged from 415 to 458 mm. In this category the physiological efficiency (HI) of converting DM to economic yield varied from 0.42 to 0.57 at the higher LAI values (> 6) with the exception of 0.225 m x 125 000 plants ha^{-1}. The lower LAI value at this treatment was probably due to overcrowding where plants attained a smaller LA on an individual basis. Row spacings of 0.225 and 0.45 m at a plant density of 125 000 plants ha^{-1} showed a higher WUE, but were associated with a lower HI. Spatial arrangements with a moderate WUE encompassed 0.90 x 150 000, 0.45 x 75 000, 0.90 x 125 000, 0.45 x 150 000 and 0.90 x 75 000 combinations with HI values ranging between 0.43 and 0.51. The LAI values varied from 5.32 to 8.98 with the lowest at a row spacing of 0.45 m with a plant density of 75 000 plant ha^{-1} and the highest at 0.45 m x 150 000 plants ha^{-1}. In line with this, treatments with low WUE consisted of 0.45 x 50 000, 0.225 x 75 000, 0.225 x 50 000, 0.90 x 50 000 and 0.225 x 150 000 plants ha^{-1} (Figure 6.2).

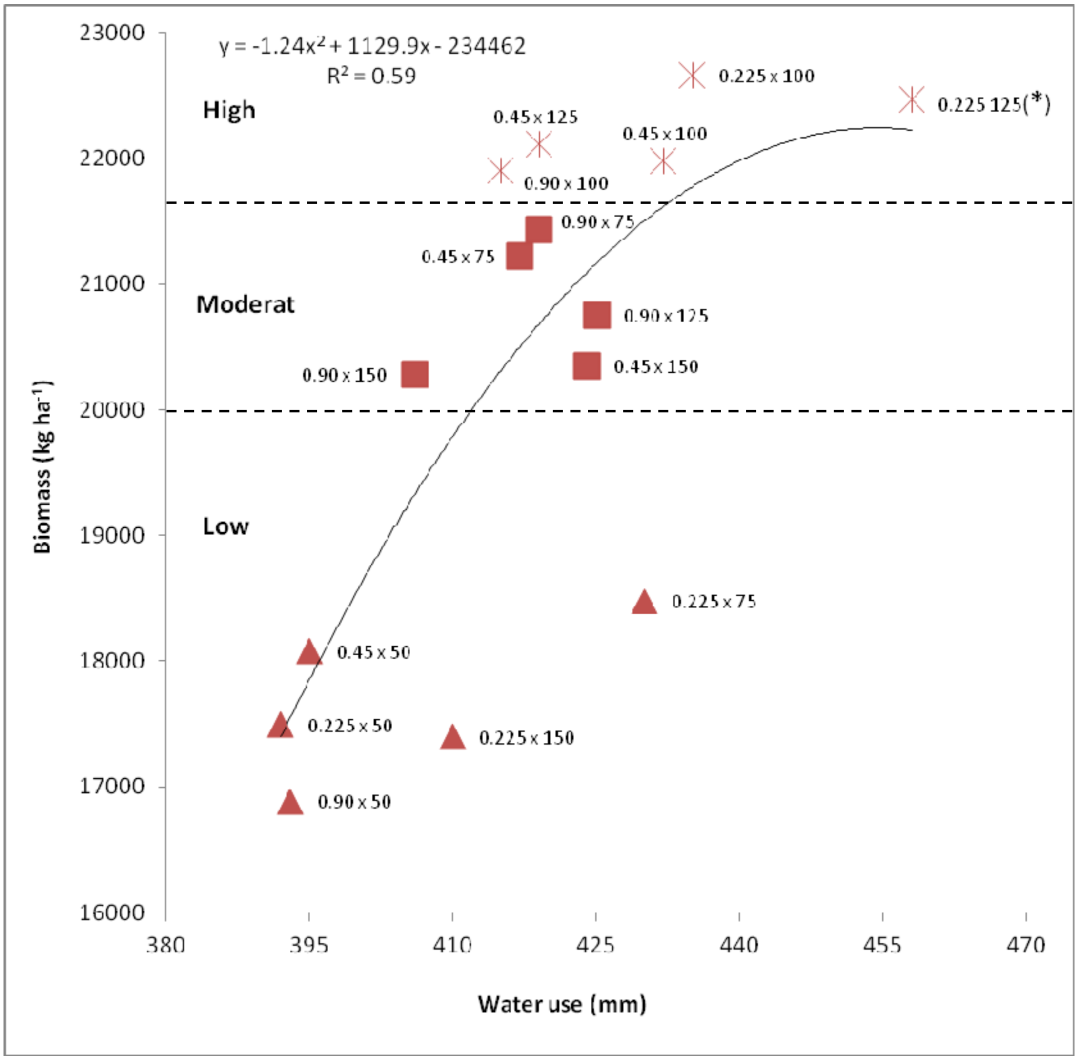

Figure 6.2 Effect of row spacing and plant density on WUE of maize (*) x 1000,

Table 6.3 **B**iomass WUE ranked from high to low with respective water use, HI and LAI

Category of WUE	RS (m)	PD (x 1000)	Biomass WUE (kg ha^{-1} mm^{-1})	Water use (mm)	HI	LAI
High	0.45	125	52.7	419	0.44	7.78
	0.90	100	52.6	415	0.56	6.62
	0.225	100	52.3	435	0.42	7.96
	0.225	125	51.3	458	0.41	5.22
	0.45	100	50.8	432	0.57	6.89
Moderate	0.90	150	49.9	406	0.45	8.98
	0.45	75	49.4	435	0.44	6.91
	0.90	125	49.1	417	0.51	5.32
	0.45	150	48.8	425	0.48	8.12
	0.90	75	47.9	424	0.43	8.72
Low	0.45	50	45.7	395	0.54	3.60
	0.225	75	45.3	430	0.49	5.46
	0.225	50	44.6	392	0.44	3.89
	0.90	50	42.9	393	0.53	3.58
	0.225	150	42.4	410	0.44	9.59

RS= row spacing, PD=plant density

The major target of spatial arrangement (row spacing by plant density) is to maximize potential economic yield with the efficient utilization of irrigation water. Basically efficient water utilization requires that plant density should be matched with the water supply intended to maximization of plant transpiration with a corresponding minimization of soil water evaporation. Hence, deviation of row spacing and plant density from the optimum (0.45 m x 100 000 plants ha^{-1}) resulted in a negative impact on biomass WUE by affecting the DM accumulation during the growing season. Selecting 0.225 m row spacing for maize production is undesirable due to two possible justifications. The first justification is that a reduction in row spacing from 0.45 to 0.225 m at an optimum plant density (100 000 plants ha^{-1}) resulted in a yield loss (19.7%) while widening to 0.90 m had no significant effect on grain yield (Table 6.2). The other undesirable aspect of using narrow row spacing (0.225 m) in maize is unfitness of the inter row width with the morphological nature of maize as well as difficulties for management operations. Therefore, selecting a row spacing of 0.225 m in maize production is out of the question. In line with this, a row spacing of 0.45 and 0.90 m at a high plant density (PD ≥ 125 000 plants ha^{-1}) was characterized by a higher LAI (≥ 7) and low HI (< 0.50) suggesting that overcrowding impaired translocation of assimilates from source (vegetative part) to sink (the grain). Increasing plant density increased total biomass production, while grain yield was reduced due to poor mobilization of assimilates to grain. On the other hand, a lower plant density (PD ≤ 75 000 plants ha^{-1}) with a row spacing of 0.45 and 0.90 m resulted in a lower LAI and relatively greater HI, which suggests lack of competition among plants. However, from an economic point of view one needs to take into account grain yield maximization with adjustment of optimum plant density. Therefore, optimum plant density depends on the objective of production for either biomass or grain yield.

Water is one the most prominent factors that limits crop production in agriculture to address food sufficiency and security. Water use efficiency is closely related with the amount of biomass produced per unit of water consumed. The higher the productivity per unit water use, the higher the WUE indicating that water consumption of a crop is directly related to DM production (Taylor *et al*., 1983; Boyer, 1996). Singh (2010) also indicated the direct proportional relation between water use and grain produced for crop WUE and an alteration in row spacing and plant density beyond an optimum resulted in a negative impact on WUE. Mohamed *et al.* (1986) reported that in a too dense stand, the photosynthetic efficiency of leaves were affected due to more competition for available soil water which adversely affected plant growth and development resulting in a low DM accumulation with corresponding decline in WUE. Moreover, Momoh & Zhou (2001) indicated that a high plant density caused water stress resulting in a reduction in growth, development and grain yield with a consequent decline in WUE. On the other hand, at low plant densities a lower LAI and less coverage of the soil surface where soil water was subjected to evaporation resulted in low productivity in terms of per unit of water consumed. Stanhill (1986), Tuong & Bhuiyan (1999) and Bayu *et al.* (2004) indicated that the soil available water at low plant densities was subjected to non-photosynthetic losses such as evaporation, seepage and runoff that results in a reduction of the total productive water use by crop plants. As this investigation showed that a row spacing of 0.45 or 0.90 m with a plant density of 100 000 plants ha^{-1} was likely to be the optimum for this ultra-fast maize hybrid under irrigation. The highest grain yield with the greatest grain yield WUE was recorded at a row spacing of 0.45 m with a plant density of 100 000 plants ha^{-1} which was not significantly more efficient than that of 0.90 m at the same plant density and therefore also justify the agronomic practices currently (0.90 m by 80 000 plants ha^{-1}) used (Table 6.2).

6.4.3 Irrigation scheduling and crop water requirements

Crop water requirement refers to the amount of water needed by a crop to grow optimally and depends on the climate, crop type and crop growth stage (FAO, 2006, 2010). Irrigation scheduling is one of the strategies to be implemented to apply water efficiently at the right time and amount. Knowledge of the optimum row spacing and plant density for the selected ultra-fast maize hybrid from this study is (0.45 or 0.90 m with a plant density 100 000 plants ha^{-1}). Crop water requirements could be scheduled on a weekly basis at four maize growth phases (Figure 6.3) *viz*. establishment (7-21 DAE), vegetative (28-49 DAE), early reproductive (56-77 DAE) and late reproductive (84-105 DAE). For more clarification, the reproductive phase is further grouped into a flowering stage (56-63 DAE), an early grain filling stage (70-84 DAE) and a late grain filling stage (91-105 DAE). Form the results it is clear that the selected ultra-fast maize hybrid could use 467 mm water from planting to crop physiological maturity (Table 6.4). Aslam *et al*. (2000) reported a mean water requirement of 375 mm for maize with growing period of 80 days which differed greatly from findings of this study. This differences might be attributed to environmental factors, cultivar and management practices. It therefore has to be emphasised that crop water requirements varies greatly throughout the growing season and maize water requirement scheduling should therefore also take into account climatic factors (temperature, rainfall, humidity and wind speed), crop variety, length of growing period, crop management system, water availability (Waldren, 1983) and the environment where maize is grown. Maize requires the greatest amount of water during the vegetative phase (28% of total) followed by early grain filling or cob formation (23%). A relatively lower water requirement was found at establishment and late grain filling phases. Therefore, the application scheduled amount of water at each growth phases is of paramount importance for proper growth and development with subsequent maximization of the yield.

Table 6.3 Crop water requirement scheduling for optimum row spacing and plant density combinations

Days after emergence	**ETo (mm day^{-1})**	**ETcrop (mm day^{-1})**	**KC**	**Water need (mm day^{-1})**	**Water need (mm week $^{-1}$)**
7	7.20	3.03	0.4	2.9	20.3
14	7.75	3.30	0.4	3.1	21.7
21	6.89	4.40	0.6	4.1	28.7
28	4.59	3.43	0.7	3.2	22.4
35	5.73	5.43	0.9	5.2	36.4
42	5.51	5.57	1.0	5.5	38.5
49	4.35	4.69	1.1	4.8	33.6
56	4.65	5.04	1.1	5.1	35.7
63	5.60	6.10	1.1	6.2	43.4
70	4.67	5.24	1.1	5.1	35.7
77	4.66	5.22	1.1	5.1	35.7
84	4.71	5.30	1.1	5.2	36.4
91	4.32	3.99	0.9	3.9	27.3
98	4.40	4.04	0.9	4.0	28.0
105	3.64	3.02	0.8	2.9	23.1
		Total			467

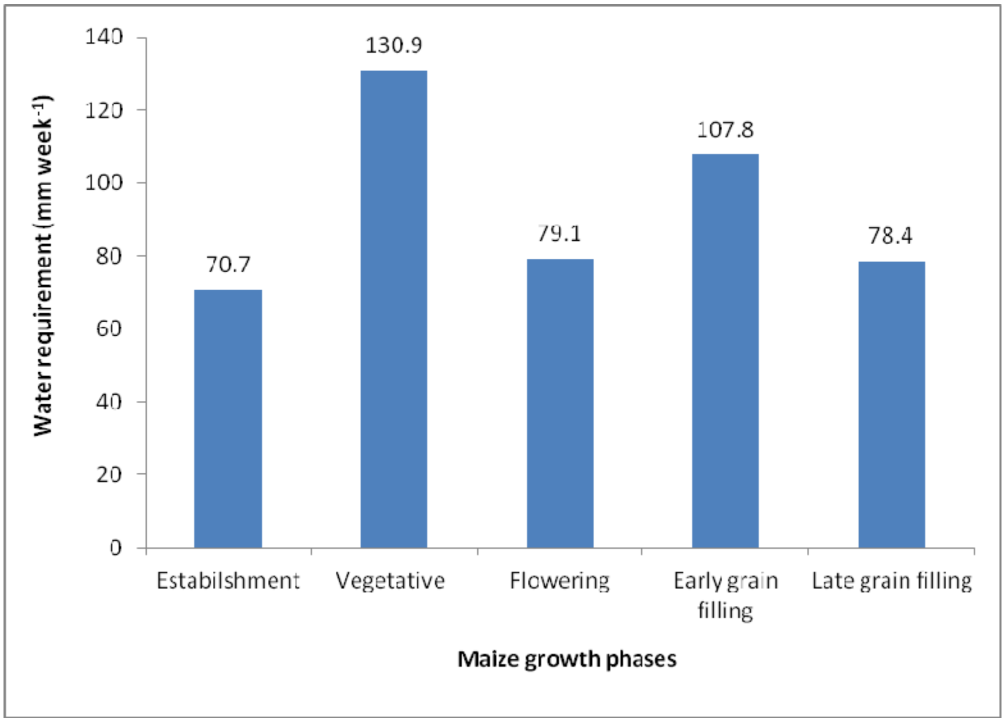

Figure 6.3 Water requirement of maize at various growth phases

6.5 Summary and Conclusion

Spatial arrangement of row spacing and plant density had a profound impact on water use and WUE of maize. The current investigation revealed that highest water use and mean daily ET occurred at the plant density of 125 000 plants ha^{-1}. The interaction effect of row spacing by plant density was significant. The significantly highest biomass WUE was gained by the row spacing of 0.45 m with the plant density of 125 000 plants ha^{-1}. Correspondingly the highest grain yield WUE was obtained from a row spacing of 0.45 m and a plant density of 100 000 plants ha^{-1}. This was followed by a row spacing of 0.90 m at the same plant density and did not differ significantly from aforementioned. Based on this finding it could be concluded that a row spacing of 0.45 or 0.90 m with a plant density of 100 000 plants ha^{-1} is the optimum, to be adopted for the selected ultra-fast maize hybrid under consideration.

CHAPTER 7

SUMMARY AND RECOMMENDATIONS

Grain yield is a function of several factors and processes, such as interception of solar radiation, metabolic efficiency of plants, translocation efficiency of photosynthates from leaves to economic parts, sink strength and genetic make-up of the crop. The photosynthetic capacity of a plant determines the overall productivity and the extent of development of each yield trait.

Sustainable maize production depends on the correct application of production inputs sustaining both the environment and agriculture. In an attempt to increase productivity, plant spacing has to be optimized, because grain yield per unit area is the product of grain yield per plant and number of plants per unit area. At low plant densities, grain yield is limited by an inadequate number of plants per unit area, whereas at too high densities, yield declines mostly because of an increase in the number of aborted kernels and/or barren plants. An optimum plant density should be maintained to efficiently exploit the growth factors, such as nutrients, sunlight and soil water to ensure productivity and economic sustainability of yields.

Considering factors influencing yield, plant density is an important factor determining grain yield of maize. Maize grain yield is the result of grain yield per plant and number of plants per unit area indicating that grain yield and number of plants per unit area are directly correlated. An optimum plant density for maximum economic yield exists for all crop species and varies with cultivar and environment. Plant densities above the optimum waste plant nutrients and water, because they lead to lower grain yields. Such reductions are often the result of fewer seeds per ear and a lower individual seed mass. One of the basic approaches to improve the productivity of ultra-fast maize hybrids under irrigation in a sustainable way is the integration of row spacing and plant density to fully exploit available resources. In this context, field experiments were conducted for two successive cropping seasons (2008/9 and 2009/10) at Kenilworth Experimental Station of the Department of Soil, Crop and Climate Sciences, University of the Free State, to evaluate crop growth, agronomic performance, phenological development, water use and WUE of an ultra-fast maize hybrid at different row spacing and plant densities under irrigation. In these experiments three row spacings (0.225, 0.45 and 0.90 m) and five plant densities (50 000, 75 000, 100 000, 125 000 and 150 000 plants ha^{-1}) were used. Treatments were combined in a factorial combination and laid out in a randomized complete block design with four replications where three replications were used for agronomic measurements. The last and largest block was used for periodic destructive sampling for growth analysis where a completely randomized design was adopted with replications consisting of five (5) randomly selected plants. Regarding soil water monitoring, twenty neutron probe access tubes were installed prior to planting in the center of each plot to a depth of 1.8 m in one of the three blocks of the agronomic study. The experiment was irrigated with a single tower center pivot irrigation system. The coefficient of uniformity was 90% and a capacity of 12 mm day^{-1}, which is sufficient for the peak water use of maize for a target yield of 10 t ha^{-1} and 100 000 plants ha^{-1}. In each season crop growth analysis, agronomic, phenologic, water use and WUE parameters were measured and the collected data were combined over seasons after carrying the homogeneity test of variances.

Growth parameters reacted differently to main and interaction effects of row spacing by plant density treatments at various growth phases. During the establishment phase, treatment effects on growth indicators were not significant. Regarding growth rate indicators, only LAI was significantly affected due to the interaction effect of row spacing by plant density with the greatest LAI recorded at a row spacing of 0.45 m with a plant density of 150 000 plants ha^{-1} (14 & 21 DAE). Significant effects were recorded for plant height and leaf area and started at 35 DAE while differences in DM accumulation per plant were recorded at 42 DAE. A row spacing by plant density interaction significantly affected growth indicators (plant height, leaf area and DM per plant) during the vegetative and reproductive phases. The tallest plants were observed at the row spacing of 0.225 m with the plant density of 125 000 plants ha^{-1} whereas leaf area (35 to 63 DAE) and DM (42 to 77 DAE) were greatest at the row spacing of 0.90 m with a plant density of 50 000 plants ha^{-1}. Similarly, LAI was significantly affected by the row spacing by plant density interaction during both the vegetative and reproductive phases. The greatest LAI was observed at the row spacing of 0.45 m with the plant density of 150 000 plants ha^{-1}. Only main effects of row spacing and plant density significantly affected NAR (14 to 63 DAE) with the highest values at the row spacing of 0.45 m and the plant density of 100 000 plants ha^{-1}. In line with this, CGR was only significantly affected by plant density (14 to 105 DAE) where the highest CGR was calculated at the plant density of 100 000 plants ha^{-1}. In general, the establishment phase was characterized by a slow accumulation of growth indicators while the vegetative phase was characterized by an exponential increase of the indicators. During the reproductive phase, the accumulation of growth indicators ceased following the onset of flowering. Grain yield, growth indicators (plant height, leaf area and DM) and growth rate indicators (LAI, NAR and CGR) are considered reliable indicators to select an appropriate row spacing and plant density combination for the ultra-fast maize hybrid under consideration. Thus, growth analysis provided an excellent opportunity to monitor the independent and interaction effects of row spacing and plant density affecting growth and yield and opened the way to manage these factors in integrated systems.

Main and interaction effects of row spacing and plant density treatments significantly influenced most agronomic traits of maize. Development of barren plants and plant lodging increased with increased plant density where the highest number of barren plants and plants lodged were recorded at the row spacing of 0.225 m with the plant density of 150 000 plants ha^{-1}. Moreover, the significantly highest number of ears per plot was also at this row spacing by plant density combination. Prolificacy was inhibited as plant density increased and as a result the highest number of ears per plant was obtained from the lowest plant density (50 000 plants ha^{-1}). The spacing by plant density interaction resulted in significant differences in ear length, seeds per row and per ear, where all traits were highest at the row spacing of 0.90 m with the plant density of 50 000 plants ha^{-1}. Only main treatments of row spacing and plant density significantly affected ear diameter. The thickest ear diameter was measured at the row spacing of 0.90 m and at the plant density of 50 000 plants ha^{-1}. The row spacing by plant density interactions resulted in significant differences in TSW, biomass, grain yield and HI. The greatest biomass production was recorded at the row spacing of 0.225 m and the plant density of 100 000 plants ha^{-1} whereas the greatest TSW was recorded at the row spacing of 0.45 m and the plant density of 50 000 plants ha^{-1}. At the row spacing of 0.45 m with the plant density of 100 000 plants ha^{-1} grain yield and HI were the greatest.

Row spacing and plant density treatments altered the phenological development of maize. Increasing row spacing from 0.225 to 0.90 m relatively prolonged the number of days to anthesis and silking. Thus, plants cultivated in narrow rows (0.225 m) reached tasseling and silking slightly earlier than plants cultivated in wider rows (0.90 m). Similarly, plants required relatively more heat units when cultivated in wider rows than in narrower rows. The longest period to anthesis and silking was observed at the lowest plant density (50 000 plants ha^{-1}) and *vice versa*. The lowest plant density had the shortest ASI but this increased as plant density increased.

Row spacing and plant density, either as main effects or the interaction thereof, had a significant impact on water use and WUE of maize. The greatest water use and daily ET were observed a at plant density of 125 000 plants ha^{-1}, whereas both parameters were lowest at a plant density of 50 000 plants ha^{-1}. The greatest biomass WUE was observed at the row spacing of 0.45 m and the plant density of 125 000 plants ha^{-1} while the lowest biomass WUE was recorded at the row spacing of 0.225 m and the plant density of 150 000 plants ha^{-1}. The grain yield WUE was highest at the row spacing of 0.45 m and the plant density of 100 000 plants ha^{-1}.

This investigation revealed that:

1 Reduction of row spacing from 0.45 to 0.225 m, averaged over plant density, negatively affected NAR but the increased from 0.45 m to 0.90 m was negligible.

2 Plant density above or below 100 000 plants ha^{-1}, averaged over row spacing negatively affected NAR and CGR.

3 Narrow row spacing (RS = 0.225 m) combined with high plant densities (PD ≥ 125 000 plants ha^{-1}) resulted in the highest LAI and plant height while lower plant densities (PD ≤ 75 000 plants ha^{-1}) resulted in lower LAI where both situations had negatively impact on the final grain yield.

4 A wide row spacing (0.90 m) combined with a low plant density (PD < 75 000 plant ha^{-1}) gave the greatest leaf area and DM per plant but a plant density lower than 100 000 plants ha^{-1} was undesirable with respect to the final yield.

5 Reducing row spacing from 0.90 m to 0.45 m slightly improved grain yield, but a further reduction in row spacing from 0.45 m to 0.225 m intensified competition and interference that resulted in a decline of grain yield.

6 Increasing plant density above or reducing it below 100 000 plants ha^{-1} had a negative impact on grain yield either due to severe competition or underutilization of resources such as light.

7 With respect to the interaction of row spacing by plant density, the highest grain yield and grain yield WUE was obtained from a row spacing of 0.45 m at a plant density of 100 000 plants followed by row spacing of 0.90 m at the same plant density.

Aspects to be considered in future for modern ultra-fast maize hybrids with respect to plant density are:

1 understanding the morpho-physiological basis that underlies ultra-fast maize hybrids to tolerate density stress;

2 studies involving a large number of ultra-fast maize hybrids should be conducted over a wider range of locations and seasons;

3 studies regarding the amount and frequency of irrigation at variable row spacing and plant density combinations;

4 studies on integration of irrigation, fertilization and cultivar at variable row spacing and plant densities;

5 inclusions of root system studies in relation to plant density effects;
6 study of light distribution in a canopy and radiation use efficiency in relation to plant density;
7 study on crop-weed competition and interference at variable plant densities in relation to crop yield.

The current investigation clearly showed that the row spacing of 0.45 or 0.90 m combined with the plant density of 100 000 plants ha $^{-1}$ was optimum for efficient light capturing, crop growth rate, photosynthetic rate and final grain yield for the hybrid and growing conditions under considerations.

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